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*This dissertation is dedicated to my mother
for her endless love and support...*

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Abstract

As concerns over environmental sustainability rise, corporations must extend their efforts to improve their environmental performance while at the same time realizing economic growth. The endeavor represents challenges on both strategic and operational fronts, in particular regarding supply chains. This dissertation is thus motivated by the opportunity for businesses to improve their overall performance through their supply chain strategies and operations. In the first research project, we address the strategic opportunities by developing a theoretical framework to identify the dynamic capabilities required to obtain environmentally sustainable supply chains. We break down the internal and external capabilities in three hierarchical levels of organizational structure, and illustrate an application of the framework with a case study on the “zero waste to disposal” initiative of Nestlé. In the second, we focus on the operational opportunities by analytically optimizing the replenishment frequency of perishable products between two supply chain levels. We model the manufacturer-retailer relationship as a Stackelberg game and show that raw material and finished goods lifetimes are interrelated through the replenishment cycle, and that they significantly impact supply chain costs. In the final project, we address both strategic and operational opportunities by empirically modelling the drivers of spoilage for days-fresh products, in our case fruits and vegetables, using daily supply chain data from Migros, Switzerland's largest retailer. We quantify to what extent inventory, promotions, delivery type, commitment changes, order variations, order cycle, and quality issues influence spoilage and emphasize the necessity for specialized supply chain processes, tracking inventory age and damage, and collaboration with supply chain partners for this fundamental product category.

Keywords: Supply chain management, perishability, retail, dynamic capabilities, environmental sustainability.

Résumé

De part la préoccupation grandissante au sujet du développement durable, les entreprises vont devoir étendre leurs efforts à ce niveau, tout en continuant à parvenir à croître économiquement. Cet effort représente un défi stratégique et opérationnel, en particulier du point de vue des chaînes d'approvisionnement. Cette thèse est donc motivée par l'opportunité pour les entreprises d'améliorer leurs performances à travers les stratégies et les opérations de chaînes d'approvisionnement. Le premier projet de recherche est consacré à l'aspect stratégique et nous développons un cadre théorique qui identifie les capacités dynamiques requises pour une chaîne d'approvisionnement durable. Nous catégorisons les capacités internes et externes en trois niveaux de hiérarchie et démontrons une application du cadre théorique sur l'initiative de "zéro déchet" chez Nestlé. Dans le deuxième projet de recherche qui se porte sur l'aspect opérationnel, nous optimisons la fréquence de réapprovisionnement des produits périssables sur deux niveaux de la chaîne. Nous utilisons un modèle de jeu Stackelberg et démontrons que les durées de vie des matières premières et des produits finis sont liées et qu'elles influencent considérablement les coûts dans la chaîne. Le dernier projet de recherche porte sur l'aspect opérationnel ainsi que sur l'aspect stratégique. Nous modélisons empiriquement les facteurs qui influencent le déchet des produits très frais, dans notre cas les fruits et légumes, en utilisant les données journalières de la chaîne d'approvisionnement de Migros, le plus grand détaillant suisse. Nous quantifions dans quelle mesure des paramètres opérationnelles ont un impact sur les déchets. En outre, pour cette catégorie fondamentale de produits, nous soulignons l'importance des procédures spécialisées de chaînes d'approvisionnement, le suivi des produits, ainsi que la collaboration entre les partenaires de la chaîne.

Mots clés : Gestion de la chaîne d'approvisionnement, périssabilité, détaillant, capacités dynamiques, durabilité.

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1 Introduction

Companies need natural resources, such as reliable raw materials supplies and energy sources, in order to maintain and expand their economic activities. However, rapid human development represents a challenge for natural systems to continuously provide the required resources. Sustainable development represents the concept of sustaining finite resources to provide for future needs, and constitutes three dimensions: economic, environmental and social. These dimensions are known as the Triple Bottom Line, introduced by John Elkington (1997). In this dissertation, we simultaneously focus on the economic and environmental dimensions, and challenge the understanding that the two dimensions characterize a tradeoff. Instead, this dissertation is motivated by the opportunities for firms to simultaneously improve environmental and economic issues across their operations; hence the title: *Improving Firm Performance through Sustainable Operations*.

The global dispersion of natural resources and demand for goods often necessitates companies to operate on an international scale. The movement of required resources or goods, information, and finances in companies' operations leads us to the topic of supply chain management. From the perspective of supply chain management, we address strategic and operational decisions that improve the economic and environmental performance of firms within their supply chain.

An overview of the research projects that compose this dissertation is presented in Table 1.1. All three research projects in this manuscript (Chapters 2 to 4) share the same motivation:

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improving environmental and economic performance in supply chains. They are complementary in that they each address different levels of the supply chain with specific research problems of practical relevance, while covering both qualitative and quantitative issues.

Chapter 2 presents a research project entitled *Dynamic Capabilities in Sustainable Supply Chain Management: A Theoretical Framework*. In this chapter, we address the strategic positioning of firms to adapt sustainability practices in their supply chains. In the field of Sustainable Supply Chain Management (SSCM) it is well established that sustainability is a source of competitive advantage for companies. In the field of strategic management, capabilities that lead to such competitive advantage are called dynamic capabilities. While previous studies have addressed firms' external capabilities to obtain more environmentally sustainable supply chains, a holistic framework focusing on both internal and external capabilities is lacking.

This chapter is motivated by the idea that the behavior of any supply chain entity is governed by its internal dynamic capabilities, such as the organizational routines and processes. The research project addresses this gap in the literature, with an emphasis on firms' internal capabilities to obtain more environmentally sustainable supply chains based on the dynamic capabilities for sensing, seizing and transforming.

First, a holistic framework is presented, with a segregation of the sensing, seizing and transforming capabilities at three hierarchical levels of organizational structure. We base our theory on literature covering SSCM and dynamic capabilities, as well as in the intersection of the two streams. Subsequently, we illustrate an application of the framework with a case study on the "zero waste to disposal" initiative of Nestlé. We systematically reviewed and analyzed both quantitative and qualitative internal data, and confirm that the dynamic capability literature can be applied to SSCM.

The framework can be used by both practitioners and academics. For the former, the framework can be used to map out and identify capabilities at several organizational levels to ensure the facilitation of each capability within the firm, while for the latter, the framework provides guidance in understanding performance differences and behavior of individual companies in a competitive space where environmental goals are strict and supply chains are increasingly complex.

To conclude this chapter, we highlight that internal and external capabilities for information transparency and integration are crucial in firms' environmental sustainability efforts.

In chapter 3, we present our second research project, entitled *Optimal Replenishment Cycle for Perishable Items facing Demand Uncertainty*. This chapter looks at the operational decisions of firms that improve their economic and environmental sustainability performance. This chapter is motivated by opportunities to increase operational efficiency caused by the costs of demand uncertainty and product perishability.

We target the food industry, in which raw materials such as fresh fruit, vegetables and dairy products are processed into products with a longer shelf life. We consider a food supply chain with an upstream manufacturer and a downstream retailer - typical to food industries, and focus on improving the optimal replenishment policy.

In our model, the manufacturer processes raw materials into finished products, which are purchased by the retailer in each replenishment cycle. The fresh raw materials of the manufacturer are highly perishable, and the finished goods at the retailer face demand uncertainty and the risk of obsolescence. We model the manufacturer-retailer relationship as a Stackelberg game, where the retailer is the leader and decides the replenishment cycle that minimizes its supply and demand mismatch cost. The manufacturer is the follower and decides its processing rate to minimize its unit cost of finished goods.

The outcome of this research is the analytical solution for the optimal replenishment cycle given demand uncertainty, considering both raw material and finished product perishability in a manufacturer-retailer setting. We further quantify the relationship between the two perishability costs, and present our results with a numerical analysis.

Our results show that the raw material and finished goods lifetimes are interrelated through the duration of the replenishment cycle, and that they have a significant impact on supply chain costs. Although raw material spoilage costs are generally low, short raw material lifetimes have a significant impact on the costs of both the manufacturer and the retailer, while short finished goods lifetimes lead to suboptimal replenishment cycles, which increases costs for both parties.

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Chapter 2 focuses uniquely on the strategic positioning of firms, while Chapter 3 targets operational efficiency in the supply chain. In Chapter 4 however, we focus on both strategic and operational improvements. We present our research project entitled *Managing Perishability in the Fruit and Vegetable Supply Chain*. This chapter is motivated by the great opportunities for cost savings and reduced environmental footprints of spoilage in fresh food supply chains. In our case we focus on imported fresh fruits and vegetables, which have long lead times. For this product category, stores struggle with unpredictable demand; distribution centers struggle with order inaccuracy and product quality; importers struggle with order inaccuracy and product handling; producers need to know how much crop they need to produce multiple months in advance.

In order to identify effective solutions, we investigate the drivers of spoilage in the days-fresh category using daily spoilage and supply chain data (457,539 store-SKU level observations) for fresh fruits and vegetables at Switzerland's largest retailer. We quantify to what extent inventory, promotions, delivery type, commitment changes, order variations, order cycle, and quality issues influence spoilage.

In doing so, we also discuss the mechanisms through which inventory age and product standards impact spoilage of days-fresh products. Our findings underline the necessity for specialized supply chain processes, tracking inventory age and damage, and collaboration with supply chain partners in the management of this fundamental product category.

Finally, Chapter 5 closes this dissertation with a summary of the main conclusions and contributions of the three research projects presented in previous chapters.

	Research project I Chapter 2	Research project II Chapter 3	Research project III Chapter 4
<i>Title</i>	<i>Dynamic Capabilities in Sustainable Supply Chain Management: A Theoretical Framework</i>	<i>Optimal replenishment cycle for perishable items facing demand uncertainty</i>	<i>Managing perishability in the fruit and vegetable supply chain</i>
<i>General Topic</i>	<ul style="list-style-type: none"> Firm capabilities required to achieve sustainable supply chains 	<ul style="list-style-type: none"> The impact of replenishment decisions on perishability and supply chain costs 	<ul style="list-style-type: none"> Drivers of spoilage for days-fresh products
<i>Motivation</i>	<ul style="list-style-type: none"> Firms need both internal and external capabilities to achieve environmental sustainability in their supply chains 	<ul style="list-style-type: none"> Raw material and finished goods perishability costs are linked through supply chain decisions 	<ul style="list-style-type: none"> High spoilage costs of days-fresh products can be reduced with improved supply chain practices
<i>Main research questions</i>	<ul style="list-style-type: none"> What are the internal and external dynamic capabilities that enable firms to achieve environmental sustainability in their supply chains? 	<ul style="list-style-type: none"> What is the optimal replenishment cycle that minimizes the retailer's mismatch and shelf space costs under demand uncertainty and finished goods perishability? What is the optimal production rate that minimizes the manufacturer's raw material spoilage costs for a given replenishment cycle? 	<ul style="list-style-type: none"> What are the drivers of spoilage for days-fresh products? Which drivers represent the most effective levers to reduce spoilage?
<i>Methods</i>	<ul style="list-style-type: none"> Theory building Case study 	<ul style="list-style-type: none"> Mathematical modelling Optimization 	<ul style="list-style-type: none"> Econometric modelling Interviews
<i>Outcome</i>	<ul style="list-style-type: none"> Identifications of dynamic capabilities for sustainable supply chain management Specification of the dynamic capabilities at three levels of hierarchy 	<ul style="list-style-type: none"> Mathematical modelling of the replenishment cycle between retailer and manufacturer as an endogenous variable, analytical solution for the optimal replenishment cycle Quantification of the relationship between raw material and finished goods perishability costs 	<ul style="list-style-type: none"> Empirical and economic analysis of drivers of spoilage for days-fresh products Managerial insights to reduce spoilage throughout the supply chain

Table 1.1: Overview of the doctoral thesis

2 Dynamic Capabilities in Sustainable Supply Chain Management: A Theoretical Framework

2.1 Introduction

The field of Sustainable Supply Chain Management (SSCM) encompasses the three dimensions of sustainable development: social, environmental, and economic. These dimensions are known as the Triple Bottom Line, introduced by John Elkington (1997). Sustainability in supply chains is a source of competitive advantage (Seuring and Müller, 2008b; Sarkis et al., 2011), as it responds to changing consumer demands for more environmentally and socially responsible products. In the field of strategic management, sources of competitive advantage, gained by timely responses and product innovation, are defined as “dynamic capabilities” (Teece and Pisano, 1994). SSCM and dynamic capabilities were linked in recent studies (Philip Beske, 2012; Beske et al., 2014), since rapidly changing consumer demands create a dynamic business environment. However, internal competences of firms specific to SSCM that enable competitive advantage were not addressed. At the center of this research therefore lies the question “What are the internal and external dynamic capabilities that enable firms to achieve environmental sustainability in their supply chains?”

In this paper we address environmental sustainability, as the source of competitive advantage. We develop a theoretical framework linking the external and internal dynamic capabilities of

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firms, thus extending previous studies at the intersection of dynamic capabilities and SSCM. We demonstrate our contribution with a company case study which reflects the “zero waste to landfill” initiative at Nestlé, one of the industry leaders in the food sector. The next sections are structured as follows. We first review three streams of literature: SSCM, dynamic capabilities, and research at the intersection that links the two fields. Next, we propose a holistic framework based on our literature review. Subsequently, we introduce the aforementioned Nestlé case study to demonstrate the framework. In the last section, we summarize our findings and propose future research directions.

2.2 Literature review

2.2.1 Sustainable Supply Chain Management

Firms can gain competitive advantage by increasing their environmental performance (Seuring and Müller, 2008b; Sarkis et al., 2011). They can achieve this by offering more environmentally sustainable products; however, both the individual firms and their supply chain need to possess or develop the necessary relevant internal resources and capabilities (Gold et al., 2010). Our work relates to the firm’s internal capabilities as well as the capabilities of their supply chain partners to produce more environmentally sustainable products. As a result, we cover the literature in SSCM in what follows.

Supply chain management is a well-established and broad topic, dealing with issues such as purchasing, logistics, finance, production, among others (Lambert and Cooper, 2000). Over the past two decades, there has been an increase in studies focusing on the environmental and social impact of supply chains (Seuring and Müller, 2008b). Many names exist for the evolving field, but the studied topics are similar: elimination of manufacturing by-products, environmental product design, corporate social responsibility, green purchasing strategies, reverse logistics and closed-loop supply chains, life-cycle assessment, certification and standardization, tradeoffs between economic and environmental costs, resource efficiency, and recycling, among others (Dyllick and Hockerts, 2002; Svensson, 2007; Linton et al., 2007; Seuring et al., 2008; Tate et al., 2010; Ashby et al., 2012; Chen et al., 2014; Martí et al., 2015).

In 2011, there were more than 300 papers in the field of SSCM (Hassini et al., 2012; Seuring, 2013). The practices in this multidisciplinary area (Linton et al., 2007) have been outlined by Zhu and Sarkis (2004) and Zhu et al. (2008). The most frequently studied supply chain entities are manufacturers as focal firms (Hassini et al., 2012), and collaboration between supply chain members being a prominent topic (Zhu and Sarkis, 2004; Vachon and Klassen, 2008). Papers in this stream use both qualitative and quantitative methodologies, with a majority of the studies emphasizing the environmental aspect of sustainability (Ashby et al., 2012; Seuring, 2013; Brandenburg et al., 2014). In what follows, we review the dynamic capabilities literature.

2.2.2 Dynamic capabilities

Firms face increased legal and extra-legal demands to incorporate environmental sustainability aspects in their business practices and supply chains (Reuter et al., 2010). These demands are dynamically changing, requiring firms to adapt their capabilities over time. Accordingly, we use the dynamic capabilities view in our framework.

Dynamic capabilities were introduced by Teece and Pisano (1994) as a paradigm explaining how firms gain and maintain competitive advantage. They state that the resource-based strategy that focuses on the exploitation of firm-specific assets is insufficient in supporting a significant competitive advantage. They argue that timely response and product innovation are possible through the renewal of internal and external competences, and effective coordination. Furthermore, they state that dynamic capabilities are high performance internal routines found in a firm's processes, and are conditioned by a firm's history. Teece et al. (1997) further develop the framework by introducing the concepts of internal replicability and external inimitability of competences that support a firm's service or product given a changing business environment. Eisenhardt and Martin (2000) argue that dynamic capabilities as defined by Teece et al. (1997) are a source of competitive advantage, but not necessarily a sustained one. They differentiate the nature of the dynamic capabilities and learning mechanisms between moderately dynamic and high-velocity markets. Helfat et al. (2007) develop the concepts of technical and evolutionary fitness, and their relationship.

Synthesizing the existing literature, Teece (2007) provides a more general framework on

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dynamic capabilities. He divides dynamic capabilities into three foundations: sensing opportunities, seizing the opportunities, and transforming. Sensing is the ability to recognize new opportunities. It involves scanning and interpretation of the internal and external environment, as well as defining new opportunities. Seizing is the ability to address opportunities. It involves maintaining and improving competences and complementary assets such as enterprise structures, procedures, designs and incentives. Transformation is the ability to recombine and to reconfigure assets and organizational structures as the enterprise grows, and as the external environment changes. It involves the continuous alignment and realignment of specific tangible and intangible assets. These foundations emphasize firms' internal capabilities.

Dynamic capabilities have been studied together with other areas such as political management, innovation, marketing and economics, among others (King and Tucci, 2002; Kor and Mahoney, 2005; Song et al., 2005; Rothaermel and Hess, 2007; Oliver and Holzinger, 2008). An extensive review of dynamic capabilities literature is provided by Barreto (2009). Next, we review the literature that examines the intersection of dynamic capabilities and SSCM.

2.2.3 Dynamic capabilities in Sustainable Supply Chain Management

Firms require internal and external dynamic capabilities to achieve more environmentally sustainable products, in collaboration with their supply chains. Research covering these dynamic capabilities holistically is missing in the literature. In this section, we cover prior research at the intersection of dynamic capabilities and SSCM and state the related research gap.

Foerstl et al. (2010) and Reuter et al. (2010) study supplier management with a dynamic capabilities perspective in the chemical industry. Foerstl et al. (2010) believe that firms which outsource production must seek active management of the supply base for the mitigation of sustainability risks. They define sustainable supplier management as effective supplier identification, assessment and monitoring measures as well as compliance incentive systems. They take a dynamic capabilities perspective to reduce reputational risks through sustainable supplier management, using case studies in the chemical industry. They limit their study to

capabilities concerning risk reduction. Foerstl et al. (2010) capture dynamic capabilities in sustainability concerning suppliers only. They propose a general framework in sustainable global supplier management, yet do not provide a comprehensive list of capabilities.

Marcus and Anderson (2006) differentiate between dynamic capabilities and competences of firms for environmental management of retailing stores, and find that dynamic capabilities need to be complemented by a broad mission including different stakeholder concerns in order to achieve environmental goals. They capture some aspects of dynamic capabilities applicable to SSCM, yet lack a comprehensive list as proposed in our framework. Furthermore, their study is limited to retailing, where the environmental goals may differ as compared to supply chain functions of manufacturing firms.

Defee and Fugate (2010) study dynamic supply chain capabilities, covering the entire supply chain environment as opposed to firm-centric capabilities. The dynamic supply chain capabilities are identified as knowledge assessing and co-evolving with partners, where the supply chain and learning orientations of a firm are the strategic basis for competitive advantage. The study however, focuses on partnerships within supply chains, and does not explicitly cover sustainability. The shift from inter-firm to inter-supply chain competition is also captured by Gold et al. (2010), where SSCM is studied together with resource based and relational views.

A framework coupling SSCM and dynamic capabilities is proposed for the first time by Beske (2012). Based on SSCM (Seuring and Müller, 2008a; Pagell and Wu, 2009) and dynamic capabilities literature, the framework underlines the overlapping characteristics of the two fields. The five dynamic capabilities identified focus mainly on partnerships. We summarize these as follows. Knowledge assessing involves the access, understanding, and acquisition of knowledge through partnerships. Partner development lies in the fact that the supply chain is only as strong as its weakest member. Co-evolving with partners aims at the development of new capabilities. Reflexive supply chain control ensures the functionality of the system against the needs of the supply chain such as information sharing with partners. Finally, supply chain re-conceptualization focuses on new partnerships.

These concepts are further developed in Beske et al. (2014), and SSCM topics introduced in Beske (2012) are also expanded. The authors qualitatively review the sustainable food supply

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chain literature to assess the relationships between dynamic capabilities and SSCM practices. The food industry is appropriate to study these relationships since consumers' demands are constantly changing towards higher safety and quality products.

The framework and empirical research in Beske et al. (2014) covers collaboration and coordination with supply chain partners. In our paper, we further include the important firm-internal processes, routines and transformation emphasized by (Teece and Pisano, 1994; Teece et al., 1997; Eisenhardt and Martin, 2000; Teece, 2007). Indeed, collaboration and coordination by definition are essential supply chain properties; however, changes in both the supply chain and firm itself are necessary to achieve more environmentally sustainable products. This is supported by previous studies in the field of green supply chain management, where management commitment and support, together with cross-functional teams are identified as important firm-internal practices, among others (Zhu and Sarkis, 2004). Moreover, partners risk perceiving the initiatives and customer pressure negatively (Ciliberti et al., 2009), highlighting the importance of internal capabilities.

Overall, our framework contributes to available literature by merging multiple features of the aforementioned studies: environmental sustainability, dynamic capabilities of different forms, and both internal and external dynamic capabilities within a supply chain management approach. In the next section, we explain and provide examples of our holistic framework, that incorporates these features, and which outlines the internal practices in firms that enable sustainability in their supply chains.

2.3 A holistic framework on dynamic capabilities in Sustainable Supply Chain Management

Gaining competitive advantage goes further than applying best practices and adopting capabilities through partnerships. Replication of best practices is illusive if organizational structures and managerial processes do not support productive activity (Teece and Pisano, 1994). Furthermore, there is a need for internal routines, or in other words patterns of practice and learning. Internal and external processes, when imitated on a standalone basis, may not be effective in improving performance, since there is a need for internal coherence. Similarly,

2.3. A holistic framework on dynamic capabilities in SSCM

Eisenhardt and Martin (2000) state that the ingredients (i.e., key commonalities of capabilities) themselves may not be sufficient in the effective implementation of dynamic capabilities. The recipe (i.e. order of implementation), together with early responsiveness are also necessary in gaining competitive advantage. Furthermore, organizationally coherent routines and capabilities need to be complemented by new organizational forms and business models together with top management input (Teece, 2007). The latter is impacted by systems processes and structures. The effectiveness of dynamic capabilities, or in other words the transformations, is measured by firm growth (Helfat et al., 2007).

Despite the emphasis on managerial skills as well as organizational structure and processes, a holistic framework underlining dynamic capabilities in SSCM capabilities is lacking. In this section we extend the framework proposed by Beske et al. (2014) by introducing internal capabilities in SSCM. Our work can be considered as incremental theory building (Eisenhardt, 1989), as it considers a broader range of capabilities and practices.

We focus on a single firm within the overall supply chain. According to the APICS definition, a supply chain is a global network used to deliver products and services from raw materials to end customers through an engineered flow of information, physical distribution, and cash. Different supply chain functions are managed by independent entities or by a single firm. In the latter case, the single firm's internal capabilities gain more importance. More significantly, the behavior of any supply chain entity is governed by its internal dynamic capabilities, such as the organizational routines and processes.

Based on the dynamic capabilities literature (Teece and Pisano, 1994; Teece et al., 1997; Eisenhardt and Martin, 2000; Helfat et al., 2007; Kor and Mesko, 2013), we reviewed the relevant capabilities for SSCM. These are grouped in Table 2.1 as the capabilities for sensing, seizing, and transforming (Teece, 2007).

The relevant capabilities listed in Table 2.1 include both internal and external capabilities. Capabilities such as decentralization, alignment of organizational forms, strategy development and corporate renewal are mainly internal, while others such as codification of processes and coordination can be both internal and external. This is in line with our holistic theoretical framework, aiming to unify external capabilities as defined by Beske et al. (2014) with internal

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Dynamic capabilities	References
Organizational structure	
Configuration <ul style="list-style-type: none"> Decentralization and decomposability Governance structures 	Teece (2007), Helfat et al. (2007)
Coordination and integration	Teece et al. (1997), Teece (2007), Eisenhardt & Martin (2000), Helfat et al. (2007)
Sensing capabilities for SSCM	
Strategy development and corporate renewal	Teece (2007), Kor & Mesko (2013)
Assessment of routine effectiveness and efficiency	Teece et al. (1997), Eisenhardt & Martin (2000)
Codification of processes	Eisenhardt & Martin (2000), Teece (2007)
Identification of opportunities <ul style="list-style-type: none"> Identification of changes in customer demands Identification of market segments 	Teece et al. (1997), Eisenhardt & Martin (2000), Teece (2007)
Alignment of organizational forms	Eisenhardt & Martin (2000)
Seizing capabilities for SSCM	
Knowledge transfer through communication	Teece (2007)
Learning	Teece et al. (1997)
Quality control processes and auditing	Teece (2007)
Executive action and follow-up	Helfat et al. (2007)
Transformation	
Development and application of new routines and processes	Teece (2007)
Development and application of new organizational structures	Teece et al. (1997)
Realignment of organizational forms and business models	Teece (2007)
Shaping competition	Teece (2007)

Table 2.1: Dynamic capabilities relevant to the environmental aspect of Sustainable Supply Chain Management in literature.

capabilities.

However, the capabilities in the dynamic capabilities literature remain broad and should be specific to SSCM. In order to provide specific capabilities, we separate the organizational structure into three management levels: top, middle, and lower management. More layers can be considered; however, for simplicity we take three levels to stylize our framework. The capabilities at each level are detailed in Table 2.2. Examples of each capability are given in the results section of our Nestlé case study.

The two major top management sensing capabilities required are the tapping of environmental initiatives that improve supply chain performance and competitiveness, and the recognition of internal and external integration systems of the environmental strategy, and its implementation. The former may be possible through performance reviews of internal processes, and close tracking of external trends on environmental issues and competitors' initiatives. The latter involves asset orchestration and realignment of organizational forms as described by

2.3. A holistic framework on dynamic capabilities in SSCM

Organizational Structure	Sensing capabilities	Seizing capabilities	Capabilities to transform and manage threats
Top management	<ul style="list-style-type: none"> • Tapping environmental initiatives that improve supply chain performance and competitiveness • Recognition of internal and external integration systems of the environmental strategy and its implementation 	<ul style="list-style-type: none"> • Environmental strategy development and re-alignment • Policies, guidelines and target creation • Allocation of responsibilities • Integration of environmental strategies to investment decisions • Internal and external communication routines • Reporting systems • Incentives schemes • Follow-up systems 	<ul style="list-style-type: none"> • Constant review of legislation and reputational assets • Review of competitors' strategy • Creating internal cross-functional taskforces • Effective external communication • Collaboration with external organizations
Middle management	<ul style="list-style-type: none"> • Tapping internal and external information gaps and enabling transparency in the firm and its supply chain • Tapping processes that facilitate the implementation of environmental target 	<ul style="list-style-type: none"> • Transmitting guidelines • Training and creating awareness of environmental strategy • Transferring performance results • Communication with partners • Adjusting environmental goals to local conditions, products and supply chain • Enabling auditing of partners • Setting communication routines • Follow-up routines and incentives schemes • Managing main partners 	<ul style="list-style-type: none"> • Constant review of legislation • Enabling transparency and information accuracy • Collaboration with local partners • Aligning global strategy with local feasibility of target to guarantee success • Partner choice • Communicating on infrastructural needs with external organizations
Lower management	<ul style="list-style-type: none"> • Tapping local opportunities through internal knowledge and idea generation for on-site target implementation • Tapping processes that facilitate on-site implementation of the environmental target 	<ul style="list-style-type: none"> • On-site process mapping and modifications • On-site and partner communication routines • Regular training programs • Local partnership development • Reporting and analysis routines 	<ul style="list-style-type: none"> • Setting short-term targets • Partner relationship management • Creation of cross-functional teams

Table 2.2: Sensing, seizing and transformation capabilities in SSCM in three levels of organizational hierarchy

Teece et al. (1997); Teece (2007); Helfat et al. (2007); Kor and Mesko (2013).

The seizing capabilities of top management are the routines that enable the sustainability initiative to be effectively and coherently implemented in middle and lower management. On the one hand, it involves developing and re-aligning environmental strategy. On the other hand, it involves putting in place the systems necessary to implement, track and incentivize the initiative, such as reporting systems and communication routines. Finally, the capabilities to meet commitments and to transform are tracking of legislation and reputational assets, creating cross-functional taskforces, and effective external communication and collaboration with external organizations. These capabilities are closely related to the sensing capabilities.

Sensing capabilities of middle management are the tapping of internal and external information gaps to enable transparency within the firm and its supply chain, and of the processes that

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facilitate implementation of the environmental targets. Both capabilities involve intensive communication within the firm and the supply chain partners to understand the needs of each party. The corresponding sensing routines are the transmission of guidelines, adjustment of targets based on local conditions, training and creating awareness of the importance of the environmental strategy, checking and aggregating performance, among others. Capabilities to transform and manage threats are mainly those that enable internal and external transparency to avoid information inaccuracies that lead to further misalignments, either by collaborating with external organizations to overcome limitations or by the choice of partners.

Lastly, lower management sensing capabilities involve tapping local opportunities and processes that facilitate on-site implementation. High integration with the local environment and internal idea generation are two ways to enable sensing. Seizing routines involve regular performance assessments, on-site modifications, developing partnerships, and communication routines. Lower level management can increase the possibility of meeting commitments by creating cross-functional teams to test the feasibility of their implementation approach and closely work with partners to ensure alignment. Furthermore, setting short-term targets may increase the chances of success, as aggregate goals may be perceived as too far-fetched to internal employees and partners.

Many routines are driven in accordance to a global goal communicated by top management. However, based on their practical learnings, middle, and lower management may also be a driver for strategy development on a global level. For example, learnings may result from demand for sustainable products or legislative requirements at a certain location. This is achieved through collaboration up and down the hierarchical levels, which corresponds to the level of integration within the firm.

Sustainability initiatives require changes in firms' strategies, and thus internal capabilities and alignment efforts. As discussed in the previous section, changes in both the supply chain and firm itself are necessary to achieve more environmentally sustainable products. Notably, organizational structures and capabilities are the key to enabling effective implementation of environmental initiatives. Subsequently, we highlight the need for information transparency and integration within the company as well as with external partners to obtain accurate and

reliable results.

Additionally, sustainability initiatives do not always result in direct economic improvements, yet may result in indirect benefits such as increased reputational assets and customer loyalty. Moreover, for decentralized firms, environmental sustainability may not be a reputational asset at every level for the firm. Therefore middle and lower levels of management need to recognize and translate the necessity of sustainability initiatives to employees, and incentivize when necessary.

It is important to note that the explained capabilities should lead to timely action. Additionally, the activities may change in nature as routines collapse over time, and as new routines are identified (Eisenhardt and Martin, 2000). In the next section, in order to facilitate the understanding of our framework, we apply it to Nestlé's "zero waste to disposal" initiative. Note that initiatives may differ across industry sectors and products (Comas and Seifert, 2013).

2.4 Illustrative case study

In this section, we describe an illustrative case based on the "zero waste (ZW) to disposal" initiative of Nestlé in its factories. Nestlé is a multinational food and beverage producer that has more than 300 000 employees, according to its 2013 Annual Report. Nestlé is therefore a suitable firm for this study, since the food and beverage industry is highly dynamic (Trienekens et al., 2012; Beske et al., 2014). Furthermore, Nestlé is a competitive firm in environmental sustainability, and according to the Dow Jones Sustainability Index, was the leader in the Food, Beverage and Tobacco industry category in this respect, in 2013. Nestlé's motivation regarding environmental sustainability on the one hand is to win consumer trust, while on the other hand to ensure long-term development by increasing resource accessibility and availability.

Supply chain environmental impacts can be improved by reducing resource wastage. The causes and prevention practices stated in literature regarding waste in the food industry are outlined in Table 2.3. Some of the practices are strategic and are in line with the results of our case study, while others are more closely related to operational practices.

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2.4.1 Overview and setting

Food and beverage companies have long been targeting to improve their environmental impacts. The Nestlé Policy on Environmental Sustainability was launched in 1991, and last reissued in 2013. To achieve the commitments resulting from this policy, targets have been set in different areas. Nestlé's targets on resource efficiency include achieving ZW to the environment in 10% of their factories by 2015, and achieving ZW in all of their European factories by 2020. Furthermore the Nestlé Zero Food Wastage Taskforce was created, aiming at food waste avoidance and sharing of good practices internally and externally.

2.4.2 Methodology

In order to study ZW in food manufacturing, we completed a two-month study period within Nestlé's Safety, Health, and Environmental sustainability department. The unit of analysis for this single case is the Nestlé "ZW for disposal" initiative.

During the study, we systematically reviewed and analyzed both quantitative and qualitative internal data. With respect to the qualitative data, the following were used to compile overview of the ZW project setting, milestones, achievements, and collected data: internal documentation, specifically presentations on ZW from different countries; environmental management systems; and standards and guidelines. A series of complementary interviews with country managers responsible for environmental sustainability involved in the ZW initiative was conducted, and the combined results were presented back to the responsible Nestlé managers. Although a single investigator performed the data collection, triangulation between different sources of information addressing the same fact, assured construct validity, as described in Yin (2003). Moreover, the report was reviewed with the key informants.

Quantitative data over a period of four years for all factories and material types were analyzed. Factories were chosen based on the quantitative data. Using this data, the quantitative analysis can be repeated, ensuring reliability of the study. Details on the choice of countries and factories are given in the data collection section. The markets involved in the chosen factories were interviewed using semi-structured interviews. The countries with the majority of their factories being ZW faced similar challenges and motivations. At the same time, countries

with few or no ZW factories had different motivations and challenges. From other internal documentation it is seen that a similar pattern occurs in markets that were not contacted, increasing internal validity. Further details are given in the data collection and analysis sections. Next, we provide details of our approach.

The dynamic capabilities listed in our framework are drawn from previous studies, and are stated to be relatively common between industry competitors, increasing the external validity of the study. Furthermore, they are used for pattern matching to increase internal validity, as recommended by Gibbert et al. (2008). We use the case to illustrate an application and to facilitate the interpretation of our framework.

2.4.3 Data collection

Contact with key informants was established. The informants provided the contact persons, internal documentation and qualitative data, as well as company governance and dynamics. Details of the ZW initiative and general standards the company follows regarding environmental sustainability such as internal and external regulations and standards, were also provided.

Internal documentation on the ZW initiative was analyzed. This includes reports on performance measures per region or business unit, as well as feedback and recommendations involving ZW from markets. Annual reports and standards followed by the company were studied to create an understanding of the current situation, and the initiatives' requirements from the markets.

To determine the interviewees in the selected markets, four years of data of waste and by-product quantities and destinations were analyzed for each factory. Here we define by-product as any material generated during the manufacture of a product that leaves the factory and is destined for reuse or recovery, including recycling, composting, and incineration with heat recovery. By-products are not limited to the materials that are manufactured; they include all materials used to support the manufacturing process. In order to find the drivers, best practices, and the challenges in the implementation of the initiative, we separated interviews in two factory groups: those who had already achieved their ZW target, and those who struggled to meet the targets.

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The choice of factories was reduced to the following categories: confectionery, milk products and dairy, prepared dishes and cooking aids, nutrition and healthcare and powdered and liquid beverages. Among the waste types, we chose organic waste as a decision parameter for three reasons. Firstly, the treatment and coordinated processing of high quantities of organic waste and by-products are more challenging as opposed to waste types such as paper or glass, where recycling infrastructure is more established. Secondly, a majority of ZW factories historically had very low amounts of waste, therefore we used the average yearly amounts of organic waste and by-products instead. Similarly, the factories that had yet to achieve ZW were filtered based on the average yearly organic waste values. Lastly, the by-product quantities varied according to the product type.

In summary, factories with high overall production volumes and the most significant amount of organic waste per production volume were chosen. Completeness and consistency of data were analyzed for the factories with the above criteria. Finally, the evolution of quantities and their destinations over four years were used to choose the most interesting factories.

Six factories were chosen, with three ZW factories in Switzerland, Germany, and the United Kingdom. The remaining three were in the US, Malaysia, and India. Due to the company being highly decentralized, market environmental sustainability managers were contacted. During the interviews, we inquired about drivers that were not initially stated in internal documents, for data completeness. The interviews took place either in person or by telephone. A set of questions were prepared to use as a basis of the semi-structured interviews. The questions focused on the initiative's internal communication, implementation on market and factory levels, drivers, best practices, and the challenges faced in implementation.

Additional interviews were conducted with environmental representatives of the internal improvement program, called Nestlé Continuous Excellence (NCE) (Büchel, 2012) involved in ZW in both manufacturing and agriculture. The current improvement program, based on lean and total productive maintenance principles scopes all operations and involves the reduction of all types of resource waste i.e. food, energy, water, labor, economic, and aims at eliminating operational discrepancies, and enabling collaboration within the SC. In the NCE program, methods such as DMAIC (Define-Measure-Analyze-Improve-Control) and GSTD

(Go-See-Think-Do) are used, and idea generation is supported at all levels of hierarchy. Based on our interview regarding NCE, alignment between both internal and external supply chain partners, and working with suppliers in agriculture are some of the most effective ways of reducing waste.

The program also aims to improve sourcing, quality, quantity, cost, and inventory. An example in agriculture is the alignment of harvesting with procurement such that the harvesting takes place in multiple phases instead of a single phase. The aim is to reduce peak inventory, losses and holding costs, while providing production stability. Another possibility is to align the marketing and promotions of products according to the harvest season of raw materials to reduce inventory. This example shows how improvement programs unfold internal capabilities and can result in competitive advantage through collaboration with external partners.

Despite legislative, infrastructural and cultural differences in markets, factories were able to achieve their targets over different geographies. In Europe, legislative requirements on waste treatment are stricter than in most non-European countries. As a result, the waste treatment and recycling infrastructure is more developed. In vast geographies such as the US and Russia, economies of scale for transportation of materials are more challenging, increasing the motivation to reduce the generation of waste. Cultural differences also change the effectiveness of implementation of the initiative. In cultures where seniority and hierarchy are well acknowledged (Schroevens et al., 2014), such as in India, top-down decisions proved more effective.

On lower levels of management, the challenges were similar despite the abovementioned differences. Particularly, factories with similar products faced comparable challenges. Subsequently, the required capabilities were the same over different markets. We describe the application of the SSCM dynamic capabilities in what follows. We limit the number of examples to keep the paper at a reasonable length.

2.4.4 Results of the case study

In this section we present the results of the case study based on the organizational structure described in our framework. The capabilities presented here for the “ZW to disposal” ini-

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tiative are naturally case-dependent. The objective is to facilitate the understanding of our general framework, considering a focal firm wanting to achieve a more sustainable supply chain. Nestlé is a highly decentralized firm, thus top, middle, and lower management levels correspond to corporate, market, and factory environmental managers.

Our findings show that corporate management sensing capabilities are firstly the realization that sustainability initiatives were beneficial for the long-term development of the firm: a more sustainable supply chain results in lower risks of raw material unavailability and enhances consumer trust. Secondly, top management was able to understand the short-term economic benefits due to their internal integration with markets. For example, factories in Germany had little or no waste prior to the ZW to disposal initiative mainly due to tight legislative constraints. When the initiative was launched, top managers contacted the managers in Germany, who had concluded that reducing waste was beneficial for their economic performance due to lower costs and income from recycled materials.

The seizing capabilities or routines are the corporate managers' ability to set up internal policies, targets, and guidelines as well as systems to enable the ZW initiative. For example, managers for environmental initiatives were assigned at each level, appropriate targets were set for each market, reporting systems and guidelines were put in place, and annual meetings with market environmental managers were organized. Additionally, corporate managers facilitated the adoption of targets by including targets to bonus programs, providing internal online courses, and providing toolkits that aid learning and integration within the firm.

Corporate managers contributed to meeting global commitments and transformation by understanding the importance of external communication of sustainability targets, which in turn shapes competition. As a result, they included their targets for the ZW initiative in their annual report, in line with their environmental policy. Furthermore, they created a food wastage taskforce to address food waste not only in the factory, but also in other supply chain members by creating cross-functional teams. One of the projects helped to reduce milk losses in Pakistan through collaboration with the farmers that supply the milk, subsequently improving milk collection and transportation infrastructure. Next, we explain the capabilities of market environmental managers.

Market environmental managers are more directly involved in the management of partners and the facilitation of implementation since they are familiar with the local environment and culture. Their sensing capabilities include tapping environmental legislation and differences with firm policies, potential market-wide partners, infrastructural necessities of the country, necessities for each product and factory in terms of reporting, and contractor capabilities and capacities. For example, in some European countries, legislation of waste disposal to landfill is becoming stricter, thus market environmental managers need to adjust their targets proactively. Additionally, market environmental managers in India, for instance, contact market-wide waste recycling companies to facilitate the administrative tasks in factories.

Managers also leverage opportunities to reduce costs and reach economies of scale of transportation of materials to a recycling site, by working with external governmental organizations. For example, in the US, some factory managers worked with the USDA to focalize transportation of materials from different factories. Furthermore, they reduced waste to landfill by communicating with surrounding firms who use by-products to generate energy in their own plant. Overall, market environmental managers' capabilities to sense opportunities are essential for the success of the ZW target.

The seizing capabilities of market environmental managers are essentially integration, through the transfer of information (between corporate and factory managers, as well as horizontally between markets) and the facilitation of implementation. Examples of these routines are transferring and adapting targets, guidelines per factory and product, organizing yearly meetings, and training factories on reporting and implementation. Other examples are aggregation of results of each factory on a monthly basis and follow-up, as well as organization of third party auditing for all factories to verify final destination of by-products. For example, the audit scope of the contractors and factories vary based on the certification of the factory. Contractors that are ISO 14001:2004 certified undertake stricter audits. These require relationship management capabilities with internal managers and external partners.

Market environmental managers contribute to meeting global commitments and transforming by keeping informed of legislative requirements, and enabling transparency and information accuracy within the firm as well as with supply chain partners, waste contractors, and other

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external organizations. For instance, in the US, suppliers of raw materials who refused to change non-recyclable or hazardous waste were abandoned. Furthermore, some factories produce products that result in by-products that cannot be recycled due to infrastructural constraints in the region. In India, for example, managers reached their goals by increasing the targets for factories where adequate infrastructure and waste contractors exist and less waste to disposal is possible. Next, we explain factory managers' capabilities in achieving ZW to disposal.

Factory managers or engineers are responsible for the implementation of environmental initiatives on-site. Their sensing capabilities are on a local scale, requiring knowledge and tapping of opportunities based on on-site conditions and processes, as well as surrounding firms, potential partners, and the motivation of employees to effectively implement waste elimination. Enhanced communication and process mapping with employees can result in idea generation and potential opportunities to reduce waste. For example, in Malaysia, employees worked with local farmers who could accept organic waste for animal feed.

Seizing capabilities for factory managers are mainly organizing effective and product-specific training programs, managing supplier and contractor relationship, keeping informed of local changes, motivating employees during weekly meetings, and reporting performance. For instance, in India, as well as other locations, regular mapping of the location of waste generation indicated where materials were not well sorted, and where containers for recyclables should be placed. In turn, factory layout was partly changed and additional equipment was rented from waste contractors. Another example is managing supplier relationships when there is direct contact with raw material producers or a single middleman. Previous projects involved training the producers in various countries to reduce milk, fruit and vegetables, coffee and cocoa losses.

Finally, factory managers achieve their challenging targets and drive action by setting short-term targets to increase employee motivation, keeping close contact with partners and contractors while creating cross-functional teams for knowledge sharing. For example, in Malaysia, managers communicated their need for a waste contractor in an industrial zone, in collaboration with neighboring factories. They recently started working with a waste contractor as a

result of their request.

In summary, all management levels in a firm require sensing, seizing and transformation capabilities to achieve more environmentally sustainable products. Furthermore, information needs to be transferred accurately throughout the organization, whether for performance indicators or best practices. A high level of integration facilitates the information transparency and the roll-out of environmental sustainability initiatives.

2.5 Conclusion

The contribution of our research is two-fold. First, we review the dynamic capabilities literature and list the capabilities relevant for SSCM. Second, we specify capabilities at three levels of hierarchy that lead to the success of sustainability initiatives within firms and their supply chains, as structured in the dynamic capabilities literature. We highlight the internal dynamic capabilities of firms in SSCM, as an additional development of the framework introduced by Beske (2012). We find that although collaboration with external partners is important, competitive advantage cannot be achieved if organizational management skills, processes and structure do not support sustainability initiatives. Particularly, information transparency and integration within the firm and with its supply chain partners are essential.

Both practitioners and academics can apply our framework. Practitioners who want to achieve more environmentally sustainable products in their supply chains can apply the framework by mapping out the capabilities in different organizational levels. Once the gaps are identified, processes can be set up to ensure each capability is facilitated, such as an improvement program or regular communication and performance meetings in cross-functional teams to ensure alignment between organizational levels. Similarly, academics can apply the framework to understand performance differences and behavior of individual companies in a competitive space where environmental goals are strict and supply chains are increasingly complex.

We illustrate the dynamic capabilities' application to SSCM through a case study on waste elimination in Nestlé factories. This illustrative case suggests that the dynamic capability literature can be applied to SSCM. One of the important findings of the case is the strong relationship between the dynamic capabilities and the continuous improvement program

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in terms of sustainability. Anand et al. (2009) focused on the elements of infrastructure to coordinate continuous improvement projects, and believe that continuous improvement is a dynamic capability when it includes a comprehensive organizational context. Many aspects of the illustrated case confirm their framework: organizational learning, coordination and integration, communication and assessment of project effectiveness, among others.

A limitation of this study is that a single case or sustainability program may not address all the dynamic capabilities proposed in the framework. Multiple cases are needed to provide a more complete framework. Furthermore, a detailed impact assessment of each capability would be required.

Further research in the field is recommended, as it may shed light on the importance of other capabilities and activities such as continuous improvement programs, particularly for improved sustainability performance in terms of economic, environmental and social dimensions of the triple bottom line. We recommend empirically grounded research to identify the research gaps in this area. Although we use a dynamic capabilities approach, since rapidly shifting consumer demands create a dynamic business environment, other approaches may also be applicable. We encourage scholars to explore intersections with other fields of research for theory building in SSCM. Finally, it would be desirable to measure, in quantitative terms, the risk reduction and growth potentials from adopting environmental sustainability practices in firms.

2.5. Conclusion

Supply Chain Phase	Causes of food waste	Waste prevention practices
Harvesting	Crops left on field Eaten by animals Suboptimal timing of harvest Poor threshing/picking techniques Contractual obligations for suppliers	Alternative channels for unsold material Organizing small farmers (diversifying and up-scaling production) Communication and cooperation between farmers to share knowledge
Sourcing	Inaccurate forecasting Poor handling	Conservative orders Daily contracts with suppliers Local products (short lead time) Varieties of raw materials with longer shelf life
Transportation	Poor infrastructure (cool chain) Poor handling	Maintaining cool chain equipment Time Temperature Indicators
Storage	Pests, disease, mould Spillage Contamination Poor infrastructure (cool chain) High variety of products Human errors Poor handling Labeling errors Take-back systems and last minute order cancellation	Centralized control of inventory Maintaining cool chain equipment Movement among stores to balance inventory Reliable storage displays FIFO Efficient handling (lead times) Stock management tools Time Temperature Indicators
Manufacturing	Process losses Contamination Quality losses, requirements (in summer for milk) Spillage Technical errors Overproduction	Clear promotional planning (collaboration with retailers) Less stringent aesthetic requirements for inbound products
Packaging	Spilling from sacks Rodents Wrong date coding Wrong labeling	Training Recycling Using recyclable materials Materials that prolong shelf-life
Sales	Spoilage Inaccurate forecasting (seasonality and promotions) Unsold fresh products Very short shelf-life (bread) Slow sales at certain periods (yoghurt) Rejected products by retailers and consumers (esthetical) Recalls (high impact) Shelf-life requirements Quality expectations Poor handling Poor stock rotation Inflated orders due to service level requirements or to make shelves look full Portion sizes	Alternative sales outlets Producers incentives on discounts to avoid product returns or waste Movement among stores to balance inventory Collaborative forecasting Forecasting software Continuous replenishment (stable demands) /re-order point systems Reliable storage systems Stock rotation in store Discounts when short shelf-life remaining Reduction of aesthetic requirements Food redistribution activities
Consumption	Poor storage (humidity/cold storage) Preparation technique Confusion over best-before and use-by dates Awareness Attitudes Portion sizes Poor meal planning Socio-economic factors	Informational tools Awareness campaigns Training programs (hospitality industry) Shopping and meal planning Improved storage conditions Portion control Clear labeling Freezing
End of Life	Not separately treated Mixed with other wastes and sent to landfill	Industrial uses Separate collection of food waste

Table 2.3: Causes of waste and prevention practices in the supply chain.(Monier et al., 2010; Mena et al., 2011; Gustavsson et al., 2011)

3 Optimal replenishment cycle for perishable items facing demand uncertainty

3.1 Introduction

Perishable products account for over 40% of sales in grocery chains (Buck and Minvielle, 2014). Factors such as limited lifetime, high safety and quality requirements, together with short lead time requirements make them highly complex to manage. For retailing only, losses can be up to 15 percent due to damage and spoilage (Buck and Minvielle, 2014; Ferguson and Ketzenberg, 2006). In the US alone, spoilage amounted to \$500 million in 2003 according to The Grocery Manufacturers of America (GMA) (Karaesmen et al., 2011). Worldwide, of all the food produced in the food supply chain (Kummu et al., 2012), around 24% is wasted in terms of kcals.

Rising consumer awareness on the resource-intensity of production and environmental consequences of food waste has led benchmarking systems such as the Dow Jones Sustainability Index to include waste generation as an important key performance indicator in the assessment of firms' environmental performance. Today, leading food manufacturers such as Nestlé and Unilever explicitly include waste elimination in their firm policies and targets. Yet, reducing waste usually depends on the operations of multiple supply chain entities. These entities make their decisions in the supply chain interdependently to avoid supply-demand

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mismatches and reduce spoilage.

Our model is motivated by products such as processed dairy products or fruit juices. Ingredients of such products typically have a short raw material lifetime. The raw materials undergo processing and are turned into finished goods. This procedure increases their lifetime due to sterilization and added preservatives. Our objective is to analyze operational and spoilage costs in a manufacturer-retailer setting for perishable products with uncertain demand. We are particularly interested in replenishment cycles, that largely influence logistics and handling costs, product freshness, as well as spoilage.

We use a Stackelberg model where both parties want to reduce their own costs, and the retailer is the leader. This situation is applicable to many developed countries, where grocery sales are dominated by powerful retailers that have large customer bases. For example, Walmart has strong bargaining power over its suppliers and can often squeeze the profits of their suppliers (Riper, 2004). At the center of this research are the following questions “What is the optimal replenishment cycle that minimizes the retailer’s mismatch and shelf-space costs under demand uncertainty and finished goods perishability?” and “What is the optimal production rate that minimizes the manufacturer’s raw material spoilage costs for a given replenishment cycle?”.

There is a lack of studies that focus on both the raw material and finished goods perishability in a two-stage supply chain model. This research contributes to the existing literature on perishable inventory under demand uncertainty by analyzing the impact of raw material and finished goods spoilage on supply chain costs. Moreover, we consider the replenishment cycle as an endogenous variable, and find the optimal replenishment cycle for a two-echelon supply chain.

Our results show that the operations of the manufacturer and retailer are highly interrelated through the replenishment cycle and the selling price of the manufacturer. We find that the disposal cost of a spoiled raw material may not significantly impact the costs in the supply chain. Nevertheless, the lifetimes of raw materials and finished goods have a significant influence on supply chain costs. Additionally, we show that short finished goods lifetimes may lead to suboptimal replenishment cycles. Due to increased unit production costs, it should

incentivize manufacturers to produce longer-lasting products. Retailers are incentivized to integrate with the manufacturer due to the manufacturer's markup and raw material sourcing decisions. Moreover, increasing production efficiency by reducing variable costs can improve both the economic and environmental impact of the manufacturer.

The remainder of the paper is organized as follows. In Section 3.2 we review the literature on inventory control policies and how they relate to replenishment frequencies. In Section 3.3 we describe the problem in general terms. In Sections 3.4.1 and 3.4.2 we analyze the retailer's and the manufacturer's problem, respectively. In Section 3.5 we provide a numerical analysis to complement our analytical results, and we discuss the managerial insights. In Section 3.6 we provide concluding remarks and suggest future research directions.

3.2 Literature review

Our model is related to supply chain inventory models with perishability and demand uncertainty, in particular for food supply chains. Perishable inventory models have been studied by scholars since the 1960s, and are motivated by applications to fresh food, blood banks, meat, chemicals, composite materials and pharmaceutical products (Gürler and Özkaya, 2008). Extensive reviews of this literature stream include Nahmias (1982), Raafat (1991), Goyal and Giri (2001), Karaesmen et al. (2011) and Bakker et al. (2012). For agricultural crops, Ahumada and Villalobos (2009) provide a review of planning model applications. Furthermore, Borodin et al. (2016) review studies involving uncertainty in agricultural supply chain management.

In our study we incorporate the perishability of raw materials and finished goods, therefore we first review studies that focus on the nature of perishable products and the importance of freshness. Van Donselaar et al. (2006) show that perishables have higher average sales, a smaller case pack size, lower coefficient of variation of weekly sales, lower potential delivery frequency and a lower minimum inventory constraint. Van Woensel et al. (2007) show that perishables in retail have higher substitution rates compared to their durable counterparts, and require cross-docking or direct delivery. Blackburn and Scudder (2009) introduce the marginal value of time for fresh produce to minimize lost value in the supply chain. Amorim et al. (2012) show that the level of freshness in delivery influences the economic performance.

Chapter 3. Optimal replenishment cycle for perishable items facing demand uncertainty

Our study differs in that we study the effect of perishability on operational decisions in the supply chain. We do so by using queuing theory with impatient customers.

A majority of studies in queuing theory for perishables, Barrer (1957); Blackburn (1972); Nahmias (1982); Graves (1982); Kaspi and Perry (1984); Gnedenko and Kovalenko (1989); Parlar and Perry (1996); Perry and Stadje (2000); Nahmias et al. (2004a,b), do not focus on optimization, but rather on characterizing system performance such as waiting times and server utilization. In this regard, Goh et al. (1993) distinguish fresh and old items in a two-stage inventory system, focusing on a single echelon only. In our model, we use the waiting time of the M/M/1 queue to model raw material arrival and spoilage costs, and subsequently determine optimal production rates for the manufacturer. We further integrate this model with the demand model of the retailer in a two-echelon system to determine the optimal replenishment cycle and manufacturer processing rates for perishable items.

We next review studies that focus on optimizing operations in the supply chain for perishable products. Among the single echelon studies, Minner and Transchel (2010) present a method to determine dynamic order quantities for fresh food and show that a constant-order policy might provide good results under stationary demand, short shelf-life, and LIFO inventory depletion. Later, Reiner et al. (2013) study in-store logistics processes for handling dairy products, and find that strategic and tactical design of in-store logistics processes lead to higher on-shelf availability and reduced obsolescence costs. Kouki et al. (2016) investigate the impact of perishability for a continuous review can-order policy to coordinate multiple items with random lifetimes. In our model we also consider perishability and inventory, but we consider two echelons, where the manufacturer and retailer both want to minimize their costs.

Among the multi-echelon studies, Ferguson and Ketzenberg (2006) study the impact of information sharing about product age on a retailer's profit in the grocery industry and found that the benefits are highest when demand variability and costs are high, and product lifetimes are short. In another paper, Ketzenberg and Ferguson (2008) analyzed a two-stage serial supply chain and compared decentralized information (whereby the supplier and retailer maximize their profits independently) to a centralized control structure where replenishment

decisions are coordinated. Later, Cai et al. (2010) optimize orders and prices for distributors and retailers of groceries, and show that coordination can benefit both parties. Tongarlak et al. (2016) and Ata et al. (2012) quantify how back-hauling and vertical differentiation can increase the retailer's margin for local food, thus increasing the small local farmer's competitiveness. Holzapfel et al. (2015) minimize total costs in a grocery distribution chain by clustering stores and selecting delivery patterns. Finally, Wu et al. (2015) model transportation economies of scale for perishable items in a network with a single supplier and multiple retailers.

The Stackelberg model has been extensively used in operations management literature to model supply chain decisions with multiple echelons (Pasternack, 1985; Choi, 1991; Kadiyali et al., 2000; Barnes-Schuster et al., 2002; René and Wein, 2003; Savaskan et al., 2004; Yu et al., 2013). In these studies, either the retailer or the manufacturer is the Stackelberg leader. We set the retailer as the leader, considering examples such as Walmart in the US (Riper, 2004), or Migros in Switzerland (Kırcı et al., 2017). Unlike prior studies which mainly optimize prices, our principal decision variables are the replenishment cycle of the retailer and the production rate of the manufacturer to minimize their respective costs.

Our model differs from previous models such that we consider both raw material and finished goods perishability. We use a queuing model to solve the optimal processing rate of the manufacturer to reduce raw material perishability. We further solve the optimal replenishment frequency, by including finished goods perishability constraints. Moreover, we conceptualize the manufacturer's and the retailer's relationship as a Stackelberg competition, with the retailer being the leader. A major departure from earlier research is that we consider the replenishment cycle as an endogenous variable, and adjust the order quantities accordingly.

3.3 Problem description

We consider a perishable inventory system with a single manufacturer and a single retailer, with raw material perishability and finished goods obsolescence. The manufacturer and retailer want to sign a contract at the beginning of a time horizon of length L . With this contract, they want to specify the replenishment cycle T , i.e., the time between two deliveries, and the order quantity $S(T)$ over the total time horizon. Hence, in every constant replenishment cycle

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T within this time horizon, the manufacturer delivers a quantity of finished products $S(T)$ to the retailer.

We model the relationship as a Stackelberg game where the retailer is the leader and the manufacturer is the follower, as in previous studies stated in Section 3.2. We use the example of Walmart (Riper, 2004) as a motivating example for a dominant retailer who have high bargaining power with suppliers.

We next present the sequence of events, as shown in Figure 3.1. At the beginning of each cycle, the manufacturer receives raw materials. The manufacturer processes the raw materials into finished goods at a production rate of r . Raw materials are processed into finished goods, which are then stored during the replenishment cycle, in a make-to-stock system. At the end of the cycle, the manufacturer sends a quantity of $S(T)$ of finished goods to the retailer. At the beginning of the following cycle, the finished goods are available for sale at the retailer. The retailer sells the finished goods during the replenishment cycle T . Due to normally distributed consumer demand uncertainty for the product, there is a mismatch between supply and demand at each replenishment cycle. All unmet demand is lost. The objectives for the manufacturer and retailer are to minimize their own costs by optimizing their processing rate r and replenishment cycle T , respectively.

Both raw materials and finished goods are perishable. Note that the lifetime constraints are tighter for the manufacturer than for the retailer, since fresh product lifetimes are shorter than those of processed products that undergo chemical processes such as dehydration, sterilization and the addition of preservatives such as salt or sugar. We can use the example of fruit juice, composed of highly perishable fruit such as berries. Once the juice is processed, the lifetime will increase due to heating or added ingredients that preserve the product.

We now present the three main assumptions in our model. Raw materials arrive at the manufacturer's factory with a Poisson rate of λ and are processed on a first-in-first-out basis with an exponential production rate of r . The production of raw materials is thus represented as a $M/M/1 + D$ queue where $+D$ represents the fixed raw material lifetime t_R . Poisson arrivals in production are common in the literature (Graves, 1982; Gilbert and Ballou, 1999). More examples are given in Soman et al. (2004), where the authors review the literature on queueing

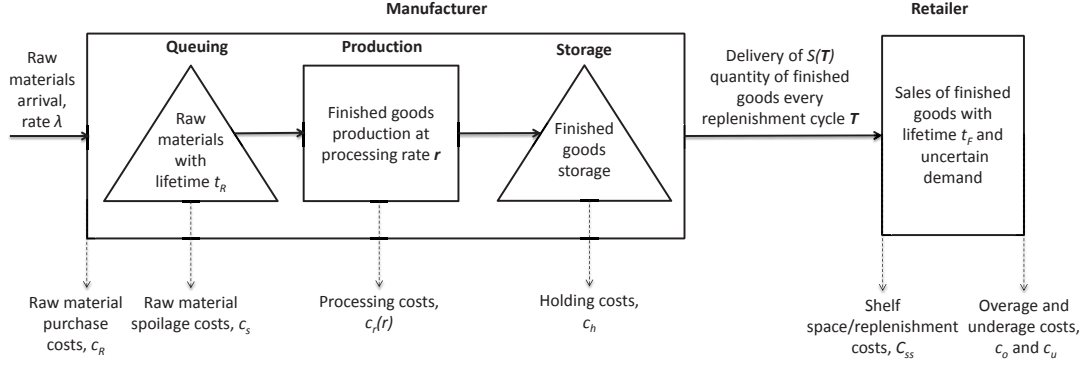


Figure 3.1: Supply chain of the manufacturer and the retailer

systems in production.

The second assumption concerns the logistics, ordering and replenishment time between two replenishment cycles. We assume that the transportation lead time is negligible. This is supported in Simchi-Levi et al. (2009, Chapter 3), where the authors state that direct shipments are prevalent in the grocery industry due to perishability and the necessity of short lead times.

Finally, we assume no inventory carryover between replenishment cycles, which causes different product ages in inventory. We explain the practical relevance through findings in the literature. It is well established that retailers try to maximize freshness (Amorim et al., 2012) and reduce inventory in stores to minimize holding and handling costs (Beamon, 1998). Perishable products are generally discounted as the expiry date approaches, or when the store is replenished with newer or fresher products (Tellis and Zufryden, 1995; Chew et al., 2014). Van Donselaar et al. (2016) state that price discounts result in sales quantities up to 14 times the regular replenishment quantity for perishable products. This implies that the stock of a perishable product, when discounted, will likely reach zero, and that inventory carryover between the replenishment cycles are low. These discount costs can be integrated in the salvage value in our model. Additionally, (Broekmeulen et al., 2004) state that handling costs are three to five times higher than the inventory costs, therefore we include shelf space and in-store replenishment costs in our model instead.

In the next sections, we first describe the retailer's problem and the manufacturer's problem separately and then minimize the costs using a Stackelberg system. A list of the notation is given in Table 3.1.

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Notation	Denotation	Comments
Retailer		
L	Time horizon	$L = N \times T$
μ	Mean demand over L	
σ	Standard deviation of demand over L	
T	Replenishment cycle, time interval between two replenishments	
S	Order quantity	
C_{ss}	Shelf space cost for the total time horizon	
$R(T)$	Shelf space cost per replenishment cycle	
p	Unit price of the product	
s	Salvage value of the product	
ϕ	Probability density function	
Φ	Cumulative density function	
C	Mismatch cost for a single replenishment cycle	
\bar{C}	Total mismatch cost over the time horizon	
$g(r, T)$	Manufacturer's cost of producing one unit	
m	Standard industry markup of the manufacturer's production cost	
c_u	Cost of underage	$c_u(T) = p - m \times g(r, T)$
c_o	Cost of overage	$c_o(T) = m \times g(r, T) - s$
t_F	Minimum finished-good shelf-life constraint given by retailer	
S_{min}	Minimum order quantity	
Manufacturer		
t_R	Raw material lifetime	
λ	Raw material arrival rate	
r	Production rate	
$W_q(r)$	Raw material waiting time	
c_R	Unit raw material cost	
c_h	Raw material holding cost per unit	
$c_r(r)$	Processing cost per cycle	$ar + b$
a	Variable operating cost	
b	Fixed cost related to rent and storage	
c_s	Raw material spoilage and disposal cost	

Table 3.1: Notation

3.4 The Stackelberg model and analytical results

3.4.1 Retailer's cost

In this section we consider the retailer's problem of reducing mismatch and shelf space and in-store replenishment costs for a perishable item when the replenishment cycle is an

3.4. The Stackelberg model and analytical results

endogenous parameter. Our objective is to minimize the retailer's costs by finding the optimal replenishment cycle T^* and the corresponding order quantity $S(T^*)$ over the given time horizon L . At each replenishment cycle the retailer places orders of $S(T)$ and receives finished products to sell in the following cycle from the manufacturer with negligible lead time.

The retailer incurs costs as a result of supply-demand mismatches: If the demand is higher than the available amount of products, the retailer incurs underage costs; otherwise, it incurs overage costs. It is well established that shelf space and in-store handling represent significant costs in retailing (Cachon, 2001; Broekmeulen et al., 2004), therefore we include the cost for shelf space allocated by the retailer for this product, assuming the shelf-space remains fixed throughout the time horizon. We assume that the demand in each replenishment cycle is independent and identically distributed, following a normal distribution with the mean μ and the standard deviation σ as shown in Figure 3.2. Then, demand for a replenishment cycle of T periods follows a normal distribution with mean μT and standard deviation $\sigma\sqrt{T}$:

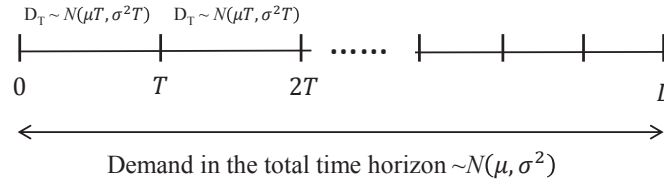


Figure 3.2: Total demand in the time horizon and periodic demand in a replenishment cycle of duration T where $T \in [0, L]$ and L is normalized to 1. D_T represents demand per replenishment cycle

The retailer's problem is given in Equation 3.1. The first two terms on the right hand-side represent the mismatch costs, and the last term represents shelf space cost. Within mismatch costs, the term x represents the demand per replenishment cycle, with $f(x | T)$ being the density function and parameters as in Figure 3.2. In the classic newsvendor problem, the overage and underage costs do not depend on the replenishment cycle. In our model we include this dependence: if the replenishment cycle is short, the mismatch will be higher due to deviations from expected demand μT , causing greater overage and underage costs.

The term $c_o(T) = c(r, T) - s$ is the overage cost with sales price p and salvage value s . The term $c_u(T) = p - c(r, T)$ is the underage cost with unit cost c based on the manufacturer's costs, which depend on the manufacturer's cost and the expected order quantity for the replenish-

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ment cycle T . The term $R(T)$ represents the general shelf-space and in-store replenishment costs of each replenishment cycle. It increases with the replenishment cycle due to higher order quantities, as described in Cachon (2001). We explain how to include the shelf space cost more in detail in Equation 3.3.

$$\begin{aligned} \text{Minimize}_{T \leq t_F} \quad C(S(T) | F) = & c_o(T) \int_0^{S(T)} (S(T) - x) f(x | T) dx \\ & + c_u(T) \int_{S(T)}^{\infty} (x - S(T)) f(x | T) dx + R(T) \end{aligned} \quad (3.1)$$

We normalize the unit time horizon to one in order to formulate the retailer's cost function. For other values of L , the same results are found by replacing T with T/L . Note that for a replenishment cycle equal to the unit time horizon, the problem is equivalent to the single-period newsvendor model.

We apply the change of variables such that $z = \frac{S(T) - \mu T}{\sigma \sqrt{T}}$, where $\Phi(z)$ and $\phi(z)$ represent the standard cumulative distribution and probability density functions for the normal distribution, respectively. The cost per replenishment cycle in Equation 3.1 can be expressed as follows:

$$C(z | T) = c_o(T) \sigma \sqrt{T} (z \Phi(z) + \phi(z)) + c_u(T) \sigma \sqrt{T} (\phi(z) - z(1 - \Phi(z))) + R(T). \quad (3.2)$$

We assume that the shelf space cost for the total time horizon, represented as $C_{ss} T$, depend on the replenishment cycle due to increasing order quantities in T for the products arriving to the retailer. In practice, $C_{ss} T$ can be found by multiplying the per unit cost of shelf space, as in Cachon (2001), with the mean demand for the replenishment cycle, μT . For long replenishment cycles, the costs arise either due to higher shelf space requirement for a product with given demand, or due to costs attributed to in-store replenishment of the shelf from the backroom. According to Broekmeulen et al. (2004), handling costs in retailing are three to five times higher than the inventory costs. For the total time horizon, the expected cost becomes the following:

$$\bar{C}(z | T) = \frac{c_o(T) \sigma (z \Phi(z) + \phi(z))}{\sqrt{T}} + \frac{c_u(T) \sigma (\phi(z) - z(1 - \Phi(z)))}{\sqrt{T}} + C_{ss} T, \quad (3.3)$$

where $T \in (0, 1]$. We now discuss the two constraints for T . We first define the minimum order quantity S_{min} as the smallest quantity that can be delivered in one replenishment cycle, therefore setting the shortest possible replenishment cycle.

Second, we restrict $T < t_F$, or in other words, the replenishment cycle is limited to the finished goods lifetime constraint, to guarantee service throughout the entire replenishment cycle and ensure product quality and consumer satisfaction. For example, if the product lifetime were 10 and the replenishment cycle 12 days respectively, the product would be unavailable during a 2-day period. For most retailers and products, the constraint $T < t_F$ is enforced in two ways. First, days-fresh perishable items are replenished with direct deliveries (Van Woensel et al., 2007) and are mixed with multiple products. Additionally, they are sold with high margins to overcome the high costs due to ordering/transportation and spoilage costs.

The second way $T < t_F$ is enforced relates to the size of retailer outlets and minimum delivery quantity. Large retailers are usually leaders in their supply chain due to high demand and sales for perishable items. As a result, their products are replenished frequently and rarely expire before sales. For leading retailers, losses due to spoilage and damages combined are as low as 3% (Buck and Minvielle, 2014). This is in line with our model, where the retailer is the leader and $\mu/S_{min} \approx T < t_F$. For smaller retailers, the picture is different. Due to minimum order quantities and case pack sizes (Van Donselaar et al., 2006), small retailers with low total demand for days-fresh perishable items may incur salvage and disposal costs too high to overcome. This will cause them to either eliminate days-fresh perishable items from their product offering, or integrate the cost of spoilage to the sales price.

3.4.2 Manufacturer's cost

On the supply side, the manufacturer uses a make-to-stock policy to satisfy the retailer's orders for the following replenishment cycle. The manufacturer first purchases raw materials from external suppliers at a unit cost of c_R . The raw materials arrive at the manufacturer's factory at a Poisson arrival rate of λ , thus we model the raw material arrival and processing as a $M/M/1 + D$ queue where $+D$ represents the fixed raw material lifetime t_R . Due to limited production capacity, the raw materials wait at the factory for an expected duration of $W_q(r)$

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before being processed, where r is the production rate. If arriving raw materials are not processed before t_R , or in other words if $W_q(r) > t_R$, the manufacturer incurs a unit spoilage cost of c_s . Fresh milk or berries are examples of raw materials that deteriorate relatively quickly.

We denote the probability that the raw materials are discarded as $P(W_q(r) > t_R)$. We adapt the formulation for impatient customers with deterministic patience given in Barrer (1957), and find the equilibrium spoiled quantity expressed as

$$P(W_q(r) > t_R) = \frac{(r - \lambda)e^{t_R(\lambda - r)}}{r(1 - e^{t_R(\lambda - r)})} \quad (3.4)$$

Following Barrer (1957), for $r = \lambda$ the probability is reduced to $P(W_q(r) > t_R) = \frac{1}{rt_R + 1}$.

Raw materials that are within their t_R lifetime limit are sent to production. The total cost of production $c_r(r)$ over a replenishment cycle increases linearly with the production rate. The production rate represents the production capacity, which is determined based on the frequency of replenishments. We use a linear production cost $c_r(r) = ar + b$, with the fixed component b related to rent and storage costs, and variable costs a related to operating costs. For example, increasing the number of shifts of production will increase the variable costs in that replenishment cycle. Linear production costs are commonly used in the literature (Shaw and Wagelmans, 1998; Akbalik and Penz, 2009).

The objective of the manufacturer is to minimize costs by deciding the optimal balance between spoilage and processing costs. The unit cost of processing for one unit in one replenishment cycle is given as $\frac{c_r(r)}{S(T)}$. Longer replenishment cycles ensure higher economies of scale at the manufacturer due to fixed cost a of production and a make-to-stock policy. We use a batch size assumption that $S(T)$ is μT , and that the term $z\sigma\sqrt{T}$ has a sufficiently small impact on the manufacturer's overall cost. In Section 3.5 we numerically show that the assumption has negligible impacts on the unit cost of the manufacturer.

The relationship between the rate of raw material arrival and production is $r \geq \lambda > \frac{S(T)}{T}$, in order to satisfy the full order quantity at each replenishment cycle. The manufacturer's

problem of minimizing the unit cost of production is formulated as follows:

$$\underset{r \geq \lambda > \frac{S(T)}{T}}{\text{Minimize}} \quad g(r, T) = c_R + c_h + \frac{c_r(r)}{S(T)} + \frac{c_s(r - \lambda)e^{t_R(\lambda - r)}}{r(1 - e^{t_R(\lambda - r)})} \quad (3.5)$$

Finally, the manufacturer incurs a unit holding cost of the finished goods, denoted by c_h . Finished products are sold to the retailer at a price of $g(r, T) \times m$, where $m \in (1, p)$ is an exogenous variable that represents the standard industry markup of the manufacturer's production cost for a given replenishment cycle T and product category, and p is the retailer's selling price.

Note that we used a unit spoilage cost of c_s . While there are physical costs of disposal, there are also indirect costs that can be considered. Waste is an important key performance indicator in the assessment of firms' environmental performance which leads to lost goodwill or damaged reputation due to increasing consumer awareness for environmental impacts.

3.4.3 Stackelberg Game

We conceptualize our supply chain as a Stackelberg competition with the retailer as the leader and the manufacturer as the follower. In many developed countries, distribution channels and product offerings to end customers are dominated by powerful retailers that have large customer bases. For example, Walmart stores are visited by more than 260 million customers each week, providing the company with strong bargaining power over its suppliers. These types of retailers often squeeze the profits of their suppliers (Riper, 2004). Moreover, agricultural food products typically have a fragmented supply base where there is usually no supplier brand awareness at the consumer level, i.e., the retailers are leaders. We therefore model the retailer as the leader, and the manufacturer as the follower. We first formulate the manufacturer's best response for all possible replenishment cycle lengths T that the retailer might announce. The manufacturer's cost is given in equation 3.5. The proof of convexity of the manufacturer's cost in r is given in Appendix A.2, which guarantees that r^* is the global optimum. To find the optimal replenishment cycle, we take the first derivative of $g(r, T)$ with respect to production rate r and set it to zero: $r^* = \{r \mid \frac{\partial g(r, T)}{\partial r} = 0\}$. The optimal processing

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rate r^* satisfies

$$\frac{e^{t_R(\lambda-r^*)}(\lambda e^{t_R(\lambda-r^*)} - \lambda + r^{*2}t_R + r^*\lambda t_R)}{(r^* - \lambda e^{t_R(\lambda-r^*)})^2} = \frac{a}{c_s S(T)}, \quad (3.6)$$

where the manufacturer's best response function in terms of T can be found by using Equation 3.6 in the manufacturer's cost function.

We next find the replenishment cycle that the retailer will set based on the optimal processing rate $r^*(T)$ of the manufacturer. We show convexity of the retailer's function in T and detailed solution of the retailer's optimum in Appendix A.1. We replace $r^*(T)$ into the retailer's cost, in the overage and underage costs $c_o(T)$ and $c_u(T)$. Our objective is to minimize the cost of the retailer, with respect to the replenishment cycle T ; however, the terms $z = \frac{S(T)-\mu T}{\sigma\sqrt{T}}$, $c_u(T)$ and $c_o(T)$ all depend on T . Due to the analytical complexity of explicitly replacing all terms in the objective function and taking the derivative with respect to T , we replace $c_u(T)$ and $c_o(T)$, following a batch size assumption for the manufacturer as explained in Section 3.4.2.

We follow the methodology introduced in Whitin (1955) and Zabel (1970), and used in Petruzzii and Dada (1999) to use a two-stage optimization in first z , then T . We show convexity of the Equation 3.2 with respect to T and z to ensure global optimality of the solution, then substitute z^* into the objective function and subsequently optimize $\bar{C}(T, z^*)$ over T . It is straightforward from the first derivative with respect to z , that the optimal order quantity is identical to the newsvendor solution, shown in Appendix A.1. We replace the optimal order in Equation 3.3, which simplifies the cost function to

$$\bar{C}(T | z^*) = \frac{(c_u + c_o)\phi(z^*)\sigma}{\sqrt{T}} + C_{ss}T. \quad (3.7)$$

where the optimal order quantity z^* is dependent on the manufacturer's best response, which is dependent on the optimal processing rate found in Equation 3.6. By taking the first derivative of the retailer's cost $\bar{C}(T, z^*)$ in Equation 3.7 with respect to T , we can show that the optimal replenishment cycle T^* satisfies

$$T^* = \left(\frac{2C_{ss}}{\sigma(p-s)\phi(z^*)} \right)^{2/3}. \quad (3.8)$$

Replacing Equation 3.8 back into Equation 3.7 and defining $\xi = \sigma(p - s)\phi(z^*)$, the retailer's minimum cost becomes

$$\bar{C}(z^* | T) = \frac{\xi^{7/3} + 2C_{ss}^{4/3}}{2C_{ss}^{5/3}\xi^{2/3}}.$$

The optimal order quantity becomes $S(T^*) = \mu \left(\frac{2C_{ss}}{\xi} \right)^{2/3} + \sigma z^* \left(\frac{2C_{ss}}{\xi} \right)^{1/3}$. If $T^* > t_F$, then the replenishment cycle is set to t_F , where

$$\bar{C}(z^* | T) = \frac{(c_u + c_o)\phi(z^*)\sigma}{\sqrt{t_F}} + C_{ss}t_F,$$

and $S(T^*) = \mu t_F + z^* \sigma \sqrt{t_F}$, with z^* equal to the newsvendor critical fractile. Note that for T^* , the minimum unit cost $g(r^*, T^*)$ of the manufacturer can be expressed as

$$g(r^*, T^*) = c_R + \frac{c_s e^{-(r^* - \lambda)t_R}}{r^* - \lambda e^{-(r^* - \lambda)t_R}} \left[r^* - \lambda + \left(r^* + \frac{b}{a} \right) \left(\frac{\lambda e^{t_R(\lambda - r^*)} - \lambda + r^{*2} t_R + r^* \lambda t_R}{r^* - \lambda e^{-(r^* - \lambda)t_R}} \right) \right]. \quad (3.9)$$

For $r = \lambda$, the optimal processing rate is $r^* = \frac{\sqrt{\frac{c_s t_R S(T)}{a}} + 1}{t_R}$, and the manufacturer's unit cost can be simplified to $g(r^*, T^*) = c_R + c_h + \frac{c_s(2ar^* t_R + b t_R + a)}{a(r t_R + 1)^2}$.

3.5 Numerical analysis and discussion

In this section we conduct a numerical analysis and discuss the managerial implications of our findings. We use the manufacturer's and retailer's costs in Section 3.4 with a time horizon of 60 days and employ the parameters, shown in Table 3.2.

Both the manufacturer and retailer's costs are convex, as established in Section 3.4. The optimal replenishment cycle is 25 days, and the optimal processing rate is 31 units/day. In Figure 3.3A we illustrate the order quantity per cycle, taking into consideration the minimum order quantity S_{min} and the finished goods lifetime constraint t_F . Our aim in Figure 3.3A is not to optimize for the replenishment cycle but to provide a view of the impact of the replenishment cycle on the order quantity. We observe a linear increase in the order quantity with values close to the mean demand. More importantly, in numerical tests the manufacturer's cost remains

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Parameter	Denotation	Set value
L	Time horizon	60 days
μ	Mean demand over L	3000
σ	Standard deviation of demand over L	1000
C_{ss}	Shelf space cost for the total time horizon	\$5000
p	Unit price	\$100
s	Salvage value	\$10
S_{min}	Minimum order quantity	500
c_R	Unit raw material cost	\$20
c_h	Raw material holding cost	\$2
$c_r(r)$	Processing cost per cycle	\$(30r+300)
c_s	Cost of spoilage	\$25
m	Manufacturer's markup	1.2
λ	Raw material arrival rate	30 units/day
t_R	Raw materials lifetime	1 day
t_F	Finished goods lifetime	40 days

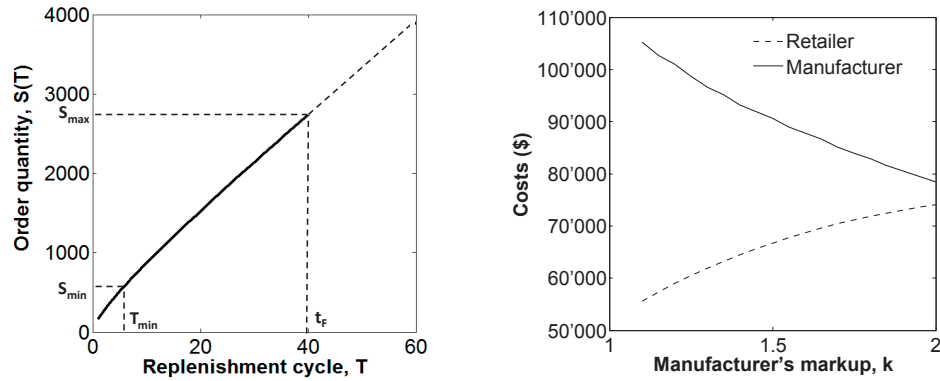
Table 3.2: Parameter inputs for numerical model

the same with and without the batch size assumption, which is in line with our approximation for unit processing costs in Appendix A.2.

Short finished goods lifetimes t_F , that are lower than the optimal replenishment cycle, result in suboptimal replenishments at the retailer. From a supply chain perspective, there is a repercussion upstream to the manufacturer. Shorter replenishment cycles mean smaller order quantities, which in turn hinders economies of scale for the manufacturer due to the fixed cost of processing. The unit cost of the finished good increases and raises costs for both parties.

Next, we analyze the effect of manufacturer markups to analyze the effect of the intermediate finished goods' selling price on the supply chain costs. From Figure 3.3B, we observe that despite the retailer leading in the Stackelberg game, higher manufacturer markups cause higher mismatch costs for the retailer. This in turn shifts the retailer's cost curve upwards. Contrarily, the manufacturer benefits from longer optimal replenishment cycles that provide for economies of scale. This presents an incentive for the retailer to seize opportunities for integration with the manufacturer.

Next, we observe the effect of raw material lifetime on the optimal decision variables, as well as costs for both parties. In Figure 3.4A, we show that the optimal processing rate decreases as the raw materials become more durable. While investments for higher production capacity



(A) The retailer's order quantity per cycle. (B) Retailer's costs increase, while the manufacturers' decrease as the markup increases

Figure 3.3: The retailer's order and the effect of manufacturer's markup on both parties.

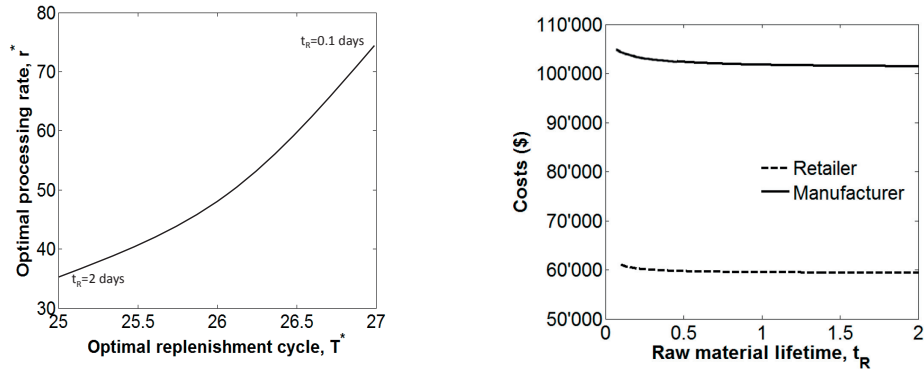
could decrease spoilage, higher processing rates could increase the fixed cost of production. This tradeoff represents an opportunity for future research.

While higher processing rates do not have a very important effect on the optimal replenishment cycle, we observe a significant increase in the manufacturer's costs for short raw material lifetimes, as shown in Figure 3.4B. This is in line with our analytical result in Equation 3.8, where the optimal replenishment cycle is only influenced by the manufacturer's cost via the critical fractile term z . The cost increase for the retailer is due to higher mismatch costs caused by higher manufacturing costs. We conclude that both parties have an incentive to improve raw material lifetime. This is achieved mainly through better agriculture, sourcing, storing and processing practices in the upstream supply chain.

Besides the direct cost impact, indirect impacts of spoilage such as lost goodwill or damaged reputation, which are usually difficult to measure, can also be an important motivation to increase raw material lifetime and reduce spoilage. This should also give manufacturers the incentive to invest in improvements or raw material conditions and quality at the agricultural level. It is already common for leaders in the food industry to collaborate with farmers to increase the quality and lifetime of raw products. Common examples include milk, fruits and vegetables, coffee and cocoa, among others.

High variable costs of processing, a , cause an increase in the percentage of the manufacturer's

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(A) The manufacturer's unit costs are composed of processing and spoilage costs. (B) Raw material lifetime increases costs for both parties.

Figure 3.4: The effect of raw material lifetime on optimal decision variables and overall costs

spoilage costs. This finding suggests that operational efficiencies in production such as lower energy and labor costs may also reduce spoilage of raw materials and improve the manufacturer's environmental performance. Furthermore, they cause the manufacturer's cost to be less sensitive to the processing rate above the optimum value. Additionally, we find that high shelf space or in-store shelf replenishment costs have a negative economic impact for both parties.

Finally, we discuss the impact of demand volatility on the supply chain costs. High demand volatility increases the costs of the retailer, while the cost increase for the manufacturer is insignificant. This is because the manufacturer delivers the expected order quantity for each replenishment cycle, where only the term relating to the mean demand is significant for manufacturing costs, as in our batch size approximation in Appendix A.2.

3.6 Conclusion

Firms struggle to estimate demand over long time horizons. The costs of demand uncertainty, coupled with the cost of perishability, decrease operational efficiency in a variety of industries. Our paper targets the food industry, in which raw materials such as fresh fruit, vegetables and dairy products are processed into products with a longer shelf life. In the food industry, deciding the optimal replenishment policy through demand forecast updates is important for

decreasing costs due to overage and underage. It can also decrease discount or disposal costs for finished products at the retailer. More broadly, firms can improve their environmental impact and reputation by reducing spoilage in their supply chains. In prior literature, Gimenez et al. (2012) also found that environmental improvements in manufacturing companies result in better economic performance.

The contribution of this paper is two-fold. First, we model the replenishment cycle as an endogenous variable, whereas previous studies considered the replenishment cycle as an exogenous parameter. We find the analytical solution for the optimal replenishment cycle given demand uncertainty and shelf space costs. Second, we consider both raw material and finished product perishability in a manufacturer-retailer setting, and quantify the relationship between the two perishability costs. Our paper has implications for both researchers and practitioners working with demand uncertainty for perishable products.

Our findings give insights on the impact of the perishability of raw materials and finished goods within the supply chain. In what relates to perishability, we summarize three main findings. First, despite spoilage representing relatively low costs, short raw material lifetimes significantly increase both the retailer's and the manufacturer's costs. It is due to the effect of product lifetime on the processing rate and thus the replenishment cycle. Second, we find that higher variable costs in processing increase the raw material spoilage costs. It suggests that efficiencies in production can also improve the environmental performances of manufacturers by reducing raw material spoilage. Third, for finished goods, we find that short lifetimes, or short time limits before the sell-by date, result in more frequent replenishments and higher costs not only for the retailer, but also for the manufacturer. This should create an incentive for manufacturers to produce longer-lasting products, in line with the findings of Amorim et al. (2012).

Our model is applicable for perishable product supply chains where decisions are decentralized, the manufacturer and retailer both want to reduce their own costs, and the retailer dominates decisions. This is observed in practice, when distribution channels and product offerings are dominated by powerful retailers that have large customer bases. Such retailers have strong bargaining power over their suppliers. Consequently, manufacturers offer a menu

Chapter 3. Optimal replenishment cycle for perishable items facing demand uncertainty

of contracts with different replenishment cycles at competitive transfer prices, often squeezing their profits. For this setting, our solution to the retailer's problem can be applied to determine the replenishment cycle that minimizes its mismatch and shelf space costs based on the manufacturer's proposals.

There are two main limitations for the application of our model. First, we consider only a single product in a simple two-echelon supply chain. We do not consider the production of other products in the same facility, which would require production scheduling. Second, we do not consider inventory carryover between replenishment cycles at the retailer, but rather discounts for less fresh items, which we represent with salvage costs.

There are many opportunities for future research to enhance the management of perishable products. Future research may integrate seasonality in the demand process and inventory carryover. Another extension might include positive lead times and multiple products or echelons in the supply chain. Additionally, modeling perishability with a $G/G/1$ queue could increase the applicability of the model.

Research in the area of perishable models in a supply chain context is rare. We thus encourage scholars to pursue empirical studies in this area. Potential future topics might include i) an empirical analysis of the impact of finished goods and raw material lifetime on supply chain costs, and ii) quantifying the effect of ordering quantities upstream, on the freshness and spoilage downstream in the supply chain.

4 Managing perishability in the fruit and vegetable supply chain

4.1 Introduction

Global food waste and loss cost is estimated to be \$940 billion a year (Magnin, 2016). Waste and loss reduction in the food supply chain directly impacts the triple bottom line of companies (John Elkington, 1997), and represents opportunities for cost savings and reduced environmental and social footprints. Nonetheless, it remains a complicated problem, requiring solutions at all levels of the supply chain. The objective of this research is to identify the drivers of waste and losses in fruit and vegetable retailing, and enable practitioners to implement the most effective solutions to this global problem. Throughout our study, we refer to waste due to product degradation and expiration or other losses, as spoilage.

We use data from Migros to identify drivers of fresh fruit and vegetable spoilage. In 2015, Migros was the largest Swiss grocery retailer with 27.4 billion Swiss Francs in sales and a market share above 21%. Their main differentiator is relatively high product availability and large product assortment, where fruit and vegetable sales account for more than 10% of total supermarket sales. As with other retailers, fresh fruit and vegetables represent a highly competitive and high-margin product group that generates traffic flow into the store, requires high availability, specialized infrastructure and involves seasonal portfolio changes. One of

Chapter 4. Managing perishability in the fruit and vegetable supply chain

the fruit and vegetable store managers stated: “We can’t risk having empty shelves during the day. If a customer walks inside the store and doesn’t find the fruit or vegetable they are looking for, they turn back without buying anything at all and go to competitors.” As with all retailers who deal with fresh produce, perishability in this category is a major concern.

Challenges for fresh fruits and vegetables are both product-related and operational: product yields depend on climatic conditions, prices are volatile, suppliers are fragmented, the products are perishable and fragile (have temperature and handling requirements), and quality-control processes are laborious. Additionally, order and replenishment decisions are more critical than for weeks/months-fresh products due to short lifetimes. All of these factors drastically influence lead time, inventory, and overall costs.

For example, Target, the second-largest discount retailer in the US, is struggling to keep their perishable products fresh. While their fresh products represent \$18.5 billion and make up one fifth of their revenue, Target is suffering from high spoilage costs compared to the industry average. Their main problem is inventory aging due to lack of store traffic for perishable products. To overcome the spoilage problem, they spent more than \$1 million per store in 25 of their stores to increase traffic and better manage inventory, while increasing their replenishment frequency and offering localized products (Safdar, 2016).

Spoilage occurs at all stages of the supply chain. According to a 2011 report by the Food and Agriculture Organization (FAO), in Europe, 45% of produced fruits and vegetables did not end up being consumed. Of those not consumed, 45% were lost at the agricultural stage, 30% at post-harvest, processing and distribution, and around 25% at the consumption stage (FAO, 2011). Higher freshness at retailers could potentially reduce losses at the consumption stage. At the retailing stage, Buck and Minvielle (2014) identify loss rates as 3 to 5 percent of volume in fresh produce at best practice retailers, 6 to 8 percent among average performers, and 9 to 15 percent at under-performing retailers, due mostly to climate and long-distance transport. Although Migros can be defined as a best practice retailer according to this definition, spoilage for fresh fruits and vegetables represents a significant part of their annual profit in the fresh fruit and vegetables category.

To understand the major causes of spoilage, we collected supply chain data and conducted

interviews with managers responsible for ordering fruits and vegetables at three levels of the supply chain: importers, DCs and stores. We utilize 495,460 day-store-SKU level observations for 100 SKUs (products), from 128 stores over a four month period to show that spoilage is affected by inventory, promotions, delivery type, commitment changes in ordering, variation in orders at two supply chain echelons, order cycle, and quality issues at a statistically significant level.

Overall, excess inventory, order cycles and variation, as well as longer delivery lead times have the greatest impact on spoilage. As the number of days of inventory increases, inventory aging and sell-by constraints cause spoilage. We show that reducing the average inventory by half a day would reduce up to 40% of current spoilage costs. Smoothing store and distribution center (DC) orders by 50% each would also improve spoilage costs by 30%, while increasing the order frequency to daily orders would reduce spoilage costs by 17%. Direct deliveries are relatively infrequent, and represent major improvement opportunities; increasing direct deliveries to 20% of total deliveries could reduce spoilage by 20%.

The contribution of this paper is two-fold. We add to the existing perishability literature by identifying and quantifying drivers of spoilage for days-fresh products in retailing. Second, we contrast the drivers of spoilage to those of weeks-fresh products. In doing so, we present an industry example of how collaborative forecasting could potentially fix incentive misalignments while reducing spoilage throughout the entire supply chain. For managers working in the days-fresh category we recommend using specialized supply chain processes, tracking and quantifying inventory age and damage, and collaboration with supply chain partners to reduce inventory age.

The rest of the paper is organized as follows. In Section 4.2 we overview the literature. Section 4.3 describes the empirical setting in detail, i.e., the supply chain, ordering processes and perishability issues. In Section 4.4, we discuss our hypotheses for the drivers of spoilage. Section 4.5 describes the data in detail, and defines the variables. In Section 4.5, we discuss the empirical model used in the estimation. We present our empirical results in Section 4.6 and discuss their managerial implications. Finally, we conclude in Section 4.7 with a discussion of the limitations of our research and future research directions.

4.2 Literature review

In our research we consider the supply chain and retailing of fresh fruits and vegetables. Consequently, our research relates to the literature on perishable inventory. There are numerous studies on managing food perishability throughout the supply chain to increase freshness and value for supply chain entities. We first review studies that use mathematical models, and subsequently those that use empirical data.

Among the studies that use mathematical modeling, Ferguson and Ketzenberg (2006) study the impact of information sharing in relation to product age on a retailer's profit in the grocery industry and found that the benefits are highest when demand variability and cost are high, and product lifetimes are short. Focusing on product characteristics, Blackburn and Scudder (2009) introduce the marginal value of time of fresh produce to minimize lost value in the supply chain. Minner and Transchel (2010) present a method to determine dynamic order quantities for fresh food with positive lead time, FIFO or LIFO issuing policy, and multiple service level constraints. They show that a constant-order policy might provide good results under stationary demand, short shelf-life, and LIFO inventory depletion. Cai et al. (2010) optimize orders and prices for distributors and retailers of groceries, and show that coordination can benefit both parties. Ata et al. (2012) quantify how backhauling and vertical differentiation can increase the retailer's margin for local food, thus increasing the small local farmer's competitiveness. Focusing on the grocery distribution chain, Holzapfel et al. (2015) minimize total costs by clustering stores and selecting delivery patterns. Finally, Kırıcı et al. (2016) optimize the replenishment frequency between a manufacturer and retailer considering both raw material and finished goods lifetimes.

We next analyze the literature on perishable inventory that uses empirical data. Van Donselaar et al. (2006) segment perishable products at a supermarket, based on lifetime. They show that perishables have higher average sales, a smaller case pack size, lower coefficient of variation of weekly sales, lower potential delivery frequency and a lower minimum inventory norm. Later, Van Woensel et al. (2007) show that perishables in retail have higher substitution rates compared to their durable counterparts, and require cross-docking or direct delivery. More recently, Reiner et al. (2013) study in-store logistics processes for handling dairy products, and

find that strategic and tactical design of in-store logistics processes lead to higher on-shelf availability and reduced obsolescence costs. Van Donselaar et al. (2016) analyze the impact of relative price discounts on product sales during promotions and provide guidance on forecasting promotional demand for perishable products.

The most relevant research for our study is Akkas et al. (2016), who explore the drivers of expiration for consumer packaged goods. They find that case size, inventory aging, negligence of shelf rotation, compliance to minimum order rules, manufacturer's sales incentives and forecast complexity are the main drivers. Although our objective is similar, there are fundamental differences between the latter study and our own. First, we focus specifically on fruits and vegetables, which are days-fresh products that are significantly different from weeks- or months-fresh products in terms of lead times, inventory levels, sales and quality (Van Donselaar et al., 2006). Second, we analyze a panel of daily observations that allows us to capture drivers of spoilage for days-fresh products. Finally, fruits and vegetables can spoil within the sellable lifetime. Therefore, our scope extends from expiration to general spoilage, which includes product damage and heterogeneous quality issues. A full contrast of results between days- and weeks-fresh items are found in Section 4.6.

Due to the difference in products we observe, the setting of the supply chain, and the data we study, we further observe the impacts of the additional drivers that we identify, namely inventory quantity, delivery types, forecast updates, order variation at two supply chain levels, order cycle, well as quality issues. We further account for product origin, packaging, season, and category.

As a result, to our knowledge, our study is the first to identify and quantify the drivers of waste and their economic impact for days-fresh perishable products using econometric modelling in the grocery supply chain.

4.3 Empirical setting

In this section, we describe the retailer's supply chain operations for imported fruits and vegetables. We do not consider local Swiss produce because the sourcing and ordering processes are different and product availability is often unpredictable.

Chapter 4. Managing perishability in the fruit and vegetable supply chain

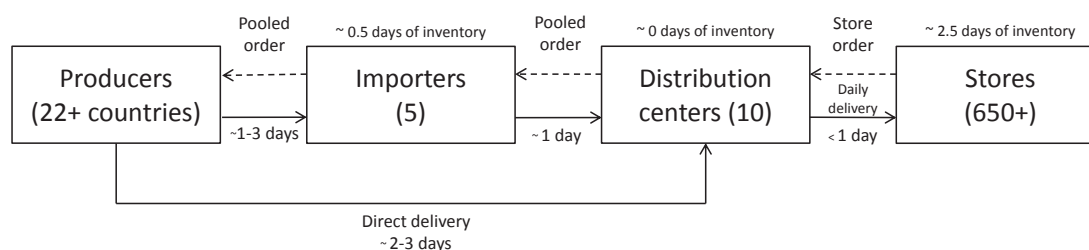


Figure 4.1: The imported fruit and vegetable supply chain. The full arrows represent product flow; the dashed arrows represent order flow.

The supply chain is shown in Figure 4.1. There are four players in the supply chain: producers, importers, DCs and stores. Producers are located in more than 22 countries and are responsible for producing, harvesting and packing the products for shipment. Migros works with five main independent and private importers based in Switzerland. Each importer is responsible for the delivery of certain categories of products to DCs. There are 10 independent DCs under the retail brand, which assemble products into pallets based on store orders and dispatch them to stores on a daily basis. Each of the 650+ retail stores receive products before store opening every morning, except on Sundays. Store managers in fruit and vegetable sections are responsible for ordering, product display and replenishment. They are evaluated on achieving sales targets, while reducing product discounts and waste. We next describe the ordering process.

The supply chain follows a pull ordering strategy. Every morning the stores place orders for the next store opening, based on factors such as weather, price, promotions, day of the week, week of the month, product quality and product season. The order triggers the product flow from the DCs to the stores. The DCs pool the orders of their stores, and pass them on to the importers, who deliver within one day. The importer typically holds less than half a day at the end of the day for safety, and the DC holds close to zero days of inventory at the end of the day, but due to transportation and ordering lead times, stores are replenished with products that are at least two days old. Tropical fruits are mainly shipped to Europe and ripened after arrival, with similar lead times from the importer onwards.

In order to guarantee product availability at stores, and account for the lead time difference

between ordering at the stores and arrival at the DC, DCs send preorders. In other words, they send their order forecast, which can be modified during the week, to importers every Thursday for the following week. Preorders are based on historical data and other factors that stores equally consider: weather, price, promotions, product and time. Yet, the DCs' preorders significantly deviate from the total daily orders placed by the stores. Consequently, the importers, who are contractually bound to deliver 100% of DC orders, need to cover for and speculate the difference between DC preorders and actual orders. They inflate or reduce their orders to the producers in advance based on historical data and experience.

There are two types of deliveries. In the first type, products first arrive from the producer to the importer, and are subsequently sent to the DCs. In the second type, products are delivered directly from the producer to the DC. In the former, the preordering system is used with a possibility of updating orders during the week, which we call a commitment change. In the latter, preorders of the week cannot be changed and are offered with a price discount from the retailer, just as in an advance purchase contract (Özer and Wei, 2006).

If the importers over-order, there are two potential scenarios. In the first, products are stored and subsequently sent to DCs in the following day, which reduces product freshness at the DC and store levels. At the DCs, it increases the likelihood of quality warnings issued from DCs to importers, while at the stores it increases the likelihood of spoilage and customer returns. In the second scenario, the product quality is too low or product age is too high, causing products to be rejected at the DC. In this case the importer finds an alternative buyer. If the products are not sold, they are donated, used as compost, turned into biofuels, or in rare cases incinerated.

The retailer differentiates itself by assuring a high in-stock level, while at the same time delivering fresh products. Besides inadequate orders which increase inventory age, high service levels can indirectly cause spoilage in the supply chain. Date coding is used to increase traceability of freshness: producers print the packaging date to individual consumer units to open cases. Ferguson and Ketzenberg (2006) show the benefits of sharing inventory age. The date is coded in a way that consumers cannot identify product age and avoids them from buying freshest products first, i.e. on a LIFO basis. The printed date code is used at two levels of the supply chain: DCs and stores. DCs check the date between their order and reception to

and from the importer. This guarantees that the importer issues products on a FIFO basis, and has not kept inventory for long durations. The store uses the date code to understand when the products should be removed from the shelves, in order to reduce customer complaints and returns. Note that the date code is not digitally stored per item or by delivery, thus information on the age at sales or arrival can not be accessed once the product leaves the supply chain echelon.

4.4 Drivers of spoilage

In this section, we motivate our hypothesis for the drivers of spoilage in stores. We classify the drivers of spoilage into two primary groups. The first is inventory age, which causes expiration due to the sell-by date (date codes) or insufficient quality due to degradation. The second is product damage or retailer’s product standards: size, color, sugar content, and packaging, among others. As in previous studies in the fruit and vegetable category, there is no continuous data available for inventory age or spoilage caused by product damage or visual/quality standards. The date code for packaged products is not digitally recorded per item or delivery, hence information on the inventory age at sales or arrival only available on print within a supply chain echelon. Damages or visual quality standards are not recorded in the system as a separate cause of spoilage. While the main drivers are not digitally available for analysis, it is possible to use other data that explain these two main causes, and therefore spoilage. We formulate our hypotheses based on these drivers (shown in Figure 4.2) which are further discussed in the following subsections.

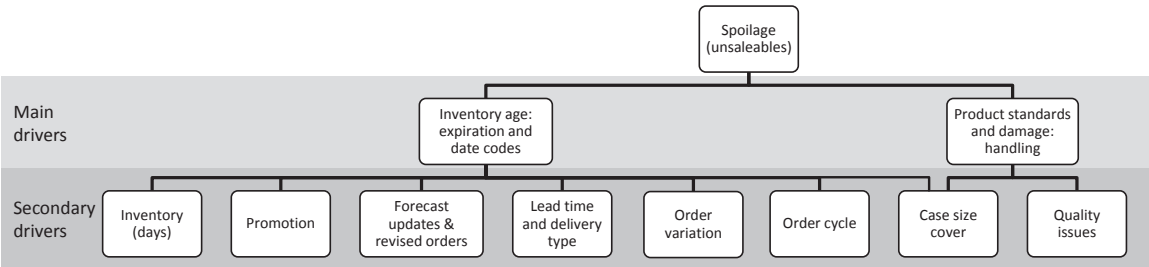


Figure 4.2: Drivers of spoilage for days-fresh products

In our main analysis, we quantify the impacts of the secondary drivers shown in Figure 4.2, on spoilage. We first use an exploratory analysis to show the importance of inventory age for days-fresh items. In this additional analysis, we try to explore the impact of inventory age on spoilage solely due to sell-by dates using a simple simulation, similar to Akkas et al. (2016), since we cannot quantify inventory age directly. We use a base-stock ordering policy under exponentially distributed sales on a FIFO basis, and different service levels at the retailer. We compare the results to real spoilage when there are no promotions (shown in Appendix A.5). Our results show that inventory age explains 100% of the spoilage at a 92% service level if we use an average of 4 days sell-by duration at the retailer. Spoilage increases as the allowable selling duration shortens and service level increases. Our result underlines the importance of inventory age for days-fresh products. Inventory age is clearly the main driver of spoilage for days-fresh products, which significantly differs from weeks-fresh products.

Inventory

For a fixed amount of sales, carrying more days of inventory at the store increases spoilage due product perishability (Akkas et al., 2016). Additionally, store managers are encouraged to hold maximum inventory at the display area and minimum inventory in the backroom to minimize handling time and inventory errors (Eroglu et al., 2013). However, products in the display are subject to higher temperatures throughout the day, which increases the speed of maturity or decay (Blackburn and Scudder, 2009). Additionally, display area inventory is subject to more handling by customers, which increases damage, and thereby spoilage. The role of inventory is discussed in Appendix A.7.

Hypothesis 1 *Spoilage increases with days of inventory at the store.*

Promotions

Promotions have an important impact on sales of fresh products, causing sales to even triple for products such as mangoes, pineapples and strawberries, as well as create traffic flow on the shop floor. High demand uncertainty, combined with other internal and external factors such as labor capacity or competitor pricing might trigger inaccurate orders, which in turn

Chapter 4. Managing perishability in the fruit and vegetable supply chain

increase inventory age. Van Donselaar et al. (2016) state that promotions are responsible for a large part of the waste and stock-outs for perishable products since demand forecasting is more difficult for products on promotion.

Hypothesis 2a *Spoilage increases with product promotions at the store.*

With regard to forecasts and orders, our interviews with importers, DCs and store managers revealed that managers are more attentive when passing preorders and orders during promotions. Both the DCs and the importers use historical promotion data to forecast orders, and sometimes even agree on forecasts and orders together. Regarding product quality, promotions often take place when the product is in the beginning of its season. It generally corresponds to the time when product quality and maturity is at its best and the supply is plentiful. In terms of delivery, products are often delivered with lower lead times due to less storage at the importer and DC. All of these factors contribute to smaller inventory age or higher quality. In this regard, it has yet to be tested whether promotions increase or decrease spoilage.

Hypothesis 2b *Spoilage decreases with product promotions at the store.*

Forecast updates and revised orders

DC weekly preorders (forecasts) are used to give an indication of what the DC thinks the stores will order the following week. However, we observe significant differences between DC preorders and orders. If preorders turn out to be significantly higher than orders, importers store the products in order to send them the next day. Consequently, products are at least one day older, and we expect them to have higher spoilage rates in stores.

Hypothesis 3a *Spoilage increases with commitment change at the DC.*

Importers are responsible for delivering 100% of orders, which often requires them to over-order from producers. If the DCs order less from importers than what they originally pre-ordered, it is likely that importers are left with extra inventory with little or no time left before

they are required to deliver the products. In this case, the freshest products are sent to DCs, and the importers sell the remaining products to alternative buyers, or the products end up unsold. Consequently, commitment changes could result in higher product freshness and reduce spoilage at the store.

Hypothesis 3b *Spoilage decreases with commitment change at the DC.*

Lead time and delivery type

Fresh products require short delivery times in order to maximize the duration in which the products can be sold and consumed (Van Donselaar et al., 2006). While direct deliveries reduce transportation lead time, lower prices for direct deliveries might incentivize DCs to order the predefined minimum quantities and store extra inventory, even if their forecast is lower. This would consequently increase product age upon arrival at the store. Additionally, deliveries via importers take longer but allow DC orders to be modified and pooled, reducing the combined forecast errors and inventory age.

Hypothesis 4a *Spoilage increases with direct deliveries from the producer to the DC.*

Direct deliveries can reduce spoilage by reducing transportation lead time by one day. Moreover, they require DCs to allocate more time and care during ordering, as they cannot modify direct delivery orders should they observe demand changes during the week. An analysis is required to understand the impact of each delivery type.

Hypothesis 4b *Spoilage decreases with direct deliveries from the producer to the DC.*

Order variation

Boute et al. (2007) state that smooth ordering patterns can dampen upstream demand variability. Demand variation is known to be one of the causes of the bullwhip effect (Lee et al., 1997; Isaksson and Seifert, 2016), causing excessive inventory. For perishables, it indirectly causes spoilage due to expiration. In this case, DC order variation pushes importers to keep more safety stock due to their 100% service level rule. Higher days of inventory at the importer

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implies that products are delivered to stores later i.e., with higher inventory age, and are prone to spoilage.

Hypothesis 5 *Spoilage increases with order variation at the DC.*

Store product managers sometimes order with high variation even though demand is stable. This increases average inventory age since products are not transferred between stores. For example, if the real demand is 5 consumer units per day, and the orders follow a 0 and 10 pattern instead of a stable 5 units ordering pattern, the average age of the products is half a day higher. Additionally, high order variation over the course of a week may also make it harder for store managers to associate a specific day's orders with its inventory and sales.

Hypothesis 6 *Spoilage increases with order variation at the store.*

Order cycle

Fruits and vegetables typically have short replenishment cycles, or are prone to discounts, given their short lifetimes (Ferguson et al., 2007). In the case that we study, store managers have the option to order everyday (the delivery cycle is one day); however, they may decide to order less frequently to reduce handling efforts at the store. We expect average inventory age, and therefore spoilage, to increase when the order cycle increases.

Hypothesis 7 *Spoilage increases with the order cycle in which the product is shipped to the store.*

Case size cover

Van Donselaar et al. (2006) state that while average case size and the inventory norm for perishables is significantly smaller than for non-perishables, average case sizes for days-fresh and weeks-fresh products are the same. For weeks-fresh products, Akkas et al. (2016) find that high case size cover (the days of demand that is covered by one case) is a driver for product expiry for consumer packaged goods. We test whether it is also valid for days-fresh products.

4.5. Data description, variable definitions and estimation model

Additionally, K  k and Fisher (2007) suggest that smaller case sizes can result in higher gross profit.

Hypothesis 8a *Spoilage increases with the case size in which the product is shipped to the store.*

On the one hand literature suggests that high case sizes result in higher spoilage rates due to higher inventory age. On the other hand: fruits and vegetables are delivered daily, have relatively small case sizes and are fast-moving products. Furthermore, case sizes are often adjusted to sales and product characteristics. Small case sizes may cause too much handling in stores and DCs, subsequently damaging the products and causing spoilage. To evaluate which is more influential, we test the opposing hypothesis.

Hypothesis 8b *Spoilage decreases with the case size in which the product is shipped to the store.*

Quality issues

Importer deliveries to DCs are subject to a maximum allowable delay, which starts from the packaging date. If timing or product quality is inadequate, the DC issues a warning, or penalty, to the importer, which facilitates the measurement of importer performance in the long run. Reasons for quality warnings are inadequate sugar content, caliber, color, firmness, maturity, existence of bruises, rotting, molding or other forms of damage. Inventory deterioration for perishables is generally modeled exponentially (Nahmias, 1982; Goyal and Giri, 2001; Blackburn and Scudder, 2009), and suggests that small quality issues at the DC are increasingly likely to result in spoiled products at the store the next day.

Hypothesis 9 *Spoilage increases with the gravity of quality issues at the DC.*

4.5 Data description, variable definitions and estimation model

Data description

In this section we describe the data we collected from different supply chain levels and define our dependent and control variables.

Chapter 4. Managing perishability in the fruit and vegetable supply chain

Our data contains 100 SKUs of imported fruits and vegetables that were sold for the first 4 months of 2016 in 128 Migros stores in the Geneva, Vaud and Neuchâtel areas of Switzerland. For data extractability and computational efficiency, we use the top-selling 100 out of 272 SKUs, which represent more than 87% of the total sales volume for imported fruits and vegetables. Our dataset consists of 495,460 store-SKU level observations at daily granularity. Our data contains sales, delivery, promotion, spoilage, preorder, case type, origin and sell-by data on a daily level. Additionally, with regard to qualitative data, we conducted interviews with importer, DC and store managers.

Variable definitions

We define our variables, in the order of the hypotheses, in what follows. The indices i , k and t represent the SKU, store and day, respectively. We additionally define indices c and w for the DC and week.

- *Spoilage* or shrinkage performance in retailers is usually measured as a percentage of sales (Buck and Minvielle, 2014) to enable yearly comparisons and benchmark store performance. Therefore we normalized spoilage as a fraction of sales as our dependent variable, measured as

$$Spoilage_{ikt} = \frac{Spoilage\ value_{ikt}}{Sales_{ikt}}.$$

- *Inventory* data is known to often be inaccurate (Raman et al., 2001a,b; Williams et al., 2014). DeHoratius and Raman (2008) found that in their study, 65% of inventory records were inaccurate. Inventory data inaccuracy for fruits and vegetables occurs due to product code entry errors during weighing by customers at the display area, or at the checkouts by employees. It is not uncommon to see negative inventory records. We adjust for such errors using inventory audit information, as well as corrections via manual changes at stores. We also additionally adjust for negative values and outliers due to obvious recording errors¹. We use the definition of days of inventory outstanding,

¹Inventory values can be high due to no display at the store for preparations for promotions, or low sales on a particular day. Excluding inventory values that are high (only using observations for less than 10 days of inventory) does not significantly change the results.

4.5. Data description, variable definitions and estimation model

and calculate the days of inventory as

$$Inventory_{ikt} = \frac{Inventory\ in\ store_{ikt}}{Sales_{ikt}}.$$

- *Promotion* is a binary variable indicating whether the product is on promotion. National promotions are planned several months in advance, with product prices remaining constant for the entire week of the promotion. We denote it as $Promotion_{it}$.
- *Commitment change* measures how much the DC's order changes with respect to its preorder, or forecast, for deliveries via importers in one week. We calculate the change in commitment to preorders as

$$Commitment\ change_{icw} = \frac{Preorder\ via\ importer_{icw} - Order\ via\ importer_{icw}}{Order\ via\ importer_{icw}}.$$

We do not observe spoilage spill-over to the next week due to short product lifetimes and sell-by constraints, and exclude a lag. If the orders are higher than the preorders, than the importer needs to provide extra products within a very short delay to the DCs. The newly arrived products are expected to be fresher, hence negative commitment change values, which occur in around 25% of the observations, do not pose an issue for spoilage.

- *Direct deliveries* represent the fraction of direct deliveries to total deliveries in DC weekly preorders for each product. We measure direct deliveries as

$$Direct\ delivery_{icw} = \frac{Direct\ delivery\ preorders_{icw}}{Total\ preorders_{icw}}.$$

- *DC order variation* is the explanatory variable that measures whether volatility in DC orders influences spoilage, as suggested by the bullwhip effect (Lee et al., 1997). We measure the daily coefficient of variation for the orders as

$$Distribution\ center\ order\ variation_{ict} = \frac{\sigma_{ict}}{\mu_{ict}}.$$

We use the rolling mean and standard deviation of orders over the past 7 days, calculated

as $\mu_{ict} = \frac{1}{7} \sum_{j=(t-6)}^t Order_{icj}$, and $\sigma_{ict} = \sqrt{\frac{\sum_{j=(t-6)}^t (Order_{icj} - \mu_{ict})^2}{7}}$, respectively. We use seven days since product origins, prices and weekly forecasts are set on a weekly basis.

- *Store order variation* is calculated similarly to that of DCs, except we use the mean and standard deviation of daily store orders. Its impact is more direct compared to DC order variation since there is no dilution effect due to order pooling. Order variations are caused mainly by inaccurate forecasts, and high employee turnover. We calculate the coefficient of variation for store orders as $Store\ order\ variation_{ict} = \frac{\sigma_{ikt}}{\mu_{ikt}}$.
- *Order cycle* represents the average time between two orders for a given product. It is measured using the four-day rolling mean of ordering data in binary form: $Order\ cycle_{ikt} = \left(\frac{1}{4} \sum_{j=(t-3)}^t OrderBin_{ikt} \right)^{-1}$, where $OrderBin_{ikt}$ is a binary variable representing the occurrence of orders for a given store-SKU-day. We use four days since it represents the average remaining product lifetime of products at the retailer. Further analysis shows that the results are the same following a 2-5 day rolling mean.
- *Case size cover* represents the days of demand (during the product shelf life) that is covered by one case. It is calculated as the quantity of consumer units in a case, divided by the demand during the product shelf-life. Consumer units are measured in kilograms or individual packages of a single product. We denote it as $Case\ size\ cover_i$.
- *Quality issues* indicates whether the product had a quality issue when it arrived at the DC. The quality problem is a score between 0 and 100, where 100 results in full product return, 0 results in acceptance with no reported quality issues, and values in between result in warnings with the score increasing with the gravity of the issue. We exclude products that scored 100 since they do not reach stores. It composes 13% of all quality issues and less than 0.08% of all deliveries within the study period. We denote it as $Quality\ issues_{it}$.

Our control variables are defined in Table 4.1. We provide summary statistics for our variables in Table 4.2.

4.5. Data description, variable definitions and estimation model

Control variable	Description
$Sales_{ikt}$	Monetary value of sales of each SKU sold on a given day
$Demand\ variation_{ikt}$	Coefficient of variation for sales for each product
$Sell-by_i$	Maximum number of days each product is allowed to spend between shipping from the producer and sales at the stores
$Weight_i$	Binary variable indicating that the weight of each consumer unit is different. Consumer units are pre-packed, individually weighed, and priced according to their weight, with the price labeled on the package.
Net_i	Binary variable indicating that the product is sold in a net, such as for oranges. Each consumer unit net weight is identical.
$Open\ case_i$	Binary variable indicating that the product is sold in an open case, where consumers choose the units they wish to purchase, and pay by weight.
$Single\ unit_i$	Binary variable indicating that the product is sold in single units, such as for mangoes, avocados and cucumbers. For these products, individual product appearance is of higher importance.
$Store_k$	Binary variable for store k.
$Distribution\ center_{ik}$	Binary variable for DC c.
$Importer_{ik}$	Binary variable for importer p.
$Category_i$	Type of product. For example, all tomatoes fall under the same category, yet there are multiple varieties. We expect SKUs in the same category to have similar spoilage fractions in most cases.
$Origin_{iw}$	Country of origin of the product. There are over 22 origins in our dataset. The product origin may change based on ripening in different countries at different times.
$Category \times week_{iw}$	Binary variable controlling for each product category-week combination. It can be interpreted as the season of the product.
$Month_t$	Month of the year
$Day\ of\ week_t$	Day of the week

Table 4.1: Control variables

Variable	Mean	Std. Dev.	Min.	Max.	N
Spoilage	0.038	0.266	0	42.523	487142
Independent variables					
Inventory (days)	2.46	3.07	0	395.60	487144
Promotion	0.15	0.36	0	1	495460
Commitment change	0.19	0.69	-1	3.46	489407
Direct delivery	0.03	0.06	0	1	495460
DC order variation	0.39	0.22	0	2.65	482449
Store order variation	0.87	0.54	0	2.65	482449
Order cycle	1.54	0.75	1	4	469347
Case size cover	0.11	0.19	0	10	478781
Quality issues	1.53	6.02	0	78.59	495460
Control variables					
Sales (CHF)	61.35	103.06	0	4758	495460
Demand variation	0.49	0.21	0	3.32	484641
Sell-by (days)	9.41	3.24	5	15	495460
Weight	0.27	0.44	0	1	495460
Net	0.14	0.34	0	1	495460
Open case	0.26	0.44	0	1	495460
Single unit	0.22	0.41	0	1	495460

Table 4.2: Summary statistics

Weather has an important influence on sales. We use weekly weather data to measure its impact on weekly sales in the DCs. We obtain data for rainfall and sunshine from 3 weather

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stations located in each of the 3 regions corresponding to the DC locations. We use average weekly rainfall, in millimeters, and weekly sunshine, as a percent of the maximum. Our results show that, on average, each extra percentage of sunshine increases sales by more than 1 800 Swiss Francs, while each extra millimeter of rainfall costs more than 16 000 Swiss Francs per DC. However, we exclude weather as a control variable for three reasons. First, DC and store managers already account for weather in their orders. As a result, weather does not influence spoilage as a percentage of sales. Second, we control for sales. Third, the cool chain is maintained during transportation and storage up until the displays are in the store. Table A.1 and Figure A.4 show the impact of weather on sales.

Switzerland has the highest organic product consumption per capita in the world, with Migros representing a quarter of organic product sales in Switzerland (Willer and Lernoud, 2016). We observe no significant difference between spoilage in organic and conventional fruits and vegetables at the stores. According to one of the importers we interviewed, which only imports organic products: "Organic products mostly spoil at production and harvesting stages. Only a fraction of the remaining harvest meet the visual requirements and are transported abroad", which explains our finding.

In our paper we do not include store order propositions of automatic ordering systems, as in Van Donselaar et al. (2010) for two reasons. First, the propositions do not include factors such as weather, promotions, price changes or long-term historical data. Second, our interviews revealed that they are not used by store managers, and that an improved proposition system is currently under development.

Estimation model

Our model covers all nine variables associated with our hypothesis: inventory, promotion, commitment change, direct delivery, DC and store order variations, order cycle, case size cover

and quality issues.

$$\begin{aligned}
Spoilage_{ikt} = & \alpha + \beta_1 Inventory_{ikt} + \beta_2 Promotion_{it} + \beta_3 Commitment change_{icw} \\
& + \beta_4 Direct delivery_{icw} + \beta_5 Distribution center order variation_{ict} \\
& + \beta_6 Store order variation_{ikt} + \beta_7 Order cycle_i + \beta_8 Case size cover_i \\
& + \beta_9 Quality issues_{it} + \beta_{10} Sales_{ikt} + \beta_{11} Demand variation_{ikt} \\
& + F_{ik} + T_t + S_{iw} + \epsilon_{ikt}
\end{aligned}$$

F_{ik} is the vector of covariates for time-invariant fixed effects for all store-SKU combinations, namely the sell-by constraint, product category, package characteristics weight, net, open case and single unit, store, distribution center, importer and all other factors that do not change over time.

Our analysis focuses on the fixed-effects model, however we also show the random effects and OLS models. We use the remaining control variables given in Table 4.1 in the random effects and OLS specifications. T_t is the time-specific fixed effects for the month and the day of the week. S_{iw} represents the covariates for origin and $Category \times week_{iw}$ fixed effects. ϵ_{ikt} denotes the error term for the observation for product i in store k and day t . While some relationships between the secondary drivers exist, the correlations are very low and further analysis show that there are no strong mediating/moderating relationships.

4.6 Results and discussion

In this section, we present the results of our estimation model. We first discuss and compare the impact of each variable on spoilage, and present additional tests to show the effects of time-invariant variables thereafter. Second, we discuss the generalizability and show the robustness of the results.

4.6.1 Estimation model results

Table 4.3 shows the coefficients' estimates for the estimation model using fixed effects, random effects and ordinary least squares models. Each variable, except for *Case size cover* which is related to Hypothesis 8 and is rejected, consistently increases or decreases spoilage for all three specifications. However, the dimension and significance level varies. The Hausman test (Hausman, 1978) indicates that the difference between the specifications are significant, and that the random effects and OLS are inconsistent. Hence, we use the results from the fixed effects model to drive our initial analysis and compare the impacts of each variable.

The standard errors are given in parenthesis. We discuss the results for these hypotheses in what follows. The estimates of the fixed effects model show that Hypotheses 1, 5, 6, 7 and 9 are all strongly supported at the $p < 0.01$ level: more days of *Inventory* (0.0238), *Order variations* at stores (0.0254) and DCs (0.00905), longer *Order cycles* (0.00947) and *Quality issues* (0.00031) at the DC all increase spoilage, as expected. Hypothesis 8 is not supported by our data.

Hypotheses 2b, 3b, and 4b are supported by our data at a $p < 0.01$ level. We discuss the results in detail in what follows. In Hypothesis 2 we tested whether *Promotions* increase (2a) or decrease (2b) inventory age and spoilage. Hypothesis 2b is supported at the $p < 0.01$ level, and shows that spoilage decreases with product *Promotions* at the store (-0.0229). This result is different from the findings of Van Donselaar et al. (2016), and can be explained with several reasons. First, we analyze fast-moving days-fresh products. Second, orders tend to be passed in advance and with higher care due to sales targets and the use of historical promotion data to forecast sales for each promotion. Third, we control for sales. Even so, we lack inventory age data, which promotions can highly influence. Finally, early promotion planning enables higher product quality and longer lifetimes thanks to improved harvest timing. In respect to damages, promotions may involve special packaging that better protects the products.

In Hypothesis 3 we tested whether *Commitment change* increases (3a) or decreases (3b) inventory age and spoilage at the store. Hypothesis 3b, supported at the $p < 0.01$ level, reveals that *Commitment changes* between preorders and orders reduce spoilage (-0.00899). There

are three main explanations. First, DCs update their orders after observing demand at the beginning of the week. Better forecasting together with higher demand at the end of the week reduces both inventory age and spoilage. The second explanation is that importers order based on preorders, but due to date codes or inventory aging, the products never reach the stores. According to interviews with one of the importers: "Even though the quality of the product is adequate, date codes prevent us from selling the products to DCs, forcing us to look for alternative buyers. It is especially challenging when products have high volumes or when the retail brand is already in the label."

The third, and more likely explanation, is that the importers do not rely on preorders, but rather their own forecasts. The importers do not receive sales information and are obliged to deliver 100% of retailer orders despite an average 3 to 4 day transportation lead time. While the retailer benefits from this situation, the importer suffers the consequences. As far as DC preorder accuracy is concerned, one of the importers stated that "Strictly following preorders would be disastrous". Lack of trust (Özer et al., 2011) between the importer and DCs presents opportunities to improve.

Both parties could potentially benefit from collaborative forecasting (Aviv, 2007) and as a consequence, reduce inventory age throughout the supply chain, as well as avoid potential bullwhip effects. However, the parties would first need to strengthen their relationship. As De Treville et al. (2004) point out: "Partially observed demand information is more difficult to use ...because of the difficulties in building the needed customer–manufacturer relationship as well as the difficulty of transforming partial demand information into useful data."

In Hypothesis 4 we tested whether *Direct delivery* increases (4a) or decreases (4b) inventory age and spoilage at the store. Hypothesis 4b, also supported at the $p < 0.01$ level, shows that the benefits of *Direct delivery* overcomes the advantages of pooling DC orders. One of the benefits of direct deliveries is an extra day of freshness (-0.0335). According to one of the importers we interviewed: "An extra day of freshness in our operations would create an enormous reduction on spoilage". Direct deliveries also improve ordering, since DCs cannot

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change their orders during the week.

In Hypotheses 8, we tested whether *Case size cover* increases (8a) or decreases (8b) spoilage, arguing that large case sizes could increase spoilage due to inventory age, and small case sizes could increase spoilage due to more handling. Both Hypotheses are rejected by our data, and show that *Case size cover* does not influence spoilage at a statistically significant level. We believe that the reasons are product type and retailer practice related. We focus on fruits and vegetables, which are days-fresh products that are very fast-moving, as opposed to most weeks-fresh products or other days-fresh products with low demand. Regarding retailer practice, we observe low average case sizes, which are well adjusted to sales. The average case size in our data covers only 11% of demand during the lifetime of the SKUs. We recommend further analysis on the effect of case size cover on spoilage for various days-fresh products in different retailer settings.

We now contrast our results with the results for weeks- or months-fresh products presented in Akkas et al. (2016). Overall, the studies only overlap on three main hypothesis, of which one in each study is not supported. In both studies inventory age significantly increases spoilage, however, the relative effect to other estimates is much higher for days-fresh products. The hypothesis that larger case sizes increase spoilage was not supported for days-fresh products. Following a FIFO policy through by increasing rotation, or reducing order cycles in our case, reduces spoilage for days-fresh products. This hypothesis is not supported for weeks-fresh products.

We next cover the hypotheses in Akkas et al. (2016) that we do not include in our study. Following larger order quantities reduces spoilage for weeks-fresh products, with less frequent deliveries requiring less transportation costs. However, this hypothesis is not applicable for days-fresh products as store managers are encouraged to order daily, as the delivery and transportation occurs everyday to keep products as fresh as possible. Likewise, giving commissions on sales to store managers via sales incentives are not applicable in our study. Sales and spoilage performance are tracked in parallel. Finally, forecasting more store-product

combinations per sales manager increases spoilage for weeks-fresh products. The number of store-product combinations does not vary over our period of analysis, thus the forecasting complexity remains the same. We control for the product, store and DC, since only one manager in each specific store or DC is in charge of ordering. Additionally, we observe that larger DCs are generally better at forecasting.

In addition to the hypotheses analysed above, we include the days of inventory, commitment changes, delivery types, order variations, promotions as well as quality issues into our analysis. These have not been explicitly studied for weeks-fresh items.

4.6.2 Economic impacts and managerial insights

Our results can be used by managers to prioritize the improvements in the fresh product supply chain. In this section we compare the economic impact of the drivers on spoilage costs and summarize the managerial insights. Figure 4.3 shows the economic impacts of improving the drivers of spoilage.

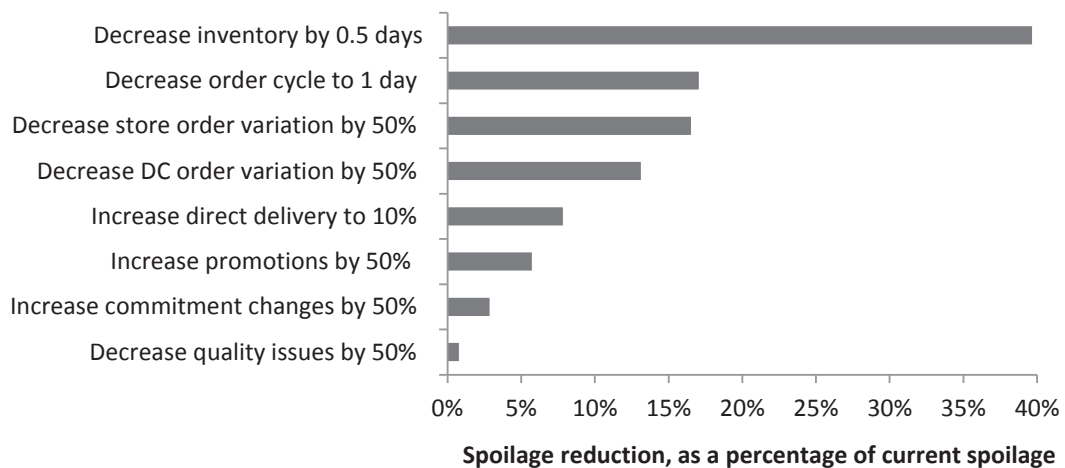


Figure 4.3: Economic impact of the drivers of spoilage

We compare the impact of feasible targets at stores and DCs. Currently the stores carry almost 2.5 days of inventory on average, which implies that if they stopped ordering, they are expected

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to stock out after 2.5 days. Part of the reason is due to aesthetic reasons, to keep the shelf display full at the end of the day. We find that reducing *Inventory* at stores, by half a day of sales, which represents only 20% of current inventory levels, would have the greatest impact on spoilage (up to 40%) without major compromise in service levels. This can be implemented by adjusting employee incentives to manage inventory and by introducing new display methods that make the shelf look fuller. We recommend managers to track inventory and service levels simultaneously in this category in order to optimize product freshness and reduce spoilage costs without damaging consumer loyalty.

Reducing the order cycle to one day, which is the current replenishment cycle, can reduce spoilage by 17%. Similarly, order variation at stores and DCs provide improvement opportunities in the order of 15% each. We note that more frequent orders with less volatility may also represent higher handling requirements at stores. Order variation and cycles can be reduced by tracking accurate inventory information, training personnel for better forecasting or building an automated ordering system that considers factors such as time, weather and substitution simultaneously. Consequently, rationing and shortage gaming can also be eliminated.

Direct deliveries are currently infrequent and represent a significant lever for improvement. Our findings show that reducing transportation lead time is crucial for the days-fresh category. An increase to 10% of total deliveries would reduce spoilage costs by 8%. However, after a certain percentage increase in direct deliveries, volumes may not be sufficient to fulfil direct delivery transportation fill rates. This would result in excess orders, which would subsequently cause spoilage at DCs.

Promotions and quality issues at the DC have the least impact on store spoilage. We do not include case cover, as the hypothesis is not supported. We also exclude commitment change, as we believe commitment changes could potentially be pushing spoilage to importers, while also reducing trust within the supply chain in the long run.

To discuss time invariant factors, namely product packaging, we show the results of the Mundlak approach (Mundlak, 1978; Chamberlain, 1984). The results are shown in Appendix

4.6. Results and discussion

Spoilage	Fixed effects	Random effects	OLS
Inventory	0.0238*** (0.00429)	0.0238*** (0.00421)	0.0240*** (0.000131)
Promotion	-0.0229*** (0.00354)	-0.0213*** (0.00341)	-0.0205*** (0.00137)
Commitment change	-0.00899*** (0.00107)	-0.00750*** (0.00102)	-0.00617*** (0.000696)
Direct delivery	-0.0335*** (0.0112)	-0.0301*** (0.00877)	-0.0297*** (0.00918)
Store order variation	0.0254*** (0.00341)	0.0239*** (0.00298)	0.0216*** (0.000939)
DC order variation	0.00905*** (0.00344)	0.0105*** (0.00326)	0.0114*** (0.00214)
Order cycle	0.00947*** (0.00141)	0.00909*** (0.00129)	0.00869*** (0.000613)
Case size cover	-0.00929 (0.0417)	0.00722 (0.0192)	0.0172*** (0.00353)
Quality issues	0.000305*** (0.000109)	0.000329*** (0.000107)	0.000346*** (7.05e-05)
Sales	-0.000103*** (1.21e-05)	-8.42e-05*** (9.54e-06)	-7.19e-05*** (4.94e-06)
Demand variation	0.00952* (0.00548)	0.00708 (0.00573)	0.00756*** (0.00233)
Open case		-0.0239*** (0.00924)	-0.0318*** (0.00411)
Single unit		-0.0383*** (0.0112)	-0.0462*** (0.00579)
Weight		-0.0316*** (0.00863)	-0.0370*** (0.00371)
Net		-0.0123 (0.00970)	-0.0209*** (0.00445)
Store-SKU fixed effects included	Yes	No	No
Other controls included ^a	Yes	Yes	Yes
Constant	-0.152*** (0.0359)	0.131*** (0.0281)	0.145*** (0.0282)
Observations	457,539	457,539	457,539
R-squared	0.075		0.098
Number of ID	9,268	9,268	
Within R-squared	0.0751	0.0749	.
Between R-squared	0.00862	0.239	.
Overall R-squared	0.0405	0.0979	.
F	6.244	.	71.36

Robust standard errors in parentheses

*** p<0.01, ** p<0.05, * p<0.1

^a Controls: sell-by constraint, product category, month, day of the week, origin and $Category \times week$

Table 4.3: Estimation model results

A.6. We find that the *Weight* type packaging significantly reduces spoilage, possibly due to higher product protection compared to other packaging types. They are often pre-packaged with cardboard or hard plastic.

4.6.3 Generalizability

In this section we discuss the generalizability of our results by analyzing sales patterns, aggregating data on a weekly and monthly basis, and using SKU categorization based on sell-by limits.

First, we show that weekly and yearly patterns of sales are similar to the findings in literature. Namely, our weekly sales pattern shown in Appendix A.3 is similar to the aggregate seasonality sales pattern presented in Van Donselaar et al. (2010). Sales are lowest during the middle of the week, and rise towards the weekend. Likewise, the yearly sales pattern is similar to that of Akkas et al. (2016), where the authors use 13 periods of 4 weeks each.

To further test for robustness and generalizability of our results, we aggregate our variables to a weekly and monthly level. Table 4.4 shows the coefficient estimates. Besides the variables *Direct delivery* and *Quality issues*, all other variables are statistically significant. *Direct delivery* is no longer significant, which is likely due to deliveries occurring on a weekly basis with pooling at the DC level. For instance, if the DC orders with direct deliveries only twice a week, and receives little or no via-importer orders the other days, the products are stored for longer, which consequently alters the relative spoilage during the week. Similarly, weekly product quality issues are no longer of significance due to variations in product quality for each daily delivery. Both these factors support our case for daily variations being more important for fresh products.

Finally, we group SKUs based on sell-by limits of products. The first group, highly perishables, includes SKUs that have a maximum sell-by date, as of packaging or shipment from the producer, of 9 days. SKUs in this group include strawberries (5 days), spinach (6 days), grapes (7 days) and tomatoes (8 days). The second group, moderately perishables, includes SKUs

with a sell-by date that is above 9 days, for example oranges, plums, kiwis and pineapples.

Table 4.5 shows results of estimation model for the two SKU groups. It is clear that SKUs in the highly perishable group are more sensitive to the drivers of spoilage (the magnitude of the coefficients are consistently higher for highly perishables). *Inventory*, *Promotion*, *Commitment change*, *Store order variation* and *Order cycle* are statistically significant for both SKU groups. However, *Direct delivery* and *Quality issues* are only statistically significant for the highly perishable group, which supports the fact that the drivers for spoilage vary between fresh products (days-fresh and weeks-fresh), and even partially within the days-fresh category.

Regarding the generalizability of the data, although we use only four months, we use 495,460 observations to conduct our analysis and use data from three different DCs, 128 stores and 100 separate SKUs. To our knowledge, our study has the highest number of store-product combinations in the days-fresh category.

The preordering system used in our case represents partial demand information transfer, common to many supply chains (De Treville et al., 2004). To test whether having the preorder system influences our results, we use yearly data of all 10 DCs, and 5 importers. 1 DC out of 10 and 1 importer out of 5 do not use preorders at all. They represent 25% of total observations. We create a binary variable for having preorders, and find that preorders alone do not explain spoilage *per se*.

4.7 Conclusion

Spoilage in fresh food supply chains is a crucial issue, with both economic and environmental impacts on all its entities. The stores struggle with unpredictable demand; the DCs struggle with order inaccuracy and product quality; importers struggle with preorder inaccuracy and product handling; producers need to know how much crop they need to produce multiple months in advance. Given these issues, a detailed analysis of the main causes of spoilage is essential to identify effective solutions.

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Spoilage	Weekly aggregated fixed-effects	Monthly aggregated fixed-effects
Inventory	0.0214*** (0.00532)	0.0389** (0.0177)
Promotion	-0.0218*** (0.00390)	-0.0217** (0.00988)
Commitment change	0.00147 (0.00131)	-0.00630 (0.00997)
Direct delivery	-0.0154 (0.0153)	-0.0825*** (0.0299)
DC order variation	0.0201*** (0.00565)	0.0232** (0.0104)
Store order variation	0.0351*** (0.00588)	0.0379*** (0.00605)
Order cycle	-0.00816 (0.00250)	-0.0202 (0.00797)
Case size cover	-0.117 (0.102)	-0.102* (0.0573)
Quality issues	0.000521** (0.000244)	0.00132** (0.000591)
Sales	-0.000108*** (2.39e-05)	-0.000103*** (3.60e-05)
Demand variation	0.0134*** (0.00504)	0.0123 (0.0122)
Store-SKU fixed effects included	Yes	Yes
Other controls included ^a	Yes	Yes
Constant	-0.0217*** (0.00815)	-0.0473* (0.0260)
Observations	113,193	29,063
Number of ID	9,279	9,289
R-squared	0.062	0.095
Within R-squared	0.0619	0.0950
Between R-squared	0.050	0.0813
Overall R-squared	0.0625	0.0888
F-statistic	24.57	9.449

Robust standard errors in parentheses

*** p<0.01, ** p<0.05, * p<0.1

Table 4.4: Weekly and monthly aggregated results

^a Controls: sell-by constraint, product category, month, day of the week, origin and *Category* × *week*

Spoilage	Fixed-effects	Fixed-effects
	Highly perishables	Moderately perishables
Inventory	0.0262*** (0.00488)	0.0211*** (0.00765)
Promotion	-0.0233*** (0.00411)	-0.0233*** (0.00606)
Commitment change	-0.0120*** (0.00145)	-0.00467*** (0.00152)
Direct delivery	-0.0298** (0.0118)	-0.0436 (0.0334)
Store order variation	0.0388*** (0.00548)	0.0138*** (0.00407)
DC order variation	-0.00609 (0.00506)	0.0240*** (0.00528)
Order cycle	0.0132*** (0.00252)	0.00618*** (0.00117)
Case size cover	-0.0415 (0.0560)	0.0488 (0.0301)
Quality issues	0.000348** (0.000135)	0.000108 (0.000125)
Sales	-0.000101*** (1.57e-05)	-0.000102*** (1.85e-05)
Demand variation	0.00724 (0.00639)	0.0110 (0.00953)
Store-SKU fixed effects included	Yes	Yes
Other controls included ^a	Yes	Yes
Constant	-0.138*** (0.0357)	-0.0343 (0.0238)
Observations	253,508	204,031
R-squared	0.077	0.075
Number of ID	6,023	3,245
Within R-squared	0.0775	0.0747
Between R-squared	0.00192	0.107
Overall R-squared	0.0313	0.0767
F-statistic	6.358	5.861

Robust standard errors in parentheses

*** p<0.01, ** p<0.05, * p<0.1

Table 4.5: Results for highly perishable SKUs and moderately perishable SKUs

^a Controls: sell-by constraint, product category, month, day of the week, origin and $Category \times week$

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There is relatively little empirical literature that studies the drivers of spoilage for days-fresh products. We contribute to existing literature by identifying drivers for spoilage in the days-fresh category and by presenting the differences from weeks-fresh products. We use daily spoilage and supply chain data from Switzerland's largest retailer to drive an econometric analysis and conduct multiple interviews at three supply chain levels.

We show that excess inventory, promotions, delivery type, commitment changes in ordering, order variations at two supply chain echelons, order cycle, and quality issues all impact spoilage at a statistically significant level. Our economic analysis shows that inventory, order variation, delivery lead time and collaboration among supply chain entities can enable the most effective improvements in spoilage costs. We further quantify the improvement potential of each driver on spoilage for days-fresh products, while categorizing them into two primary causes: inventory aging and product standards or damage.

We provide three main managerial insights that can improve spoilage performance in the days-fresh category. First and foremost, days-fresh products require specialized supply chains that address the perishability requirements: a single transport, ordering, replenishment and sales process for all products is not adequate to obtain the high service-level and low spoilage objective. Managers should prioritize direct deliveries to reduce transportation lead times in the upstream supply chain, while using live sales information to reduce information lead time downstream.

Second, collaboration in the supply chain can reduce spoilage and produce substantial economic savings while also improving environmental performance, therefore we urge managers to leverage producer and supplier relationships to improve forecasting, visibility and operations within the entire supply chain. Collaborative forecasting and ordering, particularly when there are few suppliers, can improve initial forecasts and reduce commitment changes. While commitment changes, i.e. forecast updates, are beneficial for retailers, they are potentially detrimental to retailers' relationships with entities in their upstream supply chain due to long transportation lead times.

Finally, we recommend tracking and quantifying inventory age and damage throughout the supply chain. Collecting data for quality and inventory age can enable the identification of supply chain weaknesses, while personnel training for inventory management in the downstream supply chain can reduce order variation and order cycles, which in turn reduce inventory age and spoilage.

On a more general note, we recommend implementing automatic ordering processes that use advanced data techniques at the retailer level, which are becoming more prominent (Glatzel et al., 2016) despite the high setup costs. An automatic ordering system that uses live sales data would reduce the upstream supply chain responsibilities mainly to ensuring quantity, quality, adequate logistics and data integration, while reducing downstream system responsibilities to ensuring data quality and collaboration within the supply chain. For Migros, it would eliminate the one-hour daily ordering task in more than 600 stores, and focus store manager efforts for in-store replenishment and improved display, particularly during promotions.

There are some limitations to our study. First, data could be partially inaccurate due to recording errors at the retailers (Raman et al., 2001a,b), which we try to correct using inventory correction data at the store level, and by eliminating obvious data errors. Second, there is no recorded data for inventory age, which is the main driver for spoilage in the fruit and vegetable category. We simulate spoilage due to expiration and find that it explains a significant amount of spoilage. Third, there is a lack of data for initial product quality, perishability and taste, which are very heterogeneous over time, which explains the relatively low explanatory power of our model. Fourth, we do not consider substitution due to the lack of information on substitution relationships between products and high number of products. Additionally, there is no data on competitor prices, importer and DC spoilage, and display or in-store layout.

We recommend analyzing the effects of product packaging on spoilage for a wide variety of products with multiple packaging types as a future work avenue. Additionally, it has yet to be tested whether product origin or local production has a significant influence on spoilage through inventory age when controlled for quality. Other promising avenues include the effect

Chapter 4. Managing perishability in the fruit and vegetable supply chain

of collaborative (Williams et al., 2014) and improved forecasting (Kesavan et al., 2010), multiple daily deliveries (Turan et al., 2016b,a), and the impact of promotions for substitute products on spoilage in the days-fresh category.

5 Conclusion

This dissertation studies the strategic and operational opportunities for companies to improve their economic and environmental performance. We use theory building, mathematical modelling as well as econometric modelling in three distinct research projects. We address the gaps in literature that involve methods to achieve better economic and environmental performance in firms. The first research project, presented in Chapter 2, focuses on capabilities from the perspective of individual firms. The second, presented in Chapter 3, studies the relationship of responsive decisions taken by a manufacturer and retailer in a two-echelon supply chain. In the last project, presented in Chapter 4, we further expand the scope to study three supply echelons, with a focus on the impact of products at the retailing stage. We describe each project in what follows.

In Chapter 2 we focus on the ability of organizations to succeed in their sustainability initiatives and gain competitive advantage. We use the dynamic capabilities theory and combine the literature with Sustainable Supply Chain Management (SSCM) literature to holistically outline internal and external dynamic capabilities. We highlight the importance of the organizational management skills, processes and structure within the firm, and information transparency and integration within the supply chain.

Both practitioners and academics can apply our framework. Practitioners can use the break-

Chapter 5. Conclusion

down of capabilities at three organizational levels to map out capabilities in the firm and identify gaps. In doing so, processes can be restructured to ensure alignment between organizational levels. We illustrate an application of the framework using a case study on waste elimination in Nestlé factories. Academics can apply the framework to understand performance differences and behavior of individual companies in a competitive space where environmental goals are strict and supply chains are increasingly complex. An article corresponding to Chapter 2 is published in *Supply Chain Forum: An International Journal*.

In Chapter 3, we concentrate on the core operations management issue of demand uncertainty in food supply chains. In food supply chains where raw materials such as fresh fruit, vegetables and dairy products are processed into products with a longer shelf life, demand uncertainty combined with perishability represent high underage and spoilage costs. Among other factors, replenishment decisions in the supply chain can reduce these costs. Accordingly, we contribute to literature by analytically finding the optimal replenishment frequency between manufacturers and retailers as an endogenous variable. We consider both raw material and finished product perishability, and quantify the relationship between the two perishability costs.

Our findings show that despite low costs of spoilage per unit, short raw material lifetimes and manufacturing variable costs significantly increase both the retailer's and the manufacturer's costs due to the effect of product lifetime on the manufacturing decisions. Additionally, we find that short finished goods lifetimes, or short time limits before the sell-by date, result in more frequent replenishments and higher costs for both parties. This should create an incentive for manufacturers to produce longer-lasting products, and retailers to improve the management of inventory age.

Finally, in Chapter 4, we address the issue of managing spoilage in the fresh fruits and vegetables supply chain. We consider multiple echelons of the supply chain, namely importers, distribution centers and retailers, where each struggles with spoilage costs. Our contribution is the quantification of the main causes of spoilage so as to enable effective solutions for

days-fresh products. We conduct multiple interviews at three supply chain levels and use daily spoilage and supply chain data from Switzerland's largest retailer, Migros, to perform an econometric analysis.

Our findings show that excess inventory, promotions, delivery type, commitment changes in ordering, order variations at two supply chain echelons, order cycle, and quality issues all impact spoilage at a statistically significant level. Our economic analysis shows that inventory, order variation, delivery lead time and collaboration among supply chain entities can enable the most effective improvements in spoilage costs. Our research provides guidelines to practitioners to prioritize levers for spoilage reduction initiatives.

In all three research projects, we emphasized the importance of collaboration within a firm and its supply chain. We urge managers to leverage their relationships to improve forecasting, visibility and operations within the entire supply chain. In the first project, we showed that supply chain partners can be part of the solution to enabling success of sustainability initiatives that bring competitive advantage. In the second project, we showed that even under conditions where one party has higher bargaining power, opportunities to collaborate exist and can reduce spoilage costs for both parties. In the third project, we recommended collaborative forecasting and ordering to reduce spoilage, particularly when there are few suppliers. Furthermore, we recommended implementing automatic ordering processes that use advanced data techniques at the retailer level, which are becoming more prominent (Glatzel et al., 2016) despite the high setup costs.

In addition to managerial insights and theoretical implications, this dissertation raises many future research avenues. In what relates to Chapter 2, we recommend empirically grounded research to further identify in quantitative terms, the risk reduction and growth potentials from adopting environmental sustainability practices in firms. In what relates to Chapter 3, extensions of our work include the integration of seasonality, inventory carryover, positive lead times, multiple products, multiple echelons, and modelling perishability with a $G/G/1$ queue. Additionally, we encourage scholars to pursue empirical studies to analyze the impact

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of finished goods and raw material lifetime on supply chain costs.

In what relates to Chapter 4, we recommend three main future research avenues. First, we recommend analyzing the effect of inventory age and personnel training for inventory management on spoilage. Another interesting study would be to evaluate the effect of product packaging on spoilage for a wide variety of products with multiple packaging types. Finally, it has yet to be tested whether product origin has a significant influence on spoilage through inventory age when controlled for quality.

On a more general note, digitalization of supply chain management is becoming a prominent topic among practitioners. We therefore urge academics in the field of supply chain management to focus on the impacts of supply chain digitalization on firm performance. Rutkowsky et al. (2015) confirm that firms are planning investments and expecting improvements in the digitalization area, namely for IT integration across all internal areas and with supply chain partners, as well as big data analysis for improvements in the supply chain. Major improvements are expected through digitalization, particularly in the areas of demand forecasting, inventory management and supply chain transparency.

A Appendices

A.1 Retailer's optimal solution

In this section we use the following overage and underage costs: $C_o(T) = c(T) - s$ and $C_u(T) = p - c(T)$ to optimize the following problem:

$$\text{Minimize}_{T \leq t_F} C(S(T) | T) = \frac{c_o}{T} \int_0^{S(T)} (S(T) - x) f(x | T) dx + \frac{c_u}{T} \int_{S(T)}^{\infty} (x - S(T)) f(x | T) dx + C_{ss} T.$$

Equation 3.2 is obtained from equation 3.1 using $z = \frac{S(T) - \mu T}{\sigma \sqrt{T}}$ and the change of variables and $y = \frac{x - \mu T}{\sigma \sqrt{T}}$ as below.

$$\begin{aligned} \int_{-\infty}^{S(T)} (S(T) - x) f(x | T) dx &= \sigma \sqrt{T} z \int_{-\infty}^z \frac{1}{\sqrt{2\pi}} e^{-\frac{y^2}{2}} dy - \sigma \sqrt{T} \int_{-\infty}^z y \frac{1}{\sqrt{2\pi}} e^{-\frac{y^2}{2}} dy \\ &= \sigma \sqrt{T} z \Phi(z) + \sigma \sqrt{T} \phi(z) \end{aligned} \quad (\text{A.1})$$

$$\begin{aligned} \int_{S(T)}^{\infty} (x - S(T)) f(x | T) dx &= \sigma \sqrt{T} \int_z^{\infty} [-\phi'(y)] dy - z \sigma \sqrt{T} \int_z^{\infty} \phi(y) dy \\ &= \sigma \sqrt{T} [\phi(z) - z(1 - \Phi(z))] \end{aligned} \quad (\text{A.2})$$

Appendix A. Appendices

Replacing the two equations above in our minimization problem we obtain Equation 3.2:

$$\bar{C}(z | T) = \frac{c_o(T)\sigma}{\sqrt{T}}(z\Phi(z) + \phi(z)) + \frac{c_u(T)\sigma}{\sqrt{T}}(\phi(z) - z(1 - \Phi(z))) + C_{ss}T.$$

Our objective is to minimize the cost of the retailer, with respect to the replenishment cycle T . Due to the dependency of the terms z , $c_u(T)$ and $c_o(T)$ on T , it is analytically challenging to explicitly replace all terms in the objective function and take the derivative with respect to T . Instead, we follow the methodology described in Petruzzi and Dada (1999) and Whitin (1955). We first show convexity of the function with respect to T and z to ensure global optimality of the solution. We check for convexity of Equation 3.2 in z for a given T by taking the second partial derivative with respect to z and show that it is positive.

$$\frac{\partial^2 \bar{C}(z | T)}{\partial z^2} = \frac{(c_o(T) + c_u(T))\sigma\phi(z)}{\sqrt{T}} > 0. \quad (\text{A.3})$$

We check for convexity of Equation 3.2 in T for a given z by taking the second partial derivative with respect to T ,

$$\frac{\partial^2 \bar{C}(T | z)}{\partial T^2} = \frac{(ar + b)m\sigma(3T + 1)z}{2\mu T^3\sqrt{T}} + \frac{3\sigma(c_o(T)(z\Phi(z) + \phi(z)) + c_u(T)(\phi(z) - z(1 - \Phi(z))))}{4T^2\sqrt{T}}, \quad (\text{A.4})$$

and show that the function is positive for $z > 0$, where $c_u(T) > c_o(T)$. Particularly in the case of the grocery industry, such as dairy products that undergo manufacturing and remain perishable, gross margins remain relatively high (Ailawadi and Harlam, 2004). This is also consistent with our Stackelberg model where retailers are leaders, and manufacturers are followers. Given convexity in both z and T , we can substitute z^* in Equation 3.2 and consequently solve for T^* as introduced in Whitin (1955) and Zabel (1970), and used in Petruzzi and Dada (1999). We first take the partial derivative with respect to z , and replace the solution for z^* into the original cost function and derive with respect to T to find T^* . Deriving Equation 3.2 with

respect to z yields the newsvendor critical fractile, with time-dependent unit cost.

$$\frac{\partial \bar{C}(z | T)}{\partial z} = \frac{c_o(T)\sigma\Phi(z)}{\sqrt{T}} + \frac{c_u(T)\sigma(\Phi(z) - 1)}{\sqrt{T}}. \quad (\text{A.5})$$

From $\phi'(z) = -z\phi(z)$, the optimal order-up-to level $S^*(T)$ is found by $\partial \bar{C}(z)/\partial z = 0$ as in 3.2, where

$$\Phi(z^*) = \frac{c_u(T)}{c_u(T) + c_o(T)}. \quad (\text{A.6})$$

We can therefore find $z^* = \Phi^{-1}\left(\frac{c_u(T)}{c_u(T) + c_o(T)}\right)$. Replacing Equation A.7 back into Equation 3.2, the retailer's cost for the optimal order base-stock level becomes

$$\bar{C}(T, z^*) = \frac{\sigma(p-s)\phi(z^*)}{\sqrt{T}} + C_{ss}T.$$

Note that the term $c_o(T) + c_u(T)$ becomes $p - s$, and is independent of T . Using the chain rule $\phi(z) = \frac{\partial \Phi(z)}{\partial(z)}$ and taking the first derivative with respect to T , we find

$$\frac{\partial \bar{C}(T, z^*)}{\partial T} = -\frac{\sigma(p-s)\phi(z^*)}{2T\sqrt{T}} + C_{ss}. \quad (\text{A.7})$$

The optimal replenishment cycle, T^* is therefore

$$T^* = \left(\frac{2C_{ss}}{\sigma(p-s)\phi(z^*)} \right)^{2/3}. \quad (\text{A.8})$$

Note that the term $\frac{\partial \phi(z^*)}{\partial T} = 0$ from the chain rule, and the expected order quantity is therefore, $S(T^*) = \mu \left(\frac{2C_{ss}}{\sigma(p-s)\phi(z^*)} \right)^{2/3} + \sigma z^* \left(\frac{2C_{ss}}{\sigma(p-s)\phi(z^*)} \right)^{1/3}$, where the optimal value z^* is found by Equation A.7. Replacing T^* back into Equation 3.2 and defining $\xi = \sigma(p-s)\phi(z^*)$, the retailer's

minimum becomes

$$\bar{C}(T^*, z^*) = \frac{\xi^{7/3} + 2C_{ss}^{4/3}}{2C_{ss}^{5/3} \xi^{2/3}}.$$

A.2 Proof of convexity of the manufacturer's cost

We approximate the expected order quantity to $S(T) = \mu T$, and call it a batch size assumption that the term $z\sigma\sqrt{T}$ has a sufficiently small impact on the manufacturer's overall cost. In Section 3.5 we numerically show that the assumption has negligible impacts on the overall optimum order quantity and replenishment cycle. Our numerical results also show that our approximation does not cause a significant change for the optimum. We can now show that the retailer's cost is convex in T , since $\frac{\partial^2 g(r|T)}{\partial T^2} = \frac{2(ar+b)}{\mu T^3} > 0$.

The second derivative of $P(W_q(r) > t_R)$ with respect to r is positive, and the first two terms of the objective function and the constraint are all linear, conserving convexity for $r \geq \lambda$. This condition is naturally satisfied since the queue length approaches infinity when the service rate is less than or equal to the arrival rate. Therefore the problem is convex and the solution is a global minimum.

A.3 Sales and spoilage patterns

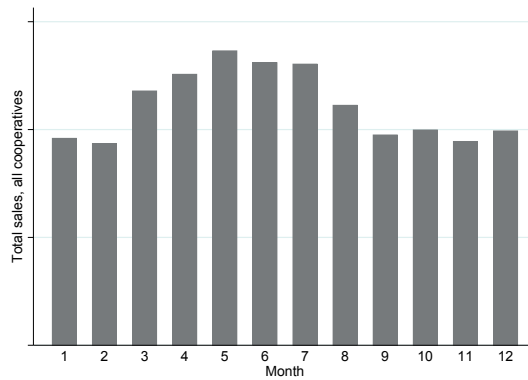


Figure A.1: Yearly sales pattern for fruits and vegetables

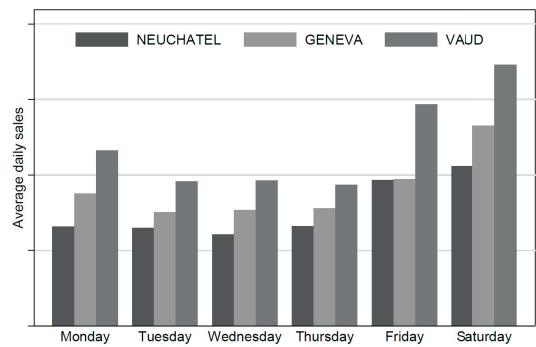


Figure A.2: Weekly sales pattern for fruits and vegetables

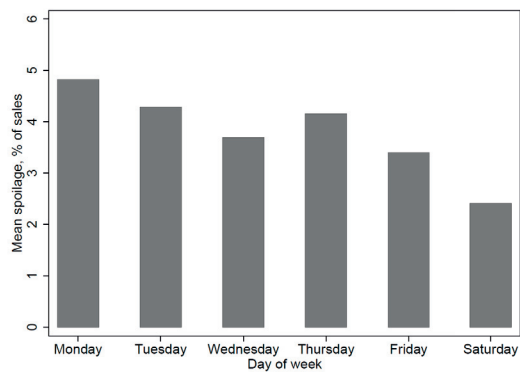


Figure A.3: For fruits and vegetables, spoilage occurs in a matter of days. It follows a pattern throughout the week due to ordering and sales patterns.

A.4 The impact of weather on sales

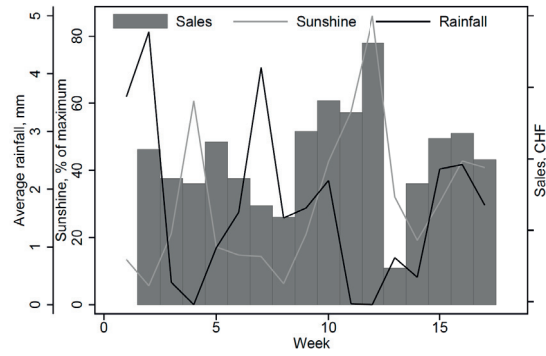


Figure A.4: The relationship between weather and fruits and vegetables sales

Weekly Sales	OLS
Weekly Rain (mm)	-16,376*** (53.62)
Weekly Sun (%)	1,823*** (8.840)
Constant	446,415*** (586.4)
Observations	495,460
R-squared	0.730
N	495460
r2_a	0.730
Standard errors in parentheses	
*** p<0.01, ** p<0.05, * p<0.1	

Table A.1: The impact of weather on fruits and vegetables sales, in CHF

A.5 Simulation results

To understand the impact of inventory age, we simulate spoilage using the base-stock ordering policy for exponentially distributed sales. We use an average of 3 and 4 days of allowable time before the product becomes obsolete and is spoiled in the store. It is generally lower for fruits, but higher for vegetables. We remove promotions data and simulate spoilage based on a FIFO policy at the retailer, which is often the case for days-fresh products. Table A.2 shows the results in terms of multiples of the real spoilage value. As expected, high service levels drive the total spoilage higher, while higher shelf-life reduces spoilage. Overall, inventory age explains all of the spoilage as the service level increases.

We explain part of the inventory age in our study using the nine measurable drivers. We note that there are other drivers that influence inventory age that we cannot capture in our model. Furthermore, real service levels, the ordering policy, product quality as well as lead times may vary over time, causing our simulation to differ from real spoilage values.

Service level	Exponential dist. 3 days	Exponential dist. 4 days
95%	3.82	1.45
90%	1.67	0.67
80%	0.59	0.26

Table A.2: Simulated spoilage value as a multiple of the real spoilage based on various distributions and service levels

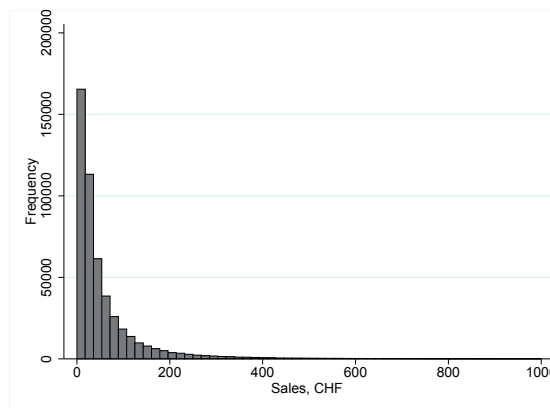


Figure A.5: Fruits and vegetables sales follow an exponential distribution

A.6 Mundlak approach

We next discuss the results of a Mundlak approach (Mundlak, 1978) on our model to analyze the effects of product- or store-specific characteristics that cannot be observed with the fixed effects model, namely packaging and origin. The Mundlak procedure, also known as the Chamberlain approach (Chamberlain, 1984), is used in panel data to observe the effects of time-invariant variables when the Hausman test concludes that there is correlation between the time-invariant unobservable and the regressors, i.e., the random effects model cannot be used. The test results are given in Table A.3.

We compare open case, single unit, weight and net type products. While the results are not clearly significant for open case, single unit and net, products sold with pre-packaging price based on the weight significantly reduces spoilage. We believe it is due to plastic and cardboard packaging which protects the product from damage relatively better than other types. Open case and single unit type of products usually do not involve packaging, while products in a net might still get damaged due to an absence of rigid protection. While the results give insights on store spoilage, according to our interviews with importers: “Pre-packaged products with the retailer label cannot be sold to alternative buyers”, indicating that packaging potentially increases spoilage at the importer level. A full supply chain analysis is required to confirm the overall impact of each packaging type.

We also studied the effects of product origin on spoilage. Although we control for the product category, we do not think the statistical results are robust enough to conclude the effects of origin on spoilage, due to limited product categories per origin. We propose such an analysis for future research and recommend using a broader range of products per origin and longer time series.

Spoilage	Mundlak OLS
Inventory	0.0238*** (0.00427))
Promotion	-0.0225*** (0.00358)
Commitment change	-0.00861*** (0.00107)
Direct delivery	-0.0375*** (0.0111)
Store order variation	0.0252*** (0.00341)
DC order variation	0.00929*** (0.00343)
Order cycle	0.00943*** (0.00141)
Case size cover	0.00187 (0.0432)
Quality issues	0.000260** (0.000108)
Sales	-0.000102*** (1.21e-05)
Demand variation	0.00665 (0.00556)
Open case	-0.000298 (0.00483)
Single unit	-0.00896* (0.00471)
Weight	-0.0173*** (0.00510)
Net	0.00627 (0.00473)
Store-SKU fixed effects included	Yes
Other controls included ^a	Yes
Constant	0.0697*** (0.0269)
Observations	457,539
Adjusted R-squared	0.0972
F-statistic	10.87

Robust standard errors in parentheses

*** p<0.01, ** p<0.05, * p<0.1

^a Controls: sell-by constraint, product category, month, day of the week, origin and *Category* × *week*

Table A.3: Mundlak approach results for the OLS model

A.7 The role of inventory in the model

All variables essentially influence inventory age or product quality issues, which are the main drivers of spoilage. Data on inventory age is often unavailable for perishables with very short lifetimes. Although the product packaging date is available, the age of the product when it arrives at different supply chain locations is not systematically recorded. As a result, inventory age cannot be included in the model.

While inventory and inventory age are related, inventory does not directly influence spoilage. The difference between inventory and inventory age can be explained with a simple example. Consider a product in two comparable stores with the same sales and days of inventory: for example, 15 consumer units of inventory, and 10 units of sales per day, which represents 1.5 days of inventory in each store. While the inventory quantity and sales are the same in both stores, the age of the product in one store is a day older and consequently more likely to spoil before sales can occur. Hence we argue that inventory, in absolute value or in days of sales, does not cause spoilage per se.

Furthermore, additional analysis shows that excluding inventory from the model does not significantly change the results. Moreover, we find that other variables do not sufficiently explain inventory to conclude any strong mediation or moderation effects.

Combining the above and the results of our simulation in section A.5, we argue that inventory aging and product quality issues are the main causes of spoilage, and that inventory should be included alongside the other variables in the regression model due to its impact on inventory age. We encourage researchers to conduct empirical studies for days-fresh products where inventory age and product quality information is available at each stage of the supply chain.

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Research Areas

Operations Management with a special interest in Supply Chain Management and sustainability performance in firms.

Education

2013-2017 **École Polytechnique Fédérale de Lausanne.**

- Doctoral researcher in Technology and Operations Management
- Dissertation topic: "Improving Firm Performance Through Sustainable Operations"
- Collaborations: Nestlé S.A., IMD Business School, Migros

2011-2013 **École Polytechnique Fédérale de Lausanne.**

- Masters in Environmental Engineering. Projects: Life Cycle Analysis of photovoltaic panels, Extended analytical solution in implementing CO2 sequestration for CCS.
- Minor in Management of Technology. Projects: Google case analysis to develop strategic improvements in asset utilization.

2007- 2011 **Middle East Technical University, Turkey.**

- Bachelors in Civil Engineering
- Projects: Marina design for Edremit, Industrial zone stormwater drainage design for Bursa

Professional Experience

2014 **Nestlé S.A., Vevey, 2 months.**

- Research collaboration with the Safety, Health and Environment department.
- Project: Interviewing and data analysis for a business case on zero waste to landfill in factories.

2013 **Nestlé S.A.**, Vevey, 6 months.

- Master project internship in the Supply Chain Development department
- Project I: Created best-practices toolkit and developed reporting, analysis and benchmarking processes to quantify and optimize energy consumption in transportation and warehousing.
- Project II: Data analysis for global initiative on reducing food waste in Nestlé's supply chain

2011- 2013 **École Polytechnique Fédérale de Lausanne**, *Teaching assistant*.

- Soil mechanics and groundwater seepage
- Calculus I and Calculus II

Publications & Working Papers

- Kırıcı, M. and Seifert, R.W., 2016. "Sustainable Supply Chain Management and Dynamic Capabilities: A theoretical framework". *Supply Chain Forum: An International Journal*.
- Kırıcı, M., Işık, B. and Seifert, R. W., "Optimal replenishment frequency under supply and demand uncertainty", under review.
- Kırıcı, M., Isaksson, O. and Seifert, R. W. "Managing perishability in the fruit and vegetable supply chain", under review.
- Seifert, R.W. and Kırıcı, M., 2017. "Digitalisation: a fresh idea for the fruit and vegetable supply chain", *IMD Tomorrow's Challenges*.
- Seifert, R.W. and Kırıcı, M., 2016. "Five capabilities for a greener supply chain", *IMD Tomorrow's Challenges*.

Conferences

- INFORMS (Institute for Operations Research and the Management Sciences) Annual Conference. San Francisco USA, 2014
- POMS (Production and Operations Management Society) 27th Annual Conference. Orlando USA, 2016. "Optimal replenishment frequency under supply and demand uncertainty".
- POMS (Production and Operations Management Society) 28th Annual Conference. Seattle USA, 2017. "Managing perishability in the fruit and vegetable supply chain".

Teaching

Supply Chain Management 2014, 2016, 2017. Master level. Teaching assistant.

Negotiation Techniques 2013, 2014, 2015. Master level. Teaching assistant.

Awards

Best Teaching Assistant Award for Negotiation Techniques course, 2014.

Student Supervision

- Altran, master thesis supervision of Nicolas Maillard. “Approaches to measure Profitability and Return On Investment of marketing events within Business to Business companies”.
- Nissan, master thesis supervision of Patrick Whitney. “Analysis of Nissan Europe’s Idea Competition”.
- Rolex, master thesis supervision of Delphine Caujolle. “Implementation of a quality system for the recycling of precious metals in the watchmaking industry”.

Professional Services

Reviewer for *International Journal of Production Research* and *Supply Chain Forum: An International Journal*

PhD Course Work

Microeconomics, 2013, EPFL.

Optimization Methods and Models, 2014, EPFL.

Qualitative Research Methods, 2014, EPFL.

Research methods I, 2014, EPFL.

Economics of Innovation and Technological Change, 2015, EPFL.

Mathematical Models in Supply Chain Management, 2015, EPFL.

Optimization and Simulation, 2015, EPFL.

ISIR Summer School on Value-Driven Inventory Management in Logistics and Supply Chains, 2015, KLU, Hamburg.

ISIR Workshop on Sustainable Logistics and Supply Chain Management, 2015, EMLYON, Lyon.

Languages

Fluent **English, Turkish, French**
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