Coordination in multi-echelon supply chain under supply and demand uncertainty

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ABSTRACT
The main purpose of this paper is to study the inventory, production, and contracting decisions of a multi-echelon supply chain with both demand and supply uncertainty. We find that the commonly used wholesale price contracts used by both up-stream and downstream supply-chain members cannot coordinate the system. We then propose a returns policy used by the manufacturer and the retailer, combined with the wholesale price contract used by the raw-material supplier and the manufacturer, which can perfectly coordinate the supply chain. Through Nash bargaining analysis, we further provide contract terms that lead to win–win situation. We also investigate the impact of the supplier’s risk attitude on the decisions, as well as the impact of spot market price for raw material on the performance of the entire supply chain.

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1. Introduction

This paper studies the supplier’s raw-material production-planning decision, the retailer’s replenishment decision, and the choice of contract for a three-tier supply chain with uncertainty about both demand and raw-material yield. The main purpose is to investigate contract terms that coordinate raw-material planning and replenishment decisions and achieve the most efficient performance of the entire supply chain. This paper differs from traditional random-yield and contracting papers in several ways: (1) Instead of focusing on a two-level supply chain that involves manufacturers and retailers, we study a three-level supply chain that includes a raw-material supplier that provides basic components and faces random yields, a manufacturer that is responsible for production, and a retailer that sells to the stochastic demand. Jaber and Goyal (2008) also consider channel coordination in a three-level supply chain; however, in contrast, they assume that both demand and raw-material yield are certain. (2) We also examine the contract terms (set by the supplier and the manufacturer respectively) in order to optimize the performance of the total supply chain. Most contract literature has focused on supply chain (systems) with perfect supply and on a two-level supply chain (Cachon, 2003). This paper examines the equilibrium inventory and supply decisions and contract decisions of the decentralized supply chain, and provides optimal contract prices that achieve the best performance of the supply chain with both yield and demand uncertainty. (3) We further investigate how a risk-averse supplier makes the production decision and compare it with that of a risk-natural supplier. To our knowledge, there is still no reference for the production-decision problem for a risk-averse supplier who faces supply uncertainty.

Because of long lead times, complicated production processes, and unpredictable factors like weather and environment, the yield of a raw-material manufacturer is often lower than the initial production quantity. The central question of this paper is: what happens to a three-level supply chain that involves both demand and raw-material yield uncertainty? We consider a Stackelberg game in which the supplier plans production for raw materials by anticipating the retailer’s order quantity and the realized yield follows a general probability distribution. What would the equilibrium order quantity and raw-material production quantity decisions be? Can simple wholesale-price contracts coordinate the three-level supply chain in the world of stochastic yields? How about the returns policy?

To address these questions, we develop a single-period, one-supplier/one-manufacturer/one-retailer supply-chain model that focuses on three major issues: replenishment, raw-material production planning, and contract prices for supply chains under both supply and demand uncertainty. In this model, the supplier and the manufacturer first propose contract terms for raw materials and finished products, respectively. The supplier is responsible for determining raw-material production quantity before the production season, and the retailer determines replenishment quantity before the demand is known. The manufacturer,
which has deterministic yield, will purchase raw materials from
the supplier at an amount that fulfils the retailer's order. In the
case that the supplier does not yield enough raw materials to
satisfy the manufacturer, it will purchase the difference from a
spot market. The manufacturer then produces the same amount
as the retailer's order quantity and the products are delivered to
the retailer. Finally, demand is observed, revenues are collected,
and profits are earned.

This paper makes four main contributions. First, we provide
insights for production, replenishment, and pricing decisions for a
multi-echelon supply chain that involves both demand and
supply uncertainty. We characterize the production decision of
the supplier and the inventory replenishment decision of the
retailer in such a system. Second, we investigate the efficiencies of
wholesale price contracts and returns policy and provide contract
terms that effectively coordinate the supply chain. We use Nash
bargaining solution to provide contract terms that lead to a win–
win situation. Third, we examine the impact of spot market on
such a supply-chain system. We find that a high spot-market
price for raw materials deteriorates the profit of the supply chain.
In the extension, we investigate how a risk-averse and uncertain
supplier makes the production decision, and we find that the
more risk-averse the supplier is, the more the supplier plans to
produce.

The paper proceeds as follows. In Section 2, we discuss related
literature and then in Section 3 we provide a description of the
model, including notations and assumptions, and we study the
integrated supply-chain problem. In Section 4, we investigate
decentralized supply chain under wholesale price contracts, and
in Section 5, we examine the decentralized supply-chain system
where the manufacturer uses a returns policy instead of a
wholesale price contract. Section 6 presents numerical examples
to illustrate further insights. Section 7 extends the model to a
risk-averse supplier and Section 8 presents conclusions, insights,
and directions for future research.

2. Related literature

This paper touches on two areas of research: research on
random yield and research on contracting in a supply chain with
demand uncertainty. There is extensive literature in the first area;
for example, Henig and Gerchak (1990) show that if the produc-
tion level of unreliable supplier is endogenous then the optimal
order level for the newsupplier would be greater than the base
case. Anupindi and Akella (1993) consider the operational issue
of quantity allocation between two uncertain suppliers. They intro-
duce three models for the supply process based on the type of
delivery contract a buyer has with the suppliers. Cirallo et al.
(1994) consider the aggregate planning problem for a single
product with random demand and random capacity. They show
that if the production level is exogenous, that is, independent of
order level, the optimal order quantity for the newsupplier does
not change. Dada et al. (2007) consider the problem of a newsup-
plier that is served by multiple suppliers, where a supplier is
defined to be either perfectly reliable or unreliable. They show
that in the optimal solution a supplier will be selected only if all
less-expensive suppliers are selected, regardless of the supplier's
reliability. Jones et al. (2001) consider a hybrid seed-corn produc-
tion problem with yield uncertainty. They assume that there are
two sequential production periods, and they analyze strategies for
determining the number of production acres for each period.
Kazaz (2004) also studies a two-stage decision-making problem
under yield and demand uncertainty, in the olive oil industry, and
determines the optimal production quantity of olives as well
as the optimal recourse order where the retail price is yield
dependent. Hsieh and Wu (2008) consider coordinated decisions
in a decentralized supply chain with uncertainties on both the
demand and supply sides. They find that coordinating with the
original equipment manufacturer (OEM) improves the manufac-
turer's expected profit and the probability of meeting down-
stream demand, yet coordinating with the manufacturer is not
necessarily beneficial to the OEM when downstream coordination
between the manufacturer and the distributor is lacking. Wang
(2009) studies a decentralized supply chain comprising a single
manufacturer and a single distributor for a short life-cycle
product with random yield and uncertain demand. By assuming
the manufacturer acts as a price-taker and the wholesale price is
exogenous, he analyzes two alternatives for doing business. One
is the traditional supply-chain arrangement; the other is a
Vendor-Managed-Inventory (VMI) arrangement. Xu (2010) also
studies the management problems of production and procure-
ment in a decentralized supply chain consisting of one supplier
with random yield and one manufacturer with stochastic
demand. He demonstrates that both the supplier and the manufac-
turer can be better off with the introduction of option con-
tracts. Schmitt and Snyder (2010) consider an inventory system
that faces both yield uncertainty and the risk of complete supply
disruptions, and they demonstrate the importance of analyzing
a sufficiently long time horizon when modeling inventory systems
subject to supply disruptions. Yeo and Yuan (2011) develop a
periodic review model in which the firm manages its inventory
under supply uncertainty and demand cancellation. They show
that the optimal inventory policy with supply uncertainty
features structural properties similar to that with supply certainty
for both the finite horizon case and the infinite horizon case.
Gerchak et al. (1988), Henig and Gerchak (1990), Yano and Lee
(1995), and Wang and Gerchak (1996) provide detailed reviews
and discussions in this field.

There is a vast amount of literature about contracting in
decentralized supply chains. How to sell to a downstream
supply-chain partner, a foundation to address more complicated
supply-chain problems, has attracted extensive attention from
academics. Without a properly designed contract, there is the
problem of double marginalization (Spengler, 1950) because the
downstream retailer does not have an incentive to order enough
inventories to maximize the total supply-chain profit. Under the
assumptions of deterministic production yields and a two-level
supply chain, Lariviere and Porteus (2001) show that the simple
wholesale-price-only contract is unable to coordinate the supply
chain; and Pasternack (1985) shows that a returns policy, when the
parameters are properly chosen, can coordinate the supply chain.
Cachon (2003) provides a detailed review of this literature.

Because the simple wholesale-price-only contract cannot coordi-
nate the supply chain, researchers have been focusing on designs
of contracts to coordinate a supply chain; for example, quantity
flexibility contracts (Tsay, 1999; Wang and Tsoa, 2006), revenue
sharing contracts (Cachon and Lariviere, 2005; Bellantuono et al.,
2009), quantity discounts (Weng, 1995; Li and Liu, 2006), sales
rebate contracts (Taylor, 2002; Wong et al., 2009), and returns
policy or buyback contracts (Pasternack, 1985; Emmons and
Gilbert, 1998; Xiao et al., 2010). Returns policy is one of the most
commonly studied coordination contracts in literature, under
many complicated situations. For example, Choi et al. (2008) carry
out a mean-variance analysis of supply chains and illustrate that a
returns policy can simultaneously achieve channel coordination
and risk control. He et al. (2009) consider a condition in which the
stochastic market demand is sensitive to both retail price and sales
effort. They show that coordination is achieved by using a properly
designed returns policy with a sales rebate and penalty (SRP)
contract. Chen and Bell (2011) investigate a channel that consists
of a manufacturer and a retailer where the retailer simultaneously

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