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Supply chain risk analysis with mean-variance models: a technical review

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Abstract Pioneered by Nobel laureate Harry Markowitz in the 1950s, the mean-variance (MV) formulation is a fundamental theory for risk management in finance. Over the past decades, there is a growing popularity of applying this ground breaking theory in analyzing stochastic supply chain management problems. Nowadays, there is no doubt that the mean-variance (MV) theory is a well-proven approach for conducting risk analysis in stochastic supply chain operational models. In view of the growing importance of MV approach in supply chain management, we review a selection of related papers in the literature that focus on MV analytical models. By classifying the literature into three major areas, namely, single-echelon problems, multi-echelon supply chain problems, and supply chain problems with information updating, we derive insights into the current state of knowledge in each area and identify some associated challenges with a discussion of some specific models. We also suggest future research directions on topics such as information asymmetry, supply networks, and boundedly rational agents, etc. In conclusion, this paper provides up-to-date information which helps both academicians and practitioners to better understand the development of MV models for supply chain risk analysis.

Keywords Mean-variance analysis · Supply chain management · Review

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1 Introduction

Managing risk in a supply chain has now been a more and more popular topic (Van Mieghem 2003). Essentially, in a supply chain context, if there are some sources of uncertainty such as demand uncertainty and supply uncertainty, the performance of the supply chain will also be affected and become uncertain. As a result, risk emerges and supply chain agents need to make decisions under risk (Zsidisin and Ritchie 2008). In supply chain systems, two sources of supply chain risk are commonly present, namely the supply chain disruption risk (SCDR) (Tang 2006; Sodhi et al. 2012) and the supply chain operational risk (SCOR) (Choi and Chiu 2012b). SCDR comes from some kinds of disruptions which affect the normal operations of the supply chain systems. For example, both natural and man-made problems such as wars, earthquakes, changes of economics policies and trading barriers, hurricanes, terrorist attacks, diseases, typhoons are called disruptions which directly lead to SCDR. SCOR refers to the some "expected" variations which commonly and normally exist. For instance, supply reliability, fluctuation of exchange rate (under normal situation), and demand uncertainty are all factors which create SCOR. No matter we examine SCDR or SCOR, it is important to establish an analytical framework for conducting systematic risk analysis.

In the operational research literature, the classical approach[1] for exploring supply chain risk is to employ an expected measure approach. For example, to investigate the level of risk associated with inventory decisions with demand uncertainty, a commonly adopted approach is to estimate the expected under-stocking risk and the expected over-stocking risk with respect to the inventory decision. Balancing these two kinds of risk will generate the optimal inventory policy. In lead time management for a just-in-time (JIT) supply chain system when supply lead time of a product is uncertain, an intuitive method to study the level of risk is to quantify the late-arrival risk and the early-arrival risk (assuming early arrival and late arrival are both undesirable) by the expected cost associated with late-arrival and expected cost associated with early-arrival, respectively. The use of expected measure is intuitive and analytically neat. However, it is far from perfect because the expected measure alone does not reveal any hint on the underlying level of uncertainty associated with the measure. To be specific, risk should include two inherent components, namely the unfavorable outcomes and the associated level of uncertainty. Expected measure can show the magnitude of the "expected unfavorable outcomes" but not the level of uncertainty. An optimal control policy which optimizes an expected measure of risk ("performance") may actually fail to address the problem properly because the likelihood of the achievability of the optimal (or around optimal) expected performance can be low. As a result, additional analytical measure should be incorporated into the analytical framework in order to derive an effective optimal control with risk consideration. In decision science and behavioral economics, it is well-known that supply chain agents, taken as decision makers, would have different kinds of attitudes towards risk. To be specific, supply chain agents can be avoiders of risk (risk-averse), lovers of risk (risk-seeking), or neutral to risk (risk-neutral). However, the expected measure alone can only capture the risk-neutral attitude. Thus, the insufficiency of the expected measure for supply chain risk analysis calls for alternative risk-related models for analysis.

In the 1950s, pioneered by the Nobel Laureate Professor Harry Markowitz, the mean-variance (MV) formulation is a ground-breaking theory for portfolio risk management in finance (Markowitz 1959). The basic idea behind Markowitz's MV framework is to consider

[1] This approach is still employed today, see e.g., Chen and Yano (2010), Tuncel and Alpan (2010), Dong and Tomlin (2012), and Gumus et al. (2012).

both the expected payoff (i.e. the "mean") and the variation of payoff (i.e., the "variance") in the analysis. The "mean" represents the benefit and the "variance" represents the risk associated with the investment decision making problem (see Levy and Markowitz 1979 for more discussions of the use of MV model to approximate expected utility). Observe that the MV model suffers an inherent theoretical flaw in which both the upside and downside variations from the "mean" are counted as risk. This hence gives rise to the use of a downside risk measure to replace the "variance". An example is the "semi-variance" where only the bad outcomes which are inferior to the "mean" (or a pre-determined threshold) are included in the calculation for risk (see Ogryczak and Ruszczynski 2001).

Over the recent past decades, it is interesting to observe that Markowitz's MV framework has extended its influence from financial studies to supply chain studies. In view of its growing importance and the establishment of the respective field of studies in supply chain risk analysis, we review the literature and select the representative papers for further analysis. By classifying the literature into three major areas, namely, single-echelon supply chain problems, multi-echelon single-period supply chain problems, and supply chain problems with information updating, we derive insights into the current state of knowledge in each area and identify some associated challenges with a discussion of some specific models. We also suggest future research directions. To the best of our knowledge, this paper is the first journal paper which conducts a technical literature review specialized on Markowitz's MV framework related supply chain models. We believe that this paper provides up-to-date information which helps both academicians and practitioners to better understand the development of MV models for supply chain risk analysis.

When preparing this technical review paper, we extensively searched the following portals for the related literature from 1st July 2012 to 17th September 2012: Google Scholars, ScienceDirect.com, IEEE Xplore Digital Library, INFORMS Pubsonline, EBSCO Business Source Complete database for the related terms such as "mean-variance", "mean risk", "supply chain risk", "inventory risk", "mean-variance analysis", "risk averse agents", "risk sensitive agents", "loss-averse", "newsvendor risk", "newsboy risk" and their combinations appearing in title or keywords. We focused on the archival journals written in English. Our initial search identified 618 papers. After initial screening of the titles and abstracts, only 89 of them were retained as the majority of the other papers either were non-analytical research papers or simply relied on the expected risk related measures. After further checking, only 52 papers remained as the others were not related to mean-risk supply chain models. From the cited references of these papers, we further found some additional related papers. We also added some papers in an ad-hoc basis because of our own acquaintance of the related literature and as advised by the referees.

The rest of this paper is organized as follows. Section 2 presents the MV models for single-echelon supply chain problems. Section 3 reviews the multi-echelon supply chain problems under the MV framework. Section 4 examines some prior research which employs the MV models in analyzing supply chains with information updating. Section 5 discusses future research directions. Section 6 concludes the paper.

2 Single-echelon problems

In the single-echelon setting, the seminal research which employs the use of an MV objective in modeling the single period single echelon supply chain inventory problem appears in a section of Lau (1980) in which the newsvendor problem with a mean-standard-deviation (expected profit and standard-deviation of profit) objective is studied. Model 2.1 shows the

MV model proposed by Lau (1980), and it is the first MV analytical model employed in exploring inventory management related problems.

Model 2.1 (Lau 1980)

$$U_{Mean\text{-}SD}(q) = E\big[\pi_{newsvendor}(q)\big] - k_{newsvendor} SD\big[\pi_{newsvendor}(q)\big], \tag{2.1}$$

where q is quantity, $\pi_{newsvendor}(q)$ is the profit function of the newsvendor, $E[\pi_{newsvendor}(q)]$ is the expected profit of the newsvendor, $k_{newsvendor}$ is the risk aversion parameter of the newsvendor, $SD[\pi_{newsvendor}(q)]$ is the standard deviation of profit of the newsvendor, $U_{Mean\text{-}SD}(q)$ is the mean-standard-deviation objective function of the newsvendor.

After that, Chen and Federgruen (2000) conduct a mean-variance analysis of various important basic inventory models which include the single period newsvendor problem as well as the multi-period (R, nQ) base stock inventory problem. For the newsvendor problem, they model a quadratic utility function for the decision maker and construct an MV efficient frontier. They investigate the "profit" and "cost" models and reveal the differences in terms of the optimal solutions. For the base stock policy, they consider the case with Poisson customer arrival. They analyze the case with the constraint on variance of cost per period. Extending Model 2.1 in which the tradeoff between "mean" and "variance" is governed by a risk-averse sensitivity coefficient k, Choi et al. (2011) study a multi-period MV model for the finite horizon periodic-review inventory policy. Since variance is non-separable in the multi-period dynamic program, the concept of primal-dual problem is employed in Choi et al. (2011). To be specific, Choi et al. (2011) first develop a separable auxiliary "dual" problem. They then analytically derive the sufficient conditions under which the solutions for the "dual" problem and the original "primal" problem converge. They also propose the details of how the dual-primal method can be implemented. Extending Chen and Federgruen (2000), Choi and Chiu (2012b, Chap. 3) investigate the multi-period (R, nQ) model by the MV approach by taking the long run-average profit as the "mean". They propose to employ the variance of on-hand inventory and the variance of single-period profit as the measures for "risk". After building the formal model, they derive the closed form expressions of the long run-average profit, and the risk related measures. They then demonstrate the way to construct the MV efficient frontier and generate several important insights. Using an MV objective function similar to Model 2.1, Liu et al. (2012) study the mass customization supply chain in which the risk-averse mass customization brand needs to decide three optimal decisions on product pricing, consumer refund rate, and level of customization (as measured by modularity). They derive the closed-form expressions of the optimal solutions. They also comment on the impacts brought by the degree of risk aversion on the optimal decision and argue that it can explain why some mass customization brands offer consumer returns policy and some don't. Choi (2013) extends Liu et al. (2012) to explore why some risk averse mass customization companies offer free return service charge to some customers (such as members) but not all. Most recently, Choi et al. (2013) extend Liu et al. (2012) and Choi (2013) to study the mass customization program and reveal that whether the risk averse mass customization company should prefer implementing "no return" to "full return with full refund" depends highly on the demand-return correlation. Liu and Nagurney (2011) explore via the MV framework the supply chain offshore outsourcing problem. They consider a supply chain which consists of multiple competing companies that are selling partially substitutable products. These companies can choose to go outsourcing for production or simply manufacture the goods in-house. In light of the exchange rate volatility, they develop a variational inequality model which comprehensively includes the decisions such as pricing, transportation, product sourcing options of the companies. They study the problem by employing a numerical approach and reveal how the levels of risk aversion of the competing companies affect the optimal decisions and the respective level of risk.

With a model different from Lau (1980) and the corresponding extended works in the single-echelon supply chains, Choi et al. (2001) consider the risk-averse newsvendor problem under a mean-variance framework for both the cases with and without the loss of goodwill stockout cost. Some preliminary findings on the influence of the loss of goodwill stockout cost are reported.[2] Choi et al. (2008b) extend Choi et al. (2001) and consider the newsvendor problem under the MV framework with decision makers possessing different risk attitude (namely, risk-averse, risk-neutral, and risk-seeking). They analytically derive the optimal solutions and explore the efficient frontiers for each case. The risk-averse models proposed by Choi et al. (2008b) are stated as follows ($V[\pi_{newsvendor}(q)]$ is the variance of profit of the newsvendor, $\xi_{newsvendor}$ is the risk tolerance threshold, $\Pi_{newsvendor}$ is the minimum expected profit threshold),

Model 2.2 (Choi et al. 2008b)

$$\begin{aligned} &\max_{q} E\left[\pi_{newsvendor}(q)\right] \\ &\text{s.t.} \quad V[\pi_{newsvendor}] \leq \xi_{newsvendor}. \end{aligned} \tag{2.2}$$

Model 2.3 (Choi et al. 2008b)

$$\begin{aligned} &\min_{q} V\left[\pi_{newsvendor}(q)\right] \\ &\text{s.t.} \quad E[\pi_{newsvendor}] \geq \Pi_{newsvendor}. \end{aligned} \tag{2.3}$$

Notice that in the newsvendor setting, Models 2.2 and 2.3 have very nice features and physical meanings. They are better than Model 2.1 in the sense that the solution is well-bounded and there won't be problem associated with negative "utility" as can be found in Model 2.1. See Choi et al. (2008b) for more details.

Vaagen and Wallace (2008), following a similar model as Model 2.3 with the addition of more constraints, construct an MV model to study the optimal multiple items assortment planning problems in fashion apparel. They propose that there exist two states of the world and argue that different product items are correlated statistically in some sense. With the objective function of minimizing the semi-variance of profit, they solve the stochastic optimization problem and find the optimal product portfolio based on the concept of hedging. They further derive an important insight which indicates that investigating hedging portfolios, among the multiple correlated products items, is an important task in order to find the optimal assortment plan. They also discuss the impacts brought by the probable misspecification of the demand distributions. Choi and Chiu (2012a) study via the MV and the mean-downside-risk frameworks the newsvendor problem. They first construct analytical models based on Models 2.2 and 2.3 for the cases when risk is quantified by variance of profit, and semi-variance of profit, respectively. They then study various environmental and economics sustainability related measures. They also examine both the cases when retail

[2]For the newsvendor problem in the presence of the loss of goodwill stockout opportunity cost, Choi et al. (2008b) and Wu et al. (2009) both provide some more analytical results. In particular, Wu et al. (2009) analytically prove that when demand is distributed following a continuous power distribution, the optimal stocking quantity under an MV newsvendor model will exceed the risk-neutral case's optimal "fractile" quantity.

Table 1 The classification of single echelon MV risk related models

	Single echelon	
	Single period	Multiple periods
MV Model 2.1[a]	Lau (1980), Wu et al. (2009), Liu and Nagurney (2011), Liu et al. (2012)	Choi et al. (2011)
MV Model 2.2	Chen and Federgruen (2000), Choi et al. (2001, 2008b), Choi and Chiu (2012a)	Chen and Federgruen (2000), Choi (2012), Choi and Chiu (2012b, Chap. 3)
MV Model 2.3	Vaagen and Wallace (2008), Choi et al. (2008b), Choi and Chiu (2012a, 2012b)	

[a]Notice that we classify the papers under each model in the sense that the optimization model is closest to it. For example, there are various variants for Model 2.1 for each specific paper but the key element of Model 2.1 is to have a linear tradeoff between "expected profit" and "variance of profit (or standard deviation of profit)" in the objective function

Table 2 The classification of single echelon non-MV risk related models

	Single echelon	
	Single period	Multiple periods
Utility function	Atkinson (1979), Eeckhoudt et al. (1995), Keren and Pliskin (2006), Tapiero and Kogan (2009), Wang et al. (2009), Choi and Ruszczynski (2011), Giri (2011)	Chen et al. (2007), Borgonovo and Peccati (2009)
Value-at-risk	Ozler et al. (2009), Chiu and Choi (2010), Chiu et al. (2011b), Jammernegg and Kischka (2012)	Zhang et al. (2009)
Conditional value-at-risk	Gotoh and Takano (2007), Cheng et al. (2009), Jammernegg and Kischka (2012)	Zhang et al. (2009), Borgonovo and Peccati (2009)
Pre-determined profit level	Sankarasubramanian and Kumaraswamy (1983)	
Loss aversion	Wang and Webster (2009), Wang (2010)	Ma et al. (2013)
Coherent measure of risk	Choi and Ruszczynski (2008), Choi (2012)	Borgonovo and Peccati (2011)

price is exogenous and endogenous. Specific insights regarding how the level of risk aversion affects the different measures of sustainability are revealed. Furthermore, they find that when the problems are properly built and "fairly" compared, the MV newsvendor problem and the mean-downside risk newsvendor problem have the same optimal solution. Table 1 summarizes the literature on MV models reviewed above and Table 2 lists the literature on non-MV models.

3 Multi-echelon problems

In addition to the single echelon MV problems reviewed above, the multi-echelon supply chain coordination problems are also well-studied under the MV framework. The first piece of work which analyzes the supply chain is one which extends Model 2.1 to a multi-echelon setting by Lau and Lau (1999). To be specific, Lau and Lau examine a two-echelon single-manufacturer and single-retailer supply chain, and study the buyback policy in a one-period setting. They formulate the retailer's decision making problem by the newsvendor model. They consider the scenario in which both the retailer and the manufacturer are risk-averse. To reflect the level of risk aversion, they employ Model 2.1 and assume that the objective functions for both the retailer and the manufacturer follow Model 2.1's format (of course, with different "k" to reflect the probable different sensitivity towards risk). They focus on the case with a normally distributed demand and derive many important managerial insights via extensive numerical analysis. To be specific, the model of Lau and Lau (1999) is given as follows,

Model 3.1 (Lau and Lau 1999)

$$U_M(q) = E\big[\pi_M(q)\big] - k_M V\big[\pi_M(q)\big], \tag{3.1}$$

$$U_R(q) = E\big[\pi_R(q)\big] - k_R V\big[\pi_R(q)\big], \tag{3.2}$$

where $E[\pi_M(q)]$ and $E[\pi_R(q)]$[3] are the expected profits for the manufacturer and the retailer, respectively, k_M and k_R are the risk aversion parameters respectively for the manufacturer and the retailer, $V[\pi_M(q)]$ and $V[\pi_R(q)]$ are the variance of profits for the manufacturer and the retailer, respectively, $U_M(q)$ and $U_R(q)$ are the mean-variance objective functions for the manufacturer and the retailer, respectively.

Similar to Lau and Lau (1999), Tsay (2002) also applies the MV objective in analyzing a two-echelon supply chain. His focus is on revealing the role played by risk sensitivity in affecting the supply chain returns and markdown money contracts. He formulates the problem under different cases with respect to the supply chain agents' strategic power. He finds that incorporating risk sensitivity of supply chain agents into the analysis is critical for the optimization of the supply chain by using these contracts. Martinez-de-Albeniz and Simchi-Levi (2006) employ the MV approach to explore the trade-offs faced by a downstream manufacturer who signs a menu of contracts with the upstream supplier. They focus their analysis on the case in which a spot market is present. The manufacturer hence faces risk no matter it purchases too many contracts or too few. They derive the set of MV efficient portfolios and generate many important analytical insights. Hung et al. (2013) study a two-echelon risk-averse supply chain in which upstream suppliers have short lead-time capacity to produce products for the retailers. They use the MV model to study how the operational risks for the retailers can be pooled among the supply chains by trading capacity. They find that the performance of their proposed hedging mechanism is robust and effective.

With a problem similar to Lau and Lau (1999), Choi et al. (2008a) analytically study the returns policy for channel coordination issue in the supply chain under another form of MV framework (based on Model 2.2). They examine both the centralized supply chain and decentralized supply chain cases. They first study the situation when information is public, and then asymmetric in the supply chain. The specific models considered in Choi et al. (2008a) are shown below,

[3] Unless otherwise specified, for brevity and consistency, the same notation in this paper will carry the same meaning across models reviewed in the literature.

Model 3.2a (Choi et al. 2008a; The upstream manufacturer acts as supply chain coordinator and channel leader. It aims at maximizing the MV supply chain's optimization problem) Manufacturer's problem (which is the same as supply chain's problem with MV consideration):

$$\begin{aligned} &\max_b E\left[\pi_{SC}\left(q_{R^*}(b)\right)\right] \\ &\text{s.t.} \quad V\left[\pi_{SC}\left(q_{R^*}(b)\right)\right] \le \xi_{SC}. \end{aligned} \tag{3.3}$$

Retailer's problem:

$$\begin{aligned} &\max_q E\left[\pi_R(q;b)\right] \\ &\text{s.t.} \quad V\left[\pi_R(q;b)\right] \le \xi_R \end{aligned} \tag{3.4}$$

where b is the buyback price (rate of partial refund) under the returns policy offered by the manufacturer, $q_{R^*}(b)$ is the retailer's optimal reactive order quantity for a given b which solves (3.4), ξ_{SC} and ξ_R are the risk tolerance thresholds respectively for the supply chain and the retailer.

Model 3.2b (Choi et al. 2008a; The upstream manufacturer acts as the channel leader who aims at maximizing its own MV optimization problem) Manufacturer's problem:

$$\begin{aligned} &\max_b E\left[\pi_M\left(q_{R^*}(b)\right)\right] \\ &\text{s.t.} \quad V\left[\pi_M\left(q_{R^*}(b)\right)\right] \le \xi_M. \end{aligned} \tag{3.5}$$

Retailer's problem: The same as (3.4).

In Model 3.2a of Choi et al. (2008a), the definition of coordination by returns policy means setting a buyback price b so as to maximize the supply chain's MV optimization problem as defined in (3.3). It is the same as finding a value of buyback price b which makes $q_{R^*}(b) = q_{SC^*}$, where

$$q_{SC^*} = \arg\left\{\begin{matrix} \max_b E[\pi_{SC}(q_{R^*}(b))] \\ \text{s.t.} \quad V[\pi_{SC}(q_{R^*}(b))] \le \xi_{SC} \end{matrix}\right\}. \tag{3.6}$$

Extending Choi et al. (2008a), Choi et al. study the two-echelon supply chain coordination problem when the agents possess different kinds of risk attitudes (i.e., risk-averse, risk-seeking, or risk-neutral) in Choi et al. (2008c). They define supply chain coordination with a similar concept as in Choi et al. (2008a) and Chiu et al. (2011a). They model the risk attitudes of the supply chain agents by the MV framework. They interestingly reveal that it can be more difficult for a supply chain with two risk averse agents to achieve coordination than a supply chain with one risk seeking and one risk averse agent. They hence conclude that the success of achieving supply chain coordination does not depend on the consistency of the risk attitude of the two supply chain agents, but it depends on "how much the risk attitudes differ" (e.g. if the retailer is very risk averse and the manufacturer is very little risk averse, the supply chain cannot be coordinated; if the retailer is mildly risk seeking and the manufacturer is mildly risk averse, the supply chain can be coordinated). After that, Wei and Choi (2010) conduct an MV analysis for the profit sharing contract on a two-echelon supply chain. They construct analytical supply chain models for the cases when the level of risk aversion of the retailer is publicly known and the information is private. They first derive the necessary and sufficient conditions for achieving coordination by a wholesale pricing and profit sharing scheme for the case when information is public. For the case when information is private, they reveal one important insight which indicates that the retailer has incentive to pretend to be more risk averse and cheat. They develop and suggest a novel method, called the minimum quantity commitment scheme, for the manufacturer to employ which can effectively prevent the retailer from providing fake information. Under an MV framework, Choi (2011) analytically studies the use of RFID in a two-echelon single-manufacturer single-retailer vendor-managed inventory supply chain selling a newsvendor product. He analytically proves that if the RFID tag cost is sufficiently small, employing RFID technology will lead to an improved supply chain performance in MV sense (i.e., both a larger expected profit and a smaller variance of profit). He also argues that it is beneficial for the manufacturer to take the initiative to share the retailer's RFID implementation cost. Chiu et al. (2011a) conduct an MV analysis of a supply chain under target sales rebate contract. They follow Model 2.3 in setting the objective for the risk averse retailer and illustrate how a target sales rebate contract can coordinate the supply chain. They consider two supply chain settings in which one does not involve sales effort and one has sales effort being a decision variable. As a remark, in the multi-echelon supply chain setting with supply chain agents having MV objectives, definitions for supply chain coordination vary. In Chiu et al. (2011a), they formally define supply chain coordination as follows,

Definition 3.1 (On supply chain coordination by Chiu et al. 2011a) A supply chain contract ϕ coordinates a supply chain if there exists an autonomy decision y^a by agents of the supply chain such that for any decision y, $y^a = \arg\max(E[\pi_{SC}(q|\phi)])$ holds, where $E[\pi_{SC}(q|\phi)]$ is the expected profit of the supply chain.

Notice that Definition 3.1 is a special case of Choi et al. (2008a)'s definition for coordination in which the best supply chain's decision is the one which maximizes the expected supply chain profit.

Recently, with a similar definition for supply chain coordination as defined by Choi et al. (2008a), Shen et al. (2013) investigate the markdown money policy in a two-echelon supply chain with a newsvendor product. Supported by industrial practice in fashion industry, they study the supply chain in which the supplier is risk averse whereas the retailer is risk neutral. They model the supplier's MV objective function in a form similar to Model 3.2b. They establish the analytical conditions for achieving supply chain coordination with a definition similar to the one proposed in Choi et al. (2008a). They also derive various managerial insights with relevance to the fashion industry.

For the two-echelon supply chain with risk averse agent(s), Gan et al. (2004, 2005) investigate the supply chain coordination challenge with various innovative ideas. To be specific, Gan et al. (2004) present the following definitions and models,

Definition 3.2 (On Pareto optimal sharing rule by Gan et al. 2004) Given an external action s of the supply chain with N agents, $\theta^*(s)$ is a Pareto-optimal sharing rule, if $u_1(\pi_1(s,\theta(s))), \ldots, u_N(\pi_N(s,\theta(s)))$ is a Pareto-optimal point of the set $\{u_1(\pi_1(s,\theta(s))), \ldots, u_N(\pi_N(s,\theta(s)))\theta \in \Theta\}$, where $u_i(\pi_i(s,\theta(s)))$ is the payoff of the ith agent.

Definition 3.3 (On supply chain coordination by Gan et al. 2004) A supply chain contract agreed upon by the agents of a supply chain is said to coordinate the supply chain if the optimizing actions of the agents under the contract: 1. Satisfy each agent's reservation payoff constraint (which is obviously no less than the respective best payoff when the contract is absent), and 2. lead to an action pair $(s^*, \theta^*(s^*))$ that is Pareto optimal.

Model 3.3 (Gan et al. 2004)

$$U_{M,Pareto}(q) = E\big[\pi_M\big(s, \theta(s)\big)\big] - \lambda_M V\big[\pi_M\big(s, \theta(s)\big)\big], \tag{3.7}$$

$$U_{R,Pareto}(q) = E\big[\pi_R\big(s, \theta(s)\big)\big] - \lambda_R V\big[\pi_R\big(s, \theta(s)\big)\big], \tag{3.8}$$

where λ_M and λ_R are the risk aversion parameters respectively for the manufacturer and the retailer.

Notice that Model 3.3 is very similar to Model 3.1 but is more general. With Model 3.3, Gan et al. (2004) derive a few important theorems as listed below:

Theorem 3.1 (Gan et al. 2004; for a supply chain with N agents, $N > 1$) *An action pair* (s^*, θ^*) *is Pareto-optimal if and only if* $s^* = \arg\max(E[\pi_{SC}(s)] - \frac{1}{\sum_{i=1}^{N} 1/\lambda_i} V[\pi_{SC}(s)])$, *and, almost surely,* $\pi_i(s, \theta^*(s)) = \frac{1/\lambda_i}{\sum_{i=1}^{N} 1/\lambda_i}\pi_{SC} + T_i$, *where* $\pi_i(s, \theta^*(s))$ *is the profit for agent* i, T_i *is a constant which can be adjusted to achieve any division of the total supply chain profit* π_{SC}.

With Theorem 3.1, Gan et al. (2004) further derive some special cases. For example, in a two-echelon single-manufacturer single-retailer supply chain similar to the one examined by Lau and Lau (1999) and Choi et al. (2008a), the following result is found in Gan et al. (2004) for the returns contract: "*If the parameters of a returns contract satisfy* $b = \frac{\lambda_R}{\lambda_R+\lambda_M}(p - v)$ and $w = \frac{\lambda_R p}{\lambda_R+\lambda_M} + \frac{\lambda_M c}{\lambda_R+\lambda_M}$, *then the returns contract along with a side payment* T_i *to the retailer coordinates the supply chain, where* w *is the unit wholesale price,* c *is the unit production cost,* p *is the unit retail selling price, and* v *is the unit salvage value of product leftover at the end of the selling season*."

Following the concept of Pareto optimality, Jornsten et al. (2012) study the real options contract in a supply chain context. The authors show how real options can be used as a means to transfer risk between the upstream supplier and the downstream retailer in the supply chain. They consider the scenario when demand is discrete, and explore the case when the supplier's goal is to design "feasible" real option contracts which can ensure all the supply chain agents can enjoy at least as much expected profit as in the status quo. Most recently, Hong et al. (2012) consider a procurement problem in which both proactive supply (contract supplier) and reactive supply (spot market) are present. In light of these two kinds of supply, the authors evaluate the effectiveness of the optimal procurement plan. They model the dependences among all the potential uncertainties and employ variance of profit as a risk measure to examine the respective level of risk associated with their optimal procurement planning. Other related MV analyses include Gaur and Seshadri (2005), Van Mieghiem (2003, 2007), and Chiu et al. (2012b).

In the scenario with multiple risk-averse retailers, Agrawal and Seshadri (2000) conduct the MV analysis to a two-echelon single-manufacturer multiple risk-averse retailers supply chain. The authors model the MV objective for each risk-averse retailer based on Model 3.1. They examine how a menu of returns contracts can be imposed on the supply chain to coordinate the ordering decisions of the individual retailers in the supply chain. Chen and Seshadri (2005) extend Agrawal and Seshadri (2000) to an optimal control problem in a continuous domain. They assume that there are an infinite number of retailers in the supply chain. They consider the situation when the retailers' coefficients of risk aversion follow a continuous stationary distribution. They analytically show that the distribution of the coefficients of risk aversion is critical in developing the supply chain coordination mechanism. They prove that

Table 3 The classification of multi-echelon MV supply chain models

	Multi-echelon	
	Single retailer	Multiple retailers
MV Model 3.1	Lau and Lau (1999), Tsay (2002), Martinez-de-Albeniz and Simchi-Levi (2006), Buzacott et al. (2011), Chiu et al. (2011a), Hung et al. (2013), Xie et al. (2011)	Agrawal and Seshadri (2000), Chen and Seshadri (2005)
MV Models 3.2a, 3.2b	Choi et al. (2008a, 2008c), Wei and Choi (2010), Choi (2011), Shen et al. (2013)	Chiu et al. (2012a)
MV Model 3.3	Gan et al. (2004, 2005), Jornsten et al. (2012)	Li et al. (2013)

Table 4 The supply chain contracts involved

Type of contracts	Papers
Channel returns (buyback)	Lau and Lau (1999), Tsay (2002), Gan et al. (2004, 2005), Choi et al. (2008a, 2008c), Li et al. (2013)
Markdown money	Tsay (2002), Shen et al. (2013)
Consumer returns	Liu et al. (2012), Choi (2013), Choi et al. (2013)
Channel rebates	Chiu et al. (2011a, 2012a, 2012b)
Options	Buzacott et al. (2011)
Profit sharing	Wei and Choi (2010)
Cost sharing	Choi (2011)
Menu of contracts	Agrawal and Seshadri (2000), Martinez-de-Albeniz and Simchi-Levi (2006), Chiu et al. (2012a)

a menu of returns contracts in a form similar to the one developed by Agrawal and Seshadri (2000) can successfully coordinate the supply chain in their model. Chiu et al. (2012a) study a two-echelon supply chain with one risk neutral supplier (called a brand) which supplies to multiple risk-averse retail buyers. The retail buyers' objective functions follow a format similar to Model 2.3. They find that the supplier can maximize its expected profit only if the expected profit of the entire supply chain is maximized. In other words, based on Definition 3.1, their findings reveal that the supplier optimizes its own profit under the necessary condition that the supply chain is coordinated. They further show that the commonly used target sales rebate (TSR) contract and the related hybrid contracts (TSR with fixed order quantity (TSR-FOQ) contract, and TSR with minimum order quantity and quantity discount (TSR-MQD) contract) will all fail to coordinate the supply chain in the presence of multiple risk-averse retail buyers. They then propose a novel menu of TSR-FOQ contracts, which include two new contract parameters, to coordinate the supply chain. Li et al. (2013) conduct an MV analysis of two-echelon fast fashion supply chains. In one of their models, they consider a fast fashion supply chain with multiple risk averse retailers holding an MV objective in a form similar to Models 3.2a, 3.2b. They argue that a simple returns policy can optimize a multi-retailer supply chain under some specific analytical conditions. A summary of the classification of multi-echelon MV models and the contracts involved are shown in Tables 3 and 4.

4 Supply chains with information updating

In Sects. 2 and 3, we have reviewed the MV analysis on supply chains when demand is uncertain but follows a stationary distribution. In this section, we consider the case in which demand distribution can be revised with the use of market information and hence there is information updating (or also known as forecast updating (see Mishra et al. 2009, and Zhu et al. 2011 for more discussions on supply chain forecast updating)). To the best of our knowledge, the first piece of work which employs an MV approach to studying a supply chain with information updating is Choi et al. (2003) in which an optimal two-stage two-ordering dynamic optimization problem with Bayesian information updating is derived. They utilize the variance of profit as a way to study the level of risk associated with different inventory policies in the supply chain. They find that information updating can reduce the level of risk, and an inventory policy which postpones all the ordering quantity to the stage with the richest amount of information will yield the lowest level of risk. Choi et al. (2004) extend the information updating model considered in Choi et al. (2003) from two stages to N stages (where $N > 2$). However, they consider the scenario in which only one single ordering is allowed in the retail inventory problem. They formulate the problem as a classical optimal-stopping optimization model, and derive the respective optimal stocking policy. They conduct an MV analysis and reveal that the level of operational risk is decreasing with the ordering time point, i.e. ordering later will lead to a smaller level of risk. This point is consistent with the findings in Choi et al. (2003). After that, Choi and Chow (2008) carry out an MV analysis for a quick response supply chain with Bayesian information updating. They first construct formal models which consider the ordering at either one of two stages (the first stage is farther away from the selling season, whereas the second stage is closer to the selling season). They show how various industrial practices such as buyback contract, price commitment practice, service commitment scheme, can be used to yield a Pareto improving supply chain (between the upstream manufacturer and the downstream retailer). Recently, Buzacott et al. (2011) study the options contract in a supply chain in which information updating is allowed. In their influential and award winning paper, they conduct an MV analysis of a class of commitment–option supply contracts. They explore the problem's structural properties and demonstrate how an MV trade-off with information revision can be carried out. They further illustrate how the options contracting mechanism with risk consideration would be different from the risk-neutral case. As a remark, in Buzacott et al. (2011), they consider a specific special case in which at an earlier stage (time point), the decision maker aims at maximizing the expected benefit-to-go of the two-stage dynamic program. While at the later stage (time point) after information updating, the decision maker has an MV objective function so that the risk issue can be incorporated into the model.

5 Future research and extensions

In the previous sections, we have discussed the use of MV approach in conducting supply chain risk analysis. We have also reviewed some representative analytical models. From all the findings and insights generated, there is no doubt that the MV framework is very versatile and useful for exploring supply chain related risk issues. In this section, we discuss several future research directions and probable extensions for the MV analysis in supply chain systems.

5.1 From mean-variance to mean-risk

In the papers reviewed in Sects. 2 to 4, we focus on MV (and mean-semi-variance) models. Obviously, a natural extension is to consider some other mean-risk models such as mean-CVaR model, mean-VaR model, etc. In fact, VaR and CVaR are risk measures originated from financial studies. In the supply chain context, they are employed in many studies such as in the newsvendor problem setting (e.g., Chen et al. 2009; Chahar and Taaffe 2009; Chiu and Choi 2010; Wu et al. 2010; Jammernegg and Kischka 2012), and other single-echelon inventory control problems (e.g., Luciano et al. 2003; Tapiero 2005). Extending the problem from single-echelon to multi-echelon will be an interesting direction for these mean-risk models (such as mean-CVaR models). Some early attempts in this direction include: Risk analysis of a pay to delay capacity reservation contract by Wu et al. (2006), an investigation of the manufacturer's returns policy in a two-echelon supply chain with two risk averse retailers by Hsieh and Lu (2010), an exploration of supply chain rebates contract by Caliskan-Demirag and Chen (2011), and a study on wholesale pricing contract's performance in a two-echelon supply chain with a retailer possessing VaR objective by Chiu et al. (2011b). Furthermore, more realistic constraints, such as service level and loss, can also be incorporated into the supply chain models. For more details, readers are referred to Jammernegg and Kischka (2012) for an excellent review.

5.2 Information asymmetric supply chains

In most of the existing supply chain MV analysis, all the model parameters and the risk sensitivity coefficients are all assumed to be publicly known to every supply chain agent. For example, in a supply chain with a risk averse retailer, the upstream supplier knows the level of risk aversion of the retailer. However, this assumption is difficult to be justified because it is nearly impossible for the upstream supplier to know in practice about the downstream retailer's risk aversion level. As a result, an extension is to consider the information asymmetry issue in which some information of supply chain agents is private. In fact, supply chain management with information asymmetry is a hot topic in recent years. Pioneered by Ha (2001), who considers a single-supplier, single-buyer supply chain under asymmetric cost information and derives a cutoff level policy, a number of studies which examine different facets of information asymmetric supply chains emerge. For instance, Corbett et al. (2004) investigate the value of getting better information about the buyer's cost structure for designing supply contracts under asymmetric information. They explore various cases with different complicated while generic contract types. They generate managerial insights regarding the value of information for each case. Yue et al. (2006) consider a market where customers need to buy two complementary goods in a bundle, and each product is offered by the corresponding separate firm. They develop a Bertrand type gaming model and derive the optimal strategies for the company to make decisions under forecast information asymmetry. Some recent studies on supply chain coordination under information asymmetry include: A study of the contracting and information sharing schemes with supply chain competition by Ha and Tong (2008), an optimal contract design for mixed channels under asymmetry information by Mukhopadhyay et al. (2008), an investigation of a supply chain contracting problem under asymmetric production cost information with adverse selection by Cakanyildirim et al. (2009), a novel proposal of employing a menu of commitment-penalty contracts in a supply chain under asymmetric demand information by Gan et al. (2009), a debate on whether the supply chain agents have full incentive to share real information by Wang et al. (2009) and Wei and Choi (2010), etc. Under the MV framework with information asymmetry, a few research issues can be considered in future research:

1. Moral hazard: In a supply chain in which one agent is the leader and one is the follower. Suppose that the follower is risk averse and has an objective following one of the MV models we have reviewed above. Does the follower have an incentive to tell lies on its own degree of risk-aversion? Or it is more beneficial to tell the truth?
2. In a multi-period supply chain, when one supply chain agent can learn another agent's private information from period to period, how can the MV framework be employed to analyze this supply chain when learning effect is present?

5.3 Supply chain networks

The current literature has only explored the relatively simple supply chains. A natural future research direction is hence to study more general and complicated supply chain "networks". For example, we can explore longer N-echelon supply chains under an MV framework. Research issues on how relative bargaining power, relative degree of risk aversion and location of the supply chain agent affect the supply chain performance and coordination schemes will be promising topics to examine. In addition, we can also study "wider" supply chains, e.g. the supply chains with multiple retailers (Agrawal and Seshadri 2000; Chen and Seshadri 2005; Chiu et al. 2012a; Li et al. 2013). In this case, more versatile supply contracts (e.g. menu of contracts with enough degree of freedom) will be needed in order to achieve coordination. To the best of our knowledge, the analysis with multiple risk-averse suppliers holding MV objectives has not yet been reported in the literature. Despite being complicated, a promising direction for future research is to study a more general supply chain network.

5.4 Multi-period supply chains

Multi-period supply chains are important dynamic systems to examine. At present, most MV analysis in a supply chain context focuses on the single-period supply chain settings. As we have reviewed in Sect. 2, for the single-echelon setting, the multi-period inventory problems have been explored under the MV framework. In fact, under other risk-aversion related models, the literature has reported some findings for inventory policies with risk averse decision maker in a multi-period setting. For example, Chen et al. (2007) pioneer the study with a framework based on the expected utility (exponential) approach to examine inventory control problems with risk averse decision makers in a multi-period setting. Thus, a new research direction is to examine under an MV framework how a multi-period multi-echelon supply chain can be coordinated. This will be much more complicated because of the probable lack of closed form solution even for a single-echelon case.

5.5 Supply chains with boundedly rational agents

The traditional literature on supply chain analytical research commonly assumes that the agents are fully rational. No matter whether the analysis follows the rational expectations framework or the game-theoretical models, the agents will always behave in a way which optimizes their respective objectives. However, it is known that decision makers (both individual and organizational) in the real world are rarely perfectly and fully rational. This is also well supported by laboratory experiments conducted in a control environment. For example, in an influential paper by Su (2008), the newsvendor based supply chain analytical models with a boundedly rational decision maker is studied. He models bounded rationality by the quantal choice model in which the decision makers will not always choose the "best" decision for sure, but will only choose the best one with a higher chance; at the

Table 5 Future extensions and research directions

	Specific areas	Remarks
5.1. From mean-variance to mean-risk	1. Consider multi-echelon supply chain systems with agents possessing mean-risk objectives (such as mean-CVaR, mean-VaR, etc.). 2. Employing other risk measures to analyze stochastic supply chains.	Mean-CVaR models have been examined in various papers but there is still much room for extension.
5.2. Information asymmetric supply chains	1. Information asymmetry on risk sensitivity parameters. 2. MV analysis with information asymmetry between supply chain agents on any other parameters.	Information asymmetry on risk sensitivity parameters is especially important because it is basically impossible to know precisely the risk preference of the supply chain partners.
5.3. Supply chain networks	1. Considering longer and/or widely supply chains. 2. Examining an $N \times M$ supply chain networks (with N echelons and M members per echelon).	MV analysis on simple two-echelon, single member per echelon supply chains is common (2×1 supply chains). Extensions to $N \times M$ supply chains are interesting but analytically challenging.
5.4. Multi-period supply chains	1. Extending from single-period models to multi-period models. 2. Both single-echelon and multi-echelon supply chain systems can be explored further.	The non-separability of variance of profit in the sense of dynamic programming makes some extensions difficult.
5.5. Supply chains with boundedly rational agents	Conducting MV analysis on the supply chains with boundedly rational risk averse agents.	This extension is analytically very complex because the bounded rationality models are difficult to study analytically. Nevertheless, the problem can also be examined by running laboratory behavioral research in a controlled environment.

same time, the decision makers may make some decisions which are not optimal with a non zero chance. Thus, for risk averse supply chain agents, they may also behave as boundedly rational decision makers. It will be interesting to examine how well a supply chain with boundedly rational risk averse (with MV objectives) agents performs under different situations. The applications of all kinds of supply chain coordination mechanisms such as supply contracts can also be examined. Table 5 shows a summary of the proposed future research and extensions.

6 Conclusion

We have conducted an extensive literature review on the applications of Markowitz's MV framework in analytical supply chain management research. By classifying the vast literature into three major areas, namely, single-echelon problems, multi-echelon supply chain problems, and supply chains with information updates, we have reviewed some important specific analytical models and derived insights into the current state of knowledge in each area. After that, we have proposed new research directions in several domains, which include (i) the extension from MV to other mean-risk models such as mean-VaR and mean-CVaR models, (ii) the MV analysis for information asymmetric supply chains, (iii) the MV study of more general supply chains such as a bigger supply chain network, (iv) the investigation of multi-period supply chains under the MV framework, and (v) the study of the case when supply chain agents are risk averse and boundedly rational. To the best of our knowledge, this paper is the first one in the supply chain management literature which presents a comprehensive technical literature review, with detailed discussions on specific analytical models, on Markowitz's MV framework related supply chain models. We believe that this paper provides up-to-date information which can help both academicians and practitioners to better understand the development and future research directions of MV supply chain models for conducting risk analysis.

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