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A joint inventory–finance model for coordinating a capital-constrained supply chain with financing limitations

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Abstract

Faced with economic recession, firms struggle to find ways to stay competitive and maintain market share. Effective coordination of the supply chain can solve this problem, but this may fail if existing capital constraints and financial flows are ignored. This study addresses the challenge by exploiting coordination through joint decision-making on the physical and financial flows of a capital-constrained supply chain. We also consider the capital-constrained member's financing limitations that lead to lost sales. Two scenarios based on non-coordinated and coordinated structures are modeled in the form of bi-objective optimization problems that simultaneously optimize system costs and service levels. The models are solved using the ε-constraint method. The results indicate that the non-coordinated model cannot satisfy more than about 50% of the demand due to capital shortage and financing limitations, while the coordinated model can satisfy all of the demand via internal financing. Furthermore, the proposed coordination scheme leads to cost reduction for the members and the total system. To motivate all members to accept the proposed coordination scheme, a cost-sharing mechanism is applied to the coordination procedure. Finally, a sensitivity analysis concerning financial parameters is provided for validating the coordination model.

Keywords: Supply chain coordination, Inventory–finance model, Capital shortage, Financing limitation, Service level, Bi-objective optimization

Introduction

Supply chain management involves coordination and cooperation among several business partners linked through flows of material, money, and information. These partners include suppliers of raw materials and basic components, manufacturers, wholesalers, distributors, transporters, retailers, banks, and financial institutes. Two key factors ensure the proper functioning of a supply chain: first is coordination between supply chain members, and second is integration of the said three flows. This study addresses both factors for enhancing supply chain profitability and effectiveness.

Supply chain coordination involves collaborative work—joint planning, joint product development, mutual information exchange, integrated information systems, cross coordination on several levels of the companies in the network, long-term cooperation, and fair sharing of risks and benefits (Skjoett-Larsen 2000). In a supply chain with a decentralized structure, each member independently optimizes its own operational and financial decisions without considering their effects on other members. Hence, a decision that is optimal for a member may cause additional costs for other members, which leads to inefficiencies in the processes of supplying, producing, distributing, and delivering goods to customers, and consequently, poor service. However, in a coordinated supply chain, all members operate to optimize the whole supply chain, leading to an increase in profitability and customer satisfaction in the supply chain.

To have an effective supply chain, proper management of upstream financial flows is as important as that of downstream physical flows (Gupta and Dutta 2011). The supply chain management literature has focused mainly on material and information flows, and financial flows have been ignored despite its great importance and inevitable effects on the physical flows (Naimi Sadigh et al. 2013; Sadeghi Rad et al. 2018; Sadeghi Rad and Nahavandi 2018). This literature stream assumes that a firm can always finance its operations at an optimal level or borrow at a constant interest rate. When financial markets are efficient, that is, external funding is plentiful and relatively inexpensive, firms have sufficient funds for daily operations, and financial and operational decisions can be made separately (Modigliani and Miller 1958). In such cases, a downstream entity in the supply chain pays the inventory ordered from an upstream entity. Consequently, financial flows become an output of logistics decisions (Luo and Shang 2015). However, capital shortage becomes a bottleneck, especially for small and medium enterprises. Financial activities complement the physical flow of materials and ensure funding of logistics operations. Thus, integrating operational and financial decisions may ensure proper implementation of operations in practice.

This study addresses both of these important issues—supply chain coordination and the integration of operational and financial decisions.

We consider an original equipment manufacturer (OEM) that faces a capital shortage and financing limitations. Specifically, financial institutions limit the OEM's financing amount for reasons such as low credit. Because of this limitation on external financing, the OEM cannot obtain as much financing as it requires to support its operations. Therefore, it cannot satisfy a portion of the demand and thus, face lost sales (lost sales refer to selling opportunities that a firm has lost because an item was out of stock). The OEM operates in a supply chain with multiple suppliers of raw materials and components (upstream members), and an auto manufacturer (downstream member). The financial problems of the OEM affect all members in the supply chain and may lead in the loss of a portion of the market share of the supply chain's final products. Thus, coordination among all members to solve the OEM's financial problems is prudent so as to improve the supply chain's performance. To understand better the proposed coordination mechanism, two scenarios are formulated: a non-coordinated supply chain (or decentralized supply chain) and a coordinated supply chain. The advantages of the second scenario for all supply chain members are illustrated using an example from a supply chain in the automotive industry.

The automotive industry is one of the world's most important economic sectors in terms of revenue and employment, and any kind of disruption in the production and profitability of a key member can be detrimental to the whole industry. Therefore, it is necessary to investigate issues such as the financial challenges and coordination of operational and financial decisions in this industry. The OEMs in automotive supply chains commonly try to establish long-term relationships with their suppliers and/or customers. Proper coordination mechanisms that align the parties' objectives can help build such relationships. This study finds ways to build these relationships in light of an OEM's financial constraints (capital shortage and financing limitations). Nevertheless, the proposed coordination mechanism can be adopted by any manufacturing business that faces such financial challenges.

This study looks for effective ways to solve the financial problems of a supply chain and improve its performance through coordination of all members in light of a difficult financial situation. To this end, this study proposes a bi-objective nonlinear optimization model that minimizes system-wide costs (including operational and financial costs) and maximizes the satisfied demand, which is equal to the optimal customer service level.

In the supply chain coordination literature, it is a novel idea to consider financing limitations (which is a real-world problem for capital-constrained firms) and the consequent lost sales. Moreover, we believe that our study is the first to address supply chain coordination together with financing issues for maximizing service level and minimizing operational and financing costs.

The rest of this paper is organized as follows. Section "Literature review" provides a brief review of the related literature. Section "Model description and solution approach" presents the proposed model, including the model's assumptions and notations, and the mathematical formulations of scenarios 1 and 2. Section "Numerical analysis" discusses the numerical results, along with a cost-sharing mechanism and sensitivity analysis of the financial parameters. Section "Conclusion" presents the conclusion and suggestions for further research.

Literature review

Our study relates to two literature streams: *supply chain coordination* and *integration of the physical and financial flows of a supply chain* (also known as *operations–finance interface*).

Supply chain coordination (SCC)

Coordination mechanisms in supply chains are generally based on centralized and decentralized decision-making processes (Jaber and Osman 2006). In a centralized decision-making process, a unique decision maker manages the whole supply chain, with the main objectives of minimizing (maximizing) the total supply chain cost (profit). By contrast, in a decentralized decision-making process with multiple decision-makers, each member focuses on its own objectives. Li and Wang (2007) conducted a review of coordination mechanisms of supply chain systems in a framework that is based on the supply chain's decision structure (centralized or decentralized) and the nature of demand (deterministic or stochastic).

Abundant research exists regarding the coordination between supply chain members. Several review papers have focused on various aspects of supply chain coordination (Fugate et al. 2006; Li and Wang 2007; Arshinder et al. 2008, 2011; Govindan et al. 2013). Accordingly, various classifications of coordination mechanisms exist in the literature.

Arshinder et al. (2008), in their review of the literature, grouped coordination mechanisms into four categories: supply chain contracts, information technology, information sharing, and joint decision-making. As major categories of coordination mechanisms, Sahin and Robinson (2002) proposed price, non-price, buy-back and returns policies, quantity flexibility, and allocation rules. Subsequently, Fugate et al. (2006) adapted their classification into three major categories: price, non-price, and flow coordination mechanisms. Bernstein and Federgruen (2007) showed the types of coordination mechanisms that allow a decentralized supply chain to generate aggregated expected profits equal to the optimal profits in a centralized system, and how the parameters of these (perfect) coordination schemes can be determined.

One common coordination mechanism is coordinating contracts, which are formulated using game theory in a decentralized structure. This stream of SCC literature uses some incentives in the form of contracts to achieve coordination among supply chain members. Some of these incentives include buy-back contracts (Padmanabhan and Png 1997; Hou et al. 2010; Shen and Zhang 2012; Tibrewala et al. 2018), revenue sharing contract (Giannoccaro and Pontrandolfo 2004; Cachon and Lariviere 2005), service level-based contracts (Sieke et al. 2012), discount policy (Xu et al. 2018a; Nouri et al. 2018), credit period (delay in payment) (Ebrahimi et al. 2019), bi-level credit period (Johari et al. 2018). The readers may refer to Cachon (2003) for comprehensive information about the structure of coordinating contracts.

Some researchers have shown that coordination can be achieved by integrating lot-sizing models (Goyal and Gupta 1989). Joint economic lot size models are especially useful planning tools in situations where companies have established long-term relationships with their suppliers or customers, which is common in the automotive industry (Glock 2012). Glock (2012) focused on coordinating inventory replenishment decisions between buyer and vendor and their impact on the performance of the supply chain. He reviewed joint economic lot size models aimed at minimizing total system costs. Some of the first studies on the coordination of inventory replenishment and production decisions between supply chain members include Goyal (1977), Goyal and Gupta (1989), and Goyal et al. (2003). Sarmah et al. (2006) classified buyer–vendor coordination models that use quantity discount as a coordination mechanism under a deterministic environment. In a recent study, AlDurgam et al. (2017) considered a single-vendor, single-manufacturer joint economic lot size problem under demand uncertainty. They developed an integrated mathematical model that investigates the impact of a variable production rate on the system. In most of these works, coordination is achieved through joint consideration of the system-wide costs. This coordination scheme is based on a centralized decision-making process. Some other works that adopted coordination by joint consideration of system-wide costs include Chen and Chen (2005), Jaber and Osman (2006), Chiadamrong et al. (2007), Jayaraman and Pirkul (2001), Kim et al. (2005), and Moussawi-Haidar et al. (2014). In this study, coordination among members is adopted through this coordination scheme.

Operations–finance interface

Supply chain management literature mostly focuses on the flow of goods and services without considering the effects of capital shortage and financial flows on operations management. Researchers in this field assume that there is always adequate working capital to supply the required inventory. However, operational decisions are constrained by limited working capital and often critically depend on external financing (Xu and Birge 2006). These constraints influence supply decisions. Nevertheless, the interaction of physical and financial flows has been ignored by many researchers in the field of operations management. The interface of finance, operations, and risk management is a relatively new research area, which deals with timely, complex, and boundary-spanning issues in a variety of settings from startups to global enterprises (Babich and Kouvelis 2018). Zhao and Huchzermeier (2015) identified three types of interdependence between operations management and corporate finance in their review of the operations–finance models: (i) financial constraints on operations, (ii) correlation between operational and financial risks, and (iii) alternative risk mitigation. Financial risks arise when there are uncertainties related to any form of financing, including credit, business, investment, and operational risks (Kou et al. 2014).

There is no specific framework for the works on the operation–finance interface in the literature. However, some classifications of existing works on supply chain finance (SCF) can be found in the review papers of Gelsomino et al. (2016) and Xu et al. (2018b).

To address the financial flows of the supply chain, some works in this field have focused on the management of accounts payables/receivables of a firm in the supply chain. Gupta et al. (1987) and Gupta and Dutta (2011) extended the application of scheduling theory to the financial decisions of the supply chain. Longinidis and Georgiadis (2011) proposed a mixed integer linear programming model that integrates financial issues with a supply chain design under stochastic demand. Jahangiri and Cecelja (2014) developed a stochastic model to maximize the profit of a firm and find the optimal strategy for paying its accounts payables. Luo and Shang (2015) studied a centralized two-division supply chain and integrated inventory decisions and cash management in the mentioned supply chain. Miloudi et al. (2016) proposed a model to optimize the working capital of a firm in a three-level supply chain by scheduling its accounts payables and receivables.

Some researchers have considered capital shortage and financing decisions. In this group, two financing methods have been proposed: (1) external financing and (2) internal financing. In the first method, the capital-constrained member gets direct financing from financial institutions such as banks (Xu and Birge 2006; Guillén et al. 2007). We note that any kind of financing from a source outside the supply chain can be considered as external financing such as bank financing, peer-to-peer lending, and so on (Interested readers are referred to Wang et al. (2020) for further information regarding peer-to-peer lending and the associated credit ratings.). The second method deals with financing from other members of the supply chain through various options such as trade credit (Jaber and Osman 2006; Lee and Rhee 2011; Lee et al. 2018).

Trade credit refers to a seller's short-term loan to a buyer, allowing the buyer to delay payment of an invoice; this has been the largest source of working capital for a majority of business-to-business firms in the United States (Lee and Rhee 2011). Aggarwal and Jaggi (1995) developed a mathematical economic order quantity model for perishable goods using delayed payments. Teng (2009) established an economic order quantity (EOQ)-based model for a retailer who receives full trade credit from its supplier and offers full or partial trade credit to its good or bad customers, respectively. Using delayed payments, Moussawi-Haidar and Jaber (2013) developed a joint model for cash and inventory management for a retailer. Taleizadeh et al. (2016) proposed an economic production quantity model (with defective items and rework processes) that considers both upstream and downstream trade credit. Yang and Birge (2018) adopted a trade credit contract as a risk-sharing mechanism for a two-level supply chain with limited working capital. Babich and Kouvelis (2018) discussed recent contributions and future directions on the interface of finance, operations, and risk management. Kouvelis and Zhao (2018) studied the impact of credit ratings on operational and financial decisions of a supply chain with a supplier and a retailer interacting via an early payment discount contract. Tang et al. (2018) compared two schemes—purchase order financing and buyer direct financing—for financing a capital-constrained supplier. Shin et al. (2018) found it beneficial to choose a trade-credit-financing policy in a centralized two-echelon supply chain model with imperfect quality items. They did not consider budget constraints in their study. Li et al. (2019) optimized dynamic credit term decisions, along with inventory production decisions in a two-level supply chain. They ignored financial constraints in their study as well. Mashud et al. (2019) extended the EOQ inventory model for deteriorating items with price-dependent demand under a two-level trade credit policy. In their study, budget constraints and external financing were not addressed. Krommyda et al. (2019) explored some effects of the global financial crisis on inventory management decisions within the general EOQ that has a partial backorder paradigm. In this study, an EOQ inventory policy is used to manage inventories in the whole supply chain. An EOQ inventory policy has many applications in real-world problems. (See e.g. Khalilpourazari and Pasandideh 2019; Khalilpourazari et al. 2019a, b, and Khalilpourazari et al. 2019b for more information about the application of an EOQ policy in different problems.) Pramanik and Maiti (2019) considered the time value of money and inflation in an inventory model with two-level partial trade credit. They did not consider financial problems such as budget shortage and limitations in financing. Chakuu et al. (2020) conducted an empirical study to explore the conditions in which logistic service providers offer inventory financing as an SCF service. Yan et al. (2020a, b) examined two financing strategies—loan and investment—for the financing of a capital-constrained supplier by a risk-averse retailer. In another study, Yan et al. (2020b) analyzed the pricing competition in a dual-channel supply chain consisting of one e-retailer that provides financing to a capital-constrained supplier. Huang et al. (2020) compared trade credit financing (TCF), credit guarantee financing, and buy-back guarantee financing as three types of SCF modes. They provided managerial insights for the application of these financing modes.

Combining supply chain coordination and operations–finance interface

A few studies in the literature have considered the coordination of supply chain members together with the integration of financial and operational decisions. Jaber and Osman (2006) proposed a centralized model where players in a two-level (supplier–retailer) supply chain coordinate their orders to minimize supply chain costs. In their model, permissible delay in payment was considered a decision variable and was adopted as a trade credit scenario to coordinate the order quantity between the two levels. They did not address budget constraints for members in their study. Dada and Hu (2008) applied a nonlinear loan schedule to coordinate the decisions of a profit-maximizing bank and a capital-constrained retailer. Yin and Xu (2010) proposed a two-level supply chain with delay in payments and inventory-in-pawn financing policy to minimize supply chain costs by coordinating material and capital flows. Lee and Rhee (2011) studied trade credit from a supplier's perspective and presented it as a tool for supply chain coordination. Chen and Wang (2012) studied the interactions between a capital-constrained retailer and its supplier under TCF. They found that trade credit can create value in a capital-constrained supply chain and partly achieve coordination. Moussawi-Haidar et al. (2014) coordinated a three-level supply chain consisting of a capital-constrained supplier, a retailer, and a financial intermediary (bank) by considering operational and financial decisions. Kouvelis and Zhao (2016) addressed two coordinating contracts (revenue sharing and buy-back contracts) in the presence of capital constraint and default risk. Feng et al. (2015) developed a revenue-sharing-and-buy-back contract to coordinate a capital-constrained supply chain. Yan et al. (2016) proposed a partial credit guarantee contract for SCF and analyzed coordination conditions for this contract. Xiao et al. (2017) designed a generalized revenue sharing contract to coordinate a supply chain with financial constraints. Johari et al. (2018) proposed a bi-level credit period (delay in payment) for a periodic review inventory system that coordinates the inventory and pricing decisions of a two-level supply chain. Ebrahimi et al. (2019) used the delay in payment contract as an incentive to coordinate a supply chain with stochastic, promotional-effort-dependent demand. Devalkar and Krishnan (2019) examined the use of trade credit in decreasing moral hazard and adopting supply chain coordination in the presence of information asymmetry and financial friction. Ding and Wan (2020) studied supply chain coordination in the presence of capital constraints and production yield uncertainty. In contrast to our research, in their study, the upstream member (supplier) is capital-constrained and needs financing from the downstream member (manufacturer).

Literature that simultaneously considers operational and financial decisions is novel, and many assumptions about the real world have not yet been considered. For example, some works have not addressed budget shortage and financing options. The primary purpose has only been to improve supply chain performance by integrating physical and financial flows. Meanwhile, other works that have considered budget constraints and financing decisions have ignored the limitation on the amount of borrowing. However, in real-world situations, some firms cannot borrow an unlimited amount of cash from financial institutions, thereby leading to lost sales due to insufficient working capital for supporting the operations.

In this study, we address both of these important issues: coordination of inventory replenishment and production decisions among all members, and the integration of operational and financial decisions. Specifically, a coordination scheme based on joint decision-making on inventory replenishment, production decisions, and financial decisions is applied to a capital-constrained supply chain with financing limitations in the automotive industry. This coordination mechanism integrates the operational and financial decisions of all members and prevents lost sales. For a better understanding of the coordination model, two scenarios are formulated: i) a non-coordinated supply chain used as a basis for the coordinated model and ii) a coordinated supply chain.

The advantages of the coordinated model for all members are illustrated by solving the model using data from a supply chain in the automotive industry.

Table 1 compares previous literature against the current paper, with the contributions of this study shown in bold and italic font. Our study, with some differences, is most related to Jaber and Osman (2006) and Moussawi-Haidar et al. (2014), which adopted the centralized decision-making process as a scheme for coordination (joint consideration of system-wide costs) in their supply chain models. They considered both inventory and financial decisions in their coordination schemes. Jaber and Osman (2006) did not consider budget constraints and external financing in their study. They applied coordination and integration of operations and finance to improve supply chain profitability. Moussawi-Haidar et al. (2014) addressed budget constraints, but they assumed that the firms could borrow an unlimited amount of cash. Moreover, internal financing in their study was limited to the trade credit granted by the supplier. We consider a three-level supply chain with multiple suppliers and multiple products. The OEM is capital constrained and faces financing limitations, leading to lost sales. To solve these difficulties, in addition to external financing, the OEM can use (1) trade credit granted by the suppliers and (2) prepayment of the auto manufacturer where needed, as two sources of internal financing in the coordination scheme proposed here.

This work contributes to the existing literature in the following ways:

- We consider financing limitations in addition to budget constraints, highlighting that there is a maximum limit on borrowing from financial institutions, which means limited financing capacity. Furthermore, we consider lost sales as a consequence of financing limitations. Previous related works used a capital-constrained firm financed from an unlimited external source, and the shortage of financing was not considered.
- In the current study, the prepayment of the downstream partner is suggested as an internal source of financing, in addition to TCF. This option leads to new decision-making regarding different financing options (loan and prepayment of the downstream partner), specifically, which option to choose and how much to finance from each source. As such, the loan amount is a decision variable in this study, whereas in previous works, the loan amount is equal to the production or inventory costs minus initial capital.
- We consider the service level to the customers as a decision variable of the coordinated supply chain. Moreover, we formulate the problem as a bi-objective optimization problem, where both the costs and the satisfied demand are optimized. To the best of our knowledge, considering this issue is novel in the related literature.
- We model a real-world supply chain in the automotive industry that has three levels and multiple products, while most previous works have been limited to the relationships in a single buyer–single vendor with a single product scenario.

Model description and solution approach

In this section, the proposed model and solution approach are explained in detail based on two scenarios. First is the decentralized non-coordinated structure, in which each member tries to optimize its own objectives. We show that under this setting, the supply chain performance is not satisfactory, and lost sales are inevitable. To improve the

Table 1 Comparison of the proposed model and the literature on incorporating SCC and operations-finance interface

References	Inventory policy	Supply chain (SC) structure	Operations decisions	Coordination mechanism	Financial constraints	Product shortage	Financing options	Financial decisions	Objective function
Jaber and Osman (2006)	EOQ	Two-level SC: a supplier, a retailer Single product	Retailer's and supplier's order quantities	Joint decision making (centralized decision making)	No financial constraint	Not allowed	TCF	Retailer's payment time to the supplier Due date of the interest-free period	Minimizing system costs
Yin and Xu (2010)	EOQ	Two-level SC: a supplier, a retailer Single product	Retailer's order quantity	Joint decision making (centralized decision making)	Budget shortage	Not allowed	TCF External financing	Retailer's payment time to the supplier Due date of the interest-free period Financing mode selection	Minimizing system costs
Dada and Hu (2008)	Newsvendor	Two-level SC: a supplier, a retailer Single product	Retailer's order quantity	Nonlinear loan schedule	Budget shortage	Not allowed	External financing	Bank's interest rate	Profit maximization (Stackelberg game)
Lee and Rhee (2011)	Newsvendor	Two-level SC: a supplier, a retailer Single product	Retailer's order quantity Wholesale price Contracts' parameters	All-unit quantity discount Buy-back contract Two-part tariff Revenue sharing contract	Budget shortage	Not allowed	TCF External financing	Trade credit interest rate Financing mode selection	Profit maximization (Stackelberg game)
Chen and Wang (2012)	Newsvendor	Two-level SC: a supplier, a retailer Single product	Retailer's order quantity Wholesale price	Delay in payment contract	Budget shortage	Not allowed	TCF	No financial decision	Profit maximization (Stackelberg game)
Moussawi-Haidar et al. (2014)	EOQ	Three-level supply chain: a supplier, a retailer, and a bank Single product	Retailer's order quantity	Joint decision making (centralized decision making)	Budget shortage	Not allowed	TCF External financing	Retailer's payment time Cash balance Financing mode selection	Minimizing system costs
Kouvelis and Zhao (2016)	Newsvendor	Two-level SC: a supplier, a retailer Single product	Retailer's order quantity Contract's parameters	Revenue sharing contract	Budget shortage	Not allowed	External financing	Bank's interest rate	Profit maximization (Stackelberg game)
Feng et al. (2015)	Newsvendor	Two-level SC: a supplier, a retailer Single product	Retailer's order quantity Contract's parameters	Revenue-sharing-and-buy-back contract (RSBB)	Budget shortage	Not allowed	No financing option	No financial decision	Profit maximization (Stackelberg game)

Table 1 (continued)

References	Inventory policy	Supply chain (SC) structure	Operations decisions	Coordination mechanism	Financial constraints	Product shortage	Financing options	Financial decisions	Objective function
Yan et al. (2016)	Newsvendor	Two-level SC: a supplier, a retailer Single product	Retailer's order quantity The wholesale price	Partial credit guarantee (PCG) contract	Budget shortage	Not allowed	TCF Bank credit financing	Bank's interest rate	Profit maximization (Stackelberg game)
Xiao et al. (2017)	Newsvendor	Two-level SC: a supplier, a retailer Single product	Retailer's order quantity Contract's parameters	Generalized revenue sharing contract	Budget shortage	Not allowed	TCF External financing	Trade credit interest rate	Profit maximization (Stackelberg game)
Johari et al. (2018)	Stochastic	Three-level SC: a supplier, a retailer, and a customer Single product	Review period Order-up-to-level Retail price	Bi-level credit period contract	No financial constraint	Back-ordered	TCF	Credit period as the contract parameter	Profit maximization
Ebrahimi et al. (2019)	Stochastic	Two-level SC: a supplier, a retailer Single product	Review period Retailer's promotional effort level The safety factor of the retailer replenishment decision	Delay in payment contract	No financial constraint	Partially Back-ordered	TCF	Credit period as the contract parameter	Profit maximization
Devalkar and Krishnan (2019)	Deterministic multi-period	Two-level SC: a supplier, a retailer Single product	Wholesale price	Delay in payment and reverse factoring contract	Financial market frictions (information asymmetry)	Not allowed	TCF External financing	Credit period The portion of early payment receivables	Profit maximization
Ding and Wan (2020)	Newsvendor	Two-level SC: a supplier, a manufacturer Single product	Manufacturer's order quantity Supplier's production quantity	Buy-back contract Cost-sharing contract	Budget shortage	Not allowed	External financing Advance payment	Bank's interest rate	profit maximization (Stackelberg game)
The proposed model	EOQ	Three-level SC: multiple suppliers, an OEM, and an auto manufacturer *Multi-product*	Order quantities of the OEM and each supplier The OEM's production quantity *Service level*	Joint decision making (centralized decision making)	Budget shortage *Financing limitation*	*Lost sales*	TCF External financing Pre-payment	Financing mode selection *Debt amount* Payment time to suppliers Due dates of the interest-free periods *Prepayment rate of the auto manufacturer*	*Two objectives:* Minimizing system costs *Maximizing the satisfied demand* *(bi-objective optimization)*

supply chain performance, a second scenario is proposed in which all members operate in a way that optimizes the financial and operational decisions of the entire system by adopting a coordination scheme. In the end, we apply a cost-sharing mechanism for sharing the benefits of coordination among all members. This can be a motivation tool for all members to accept the proposed coordination scheme.

Assumptions and notations

We consider a three-level multi-product supply chain in the automotive industry. Figure 1 shows the structure of the mentioned supply chain. This supply chain includes several suppliers of raw materials and the components of automobile original parts, a capital-constrained OEM that manufactures original parts of automobiles (powertrain components including engines, gearboxes, and axles), and an auto manufacturer.

In the said supply chain, the necessary components and materials (shown by index k) are shipped from outside sources to the suppliers $(S_1, S_2, \ldots, S_K)$. These components are purchased by the OEM to produce the original parts of automobiles (shown by index n) according to the deterministic demand of the auto manufacturer. Afterward, these original parts are shipped to the auto manufacturer for assembling and producing final products (shown by index j). All of these activities take place continuously during the planning horizon (T).

The auto manufacturer has a predetermined production capacity for each final product j, which can be considered as the deterministic demand (shown by D_j) in the specified planning horizon (T). The OEM manufactures original parts of the final products (shown by index n) according to the auto manufacturer's demand. The demand for the original parts manufactured by the OEM (D_n) can be calculated simply according to D_j, that is, $D_n = \sum_j m_{jn} D_j$, where m_{jn} represents the quantity of part n needed for producing each unit of product j. The ordering and replenishment of required components and materials by the OEM take place in multiple periods during the planning horizon. Note that each component k is purchased from one supplier (S_k).

The OEM faces liquidity constraints and limitations in short-term financing, leading to lost sales and consequently, an unsatisfactory service level. In this study, we define service level as the satisfied demand of original parts divided by the total demand of original parts, which is shown by α_n ($\alpha_n = \frac{\textit{Satisfied demand of part } n}{\textit{Total demand of part } n}$). It is a decision variable for the proposed model.

The inventory policy adopted in the proposed problem is based on the EOQ inventory policy, with some different and additional assumptions. Table 2 provides a comparison between the classical EOQ assumptions and the assumptions of the proposed model.

The notations of the mathematical formulation are given in Table 3.

The mathematical formulation of the non-coordinated supply chain

In this section, we model the decentralized non-coordinated supply chain in which each member optimizes its own problem without considering other members' costs and benefits. As such, three models are discussed, namely, the OEM's, the suppliers', and the auto manufacturer's models.

The OEM's model

As previously mentioned the OEM is faced with capital shortage and financing limitations. Since the OEM does not have sufficient initial budget to carry out its operations and the amount of external financing is limited, it might not be able to satisfy all of the auto manufacturer's demand, which leads to lost sales. In this case, the OEM should decide on the fraction of satisfied demand for original parts (α_n) while minimizing cost. To deal with this situation, we propose a bi-objective model that simultaneously minimizes the operational–financial costs of the OEM (Π_{OEM}) and maximizes satisfied demand of the original parts ($\sum_n \alpha_n D_n$).

The first objective function includes inventory replenishment costs (ordering, purchasing, and inventory carrying costs), fixed and variable production costs, and the cost of capital for borrowing the required capital. Inventory carrying cost or holding cost is the opportunity cost of the capital tied up in the inventories plus other costs (storage, obsolescence, damage, deterioration, insurance, etc.). Therefore, in this study, the parameter h_k only represents the "cost of capital," and s_k represents the "other costs," which we refer to as the storage cost of component k for the OEM.

Lemma 1 *The opportunity cost of the capital tied up in the inventories is calculated as follows*:

$$H(k) = h_k \frac{\left((Q_k - t_k D_k)^+\right)^2}{2D_k}, \text{where} \quad (x)^+ = \max(x, 0) \text{ and } k = 1, 2, \ldots, K. \tag{1}$$

Proof See "Appendix 1".

The OEM replenishes its inventory from suppliers in the shipments of size Q_k every $T_{OEM_k} = Q_k / D_k$ units of time where $D_k = \left(\sum_n N_{nk} \alpha_n D_n\right)$. We model the OEM's problem as a bi-objective optimization problem that minimizes the total costs of inventories, production, and finance per unit time, and maximizes the satisfied demand:

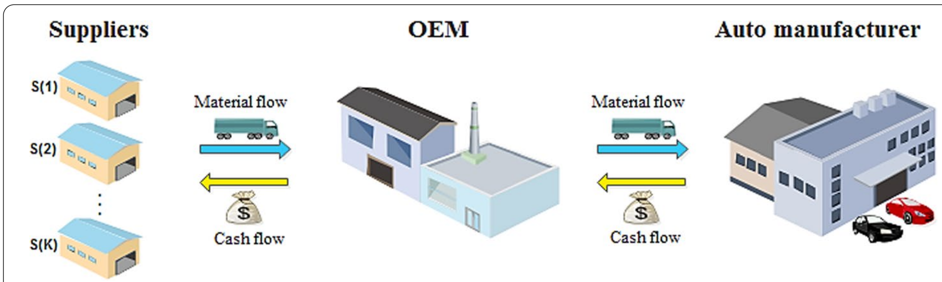

Fig. 1 The structure of the supply chain considered in this study

$$\min TC_{OEM} = \sum_k A_k \frac{\sum_n N_{nk}\alpha_n D_n}{Q_k} + \sum_k w_k * \left(\sum_n N_{nk}\alpha_n D_n\right) + \sum_k s_k \frac{Q_k}{2} + \sum_k H(k) \frac{\sum_n N_{nk}\alpha_n D_n}{Q_k} + \sum_n (F_n + v_n\alpha_n D_n) + Dbt\left((1+i)^T - 1\right) \tag{2}$$

$$\text{Max}\omega = \sum_n \alpha_n D_n \tag{3}$$

$$\text{s.t} \quad Dbt \le M \tag{4}$$

$$\sum_k w_k * \left(\sum_n N_{nk}\alpha_n D_n\right) + \sum_n (F_n + v_n\alpha_n D_n) + \sum_k s_k \frac{Q_k}{2} + \sum_k A_k \frac{\sum_n N_{nk}\alpha_n D_n}{Q_k} \le B + Dbt \tag{5}$$

$$B + Dbt + \sum_n p_n\alpha_n D_n - \sum_k w_k * \left(\sum_n N_{nk}\alpha_n D_n\right) - \sum_n (F_n + v_n\alpha_n D_n) - \sum_k s_k \frac{Q_k}{2} - \sum_k A_k \frac{\sum_n N_{nk}\alpha_n D_n}{Q_k} - Dbt(1+i)^T \ge L \tag{6}$$

The first objective (2) is to minimize the OEM's total costs, which include ordering cost (first term), purchasing cost (second term), storage cost (third term), the opportunity cost of the capital tied up in inventories (fourth term), fixed and variable production costs (fifth term), and loan repayment at the end of the time horizon (sixth term). The first constraint (4) represents the limitation of external financing (debt). The second (5), demonstrates the OEM's budget constraint, and the third constraint (6) implies that the amount of cash by the end of the time horizon should not be less than the lower limit (L) determined by the manager.

Table 2 Comparison between EOQ policy and inventory policy of the current paper

Characteristics	This paper's inventory policy	Classical EOQ policy
Demand	Constant	Constant
Lead time	No lead time	No lead time
Products	Multiple products	Single product
Capacity	Limited budget Limited financing capacity	No limit
Service	Lost sales are allowed	Product shortage is not allowed
The unit cost of inventory	Variable (in the coordinated scenario, the unit cost of inventory is determined according to the trade credit terms)	Constant
Time of payment	Variable from the time of product delivery to a maximum allowed limit	At the time of product delivery

Table 3 Summary of notations

Indices	
j	Index of final products at the auto manufacturer (j = 1, 2, …, J)
n	Index of OEM's products (n = 1, 2, …, N)
k	Index of components purchased from supplier S_k by the OEM (k = 1, 2, …, K)
Parameters related to the suppliers' decisions	
S_k	The supplier of component k for the OEM
D_k	Demand for component k
T_{S_k}	Cycle time of replenishment for supplier k
s'_k	The unit storage cost of component k for supplier S_k
h'_k	The unit holding cost of component k for supplier S_k, representing the cost of capital, excluding the storage cost
A'_k	The fixed ordering cost of component k by supplier S_k
c_k	The unit cost of component k purchased from external sources by the supply chain suppliers
r_k	Rate of return for supplier S_k
Parameters related to the OEM's decisions	
D_n	Demand for part n
T_{OEM_k}	Cycle time of replenishment for OEM
F_n	Fixed cost of producing part n at the OEM
v_n	Variable production cost for each unit of part n at the OEM
p_n	The unit price of part n produced by the OEM
w_k	The unit cost of component k purchased from suppliers in the supply chain by the OEM
N_{nk}	The quantity of component k needed for producing each unit of part n
s_k	The unit storage cost of component k for the OEM
h_k	The unit holding cost of component k for the OEM, representing the cost of capital, excluding the storage cost
H_k	The opportunity cost of the capital tied up in the inventories
A_k	The fixed ordering cost of component k by the OEM
r_{OEM}	Rate of return (ROR) for the OEM
i	The interest rate of external financing
γ_k	Penalty rate for the delay in payment to supplier S_k
$tmax_k$	Maximum deadline for payment to supplier S_k
M	Maximum limit for external financing (Debt)
B	Initial budget
L	Minimum cash level at the OEM, determined by the manager
Parameters related to the auto manufacturer's decisions	
D_j	Total demand for final product j
m_{jn}	The quantity of part n needed for producing each unit of final product j
p_j	The unit price of product j produced by the auto manufacturer
r_{AM}	Rate of return for the auto manufacturer
Decision variables	
OEM	
Q_k	Order quantity for component k ordered by the OEM to the supplier S_k
α_n	The service level of original part n

Table 3 (continued)

t_k	The OEM's payment time to supplier S_k
Dbt	The required amount of external financing for the OEM
Suppliers	
d_k	The due date of the interest-free period
λ_k	The coefficient of replenishment for supplier S_k
Auto manufacturer	
β	The prepayment rate of the auto manufacturer

The suppliers' model

Each supplier supplies one component for the OEM. They replenish their inventory from outside vendors in the shipments of size $\lambda_k Q_k$ every $T_{S_k} = \lambda_k Q_k / D_k$ units of time where $D_k = \left(\sum_n N_{nk}\alpha_n D_n\right)$ and $\lambda_k = 1, 2, \ldots$ and deliver Q_k to the OEM every $T_{OEM_k} = Q_k / D_k$ units of time (Fig. 2). Note that if $\lambda_k = 1$, the suppliers follow the lot-for-lot policy. Figure 2 shows the inventory levels of each supplier and the OEM. According to Fig. 2, the average of each supplier's inventory per cycle can be calculated as the area under the inventory level, that is, $(\lambda_k - 1)Q_k T_{OEM_k} + (\lambda_k - 2)Q_k T_{OEM_k} + \cdots + Q_k T_{OEM_k} = Q_k T_{OEM_k} \sum_{i=1}^{\lambda_k} (\lambda_k - i)$, which is equal to $\frac{Q_k^2 \lambda_k (\lambda_k - 1)}{2D_k}$.

Similar to the OEM's problem, two elements are considered for inventory holding cost—the storage cost and cost of capital. Since the suppliers pay immediately to their vendors, the amount of inventory that is included in the cost of capital is the same as the one included in the storage cost. Thus, we calculate the total inventory holding cost for supplier k in the planning horizon as $\left(s'_k + h'_k\right)\frac{Q_k(\lambda_k - 1)}{2}$ by dividing the holding cost per period, ($\left(s'_k + h'_k\right)\frac{Q_k^2 \lambda_k (\lambda_k - 1)}{2D_k}$), by T_{s_k}.

It is supposed that the suppliers have sufficient budget. Thus, we just considered inventory replenishment costs for the suppliers such as procurement, ordering, and holding costs. The cost function of each supplier k in the planning horizon (1 year) is modeled as follows:

$$\mathrm{TC}_{S_k} = c_k\left(\sum_n N_{nk}\alpha_n D_n\right) + A'_k \frac{\sum_n N_{nk}\alpha_n D_n}{\lambda_k Q_k} + \left(s'_k + h'_k\right)\frac{Q_k(\lambda_k - 1)}{2} \tag{7}$$

The auto manufacturer's model

The auto manufacturer produces the final products of the supply chain. It supplies the required original parts from the OEM. It is assumed that the required parts are shipped every day from the OEM to the auto manufacturer to be included in the production line of automobiles. The auto manufacturer pays for these parts at the end of the planning horizon. The majority of the auto manufacturer's inventory costs are related to the procurement of original parts. Therefore, in this study, the auto manufacturer's cost function is modeled only as the sum of the procurement cost of parts from the OEM, since inventory holding and ordering costs are negligible as compared with the procurement cost.

$$\mathrm{TC}_{AM} = \sum_{n} p_n \alpha_n D_n \tag{8}$$

(Note that AM refers to the auto manufacturer in the mathematical terms and tables in the rest of this paper.)

Supply chain coordination model

In the coordination scheme, the suppliers offer trade credit to the OEM as a financing source in exchange for an increase in the OEM's orders. Having delayed (extended) its payments, the OEM invests its cash, if any, until t_k and gains interest equal to $\sum_k w_k * Q_k * \left[(1+r_{OEM})^{t_k} - (1+\gamma_k)^{(t_k-d_k)^+}\right]$ units of cash each period, where $(x)^+ = \max(x, 0)$. Meanwhile, the auto manufacturer pays in advance a fraction of payables to help the OEM improve its service level by increasing its production rate. Consequently, the auto manufacturer incurs an opportunity cost by prepaying. The members' cost functions are rewritten based on the aforementioned assumptions ($\mathrm{TC}^c_{.}$ refers to the cost function of the members and supply chain under the coordination scheme.). The OEM's cost function in the coordinated model becomes:

$$\begin{aligned} TC^c_{OEM} = {} & \sum_k A_k \frac{\sum_n N_{nk}\alpha_n D_n}{Q_k} + \sum_k s_k \frac{Q_k}{2} + \sum_k H(k) \frac{\sum_n N_{nk}\alpha_n D_n}{Q_k} \\ & + \sum_n (F_n + v_n \alpha_n D_n) + \sum_k w_k * \left(\sum_n N_{nk}\alpha_n D_n\right) + Dbt\left((1+i)^T - 1\right) \\ & - \sum_k w_k * \left(\sum_n N_{nk}\alpha_n D_n\right) * \left[(1+r_{OEM})^{t_k} - (1+\gamma_k)^{(t_k-d_k)^+}\right] \end{aligned} \tag{9}$$

The last term in the objective function is the capital gain of the OEM from extending its payables. There are upper bounds on the OEM's payment time to the suppliers, which are considered as constraints for the coordination problem:

$$t_k \le t\max k \forall k = 1, 2, \ldots, K \tag{10}$$

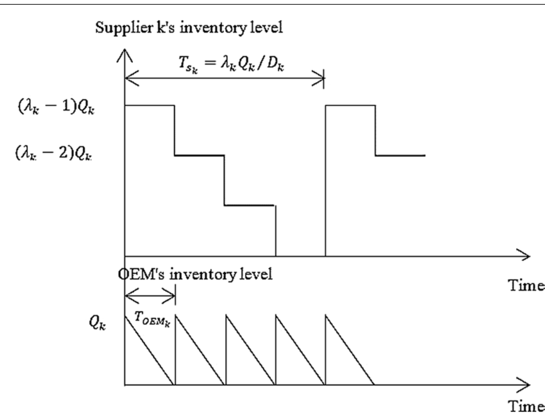

Fig. 2 Inventory levels for each supplier and the OEM

The budget constraint in (5) will change based on the coordination settings as:

$$\begin{aligned}&\sum_k w_k * \left(\sum_n N_{nk}\alpha_n D_n\right) * (1+\gamma_k)^{(t_k-d_k)^+} + \sum_n (F_n + v_n\alpha_n D_n) + \sum_k s_k \frac{Q_k}{2}\\&+\sum_k A_k \frac{\sum_n N_{nk}\alpha_n D_n}{Q_k} \le B + Dbt + \beta * \left(\sum_n p_n\alpha_n D_n\right)\end{aligned} \tag{11}$$

The balance of the cash at the end of the time horizon in (6) is rewritten as follows:

$$\begin{aligned}&B + Dbt + \sum_n p_n\alpha_n D_n + \sum_k w_k\left(\sum_n N_{nk}\alpha_n D_n\right)\left((1+r_{OEM})^{t_k}-1\right) - \sum_n (F_n + v_n\alpha_n D_n)\\&-\sum_k w_k * \left(\sum_n N_{nk}\alpha_n D_n\right) * (1+\gamma_k)^{(t_k-d_k)^+} - Dbt(1+i)^T \ge L\end{aligned} \tag{12}$$

In the coordination scheme, the members should decide on the due date of the interest-free period (d_k). According to this setting, as the OEM delays its payments, an opportunity cost is incurred by the suppliers, which is added to their cost function. The cost function for each supplier k is rewritten as:

$$\begin{aligned}\mathrm{TC}^c_{S_k} =& c_k\left(\sum_n N_{nk}\alpha_n D_n\right) + A'_k\frac{\sum_n N_{nk}\alpha_n D_n}{\lambda_k Q_k} + \left(s'_k + h'_k\right)\frac{Q_k(\lambda_k-1)}{2}\\&+ w_k\left(\sum_n N_{nk}\alpha_n D_n\right)\left[(1+r_k)^{t_k} - (1+\gamma_k)^{(t_k-d_k)^+}\right]\end{aligned} \tag{13}$$

By adding the opportunity cost due to prepayment to the auto manufacturer's objective function, it becomes:

$$\mathrm{TC}^c_{AM} = \sum_n p_n\alpha_n D_n + \beta\left(\sum_n p_n\alpha_n D_n\right)\left((1+r_{AM})^T - 1\right) \tag{14}$$

where β is the prepayment rate that is a decision variable in the coordinated scenario.

According to the members' cost functions, we can write the coordinated nonlinear bi-objective supply chain model as follows:

$$\min Z = \mathrm{TC}^c_{OEM} + \sum_k \mathrm{TC}^c_{S_k} + \mathrm{TC}^c_{AM} \tag{15}$$

$$\max \omega = \sum_n \alpha_n D_n \tag{16}$$

subject to (4), (10), (11), and (12).

All of the variables are assumed to be positive to decrease the problem's complexity, that is, the variables of time, t_k and d_k, and the coefficient λ_k are considered as positive continuous variables. Moreover, λ_k has a lower bound which is equal to 1.

Solution approach

To solve the bi-objective optimization models in both scenarios, we use the ε-constraint method by considering the cost function as the main objective and the other objective as a constraint of the problem. It is assumed that $\alpha_1 = \alpha_2 = \cdots = \alpha_n = \alpha$ (here $n = 3$), that is, all of the n parts should be produced in equal quantities. In other words, the demand satisfaction level for all parts should be the same. Based on this assumption, maximizing the satisfied demand for original parts ($\sum_n \alpha D_n$) is equal to the maximization of the service level for original parts (α). As such, for simplicity, in the ε-constraint method, we use $\alpha \geq x(where\, \varepsilon = 0.1, 0.2, \ldots, 1)$ in the constraints of the models instead of $\sum_n \alpha_n D_n \geq y$ (where y is the lower bounds of the satisfied demand). In this method, the non-dominated (Pareto) solutions are found according to different service levels. The best solution among these non-dominated solutions is chosen according to the experts' opinions. In the optimal solution of the proposed model, it can be proved that t_k is less than or equal to d_k. This reduces the problem's complexity.

Lemma 2 *t_k is less than or equal to d_k in the optimal solution of the proposed model.*

Proof See "Appendix 2".

After simplifying the model according to the above-mentioned lemma and assumptions, the models are solved by *the* ε-constraint method in the general algebraic modeling system (GAMS).

Numerical analysis

In this section, we compare the two scenarios explained in the previous section. We show the effects of coordinating a budget-constrained supply chain on the financial and operational decisions of the members. Furthermore, a cost-sharing mechanism is developed to share coordination benefits among all members. In the end, we provide a sensitivity analysis to show the sensitivity of the model variables and cost function to some critical financial parameter fluctuations.

Data

The models are solved using data from an OEM of an automotive supply chain in Iran (Table 4). This supply chain includes 10 suppliers of strategic components and materials for the OEM (Each component is supplied by only one supplier; thus, K = 10), which produces three kinds of original parts (powertrain components including engines, gearboxes, and axles) for the auto manufacturer (N = 3), and an auto manufacturer with 2 kinds of final products (J = 2; Fig. 1). The required data are collected from the company's archives and analyzed under the supervision of the OEM's supply chain manager. In solving the model, the initial budget (B) and minimum cash level at the OEM (L) are assumed to be zero.

Table 4 Data from an OEM in the automotive supply chain for the model parameters (Prices are in terms of 1000 units of cash)

j = 1, 2 (index of final products)	J		D_j (units of product)		F_j		V_j	
	1		15,000		6000		90	
	2		10,000		5700		130	
n = 1, 2, 3 (index of original parts)	**N**		P_n		F_n		V_n	
	1		3700		2800		370	
	2		4500		3000		410	
	3		2900		1950		290	
$k = 1, 2, \ldots, 10$(index of strategic components and materials)	**K**	A_k	s_k	w_k	c_k	s_k	A_k	$tmax_k$ (in days)
	1	120	4	100	60	4	230	40
	2	100	3	150	100	2	200	70
	3	250	2	75	50	1	190	60
	4	140	3	56	30	2	160	50
	5	100	1	68	48	1	210	40
	6	160	2	95	65	1	169	60
	7	173	3	110	90	2	180	60
	8	185	5	80	65	4	200	60
	9	149	6	90	70	4	175	90
	10	137	6	79	60	4	180	40
MaxDbt	***i*** **(Annual rate)**	r_{OEM} **(Annual rate)**	r_{AM} **(Annual rate)**	h_k **(Annual rate)**	r_k **(Annual rate)**	y_k **(Annual rate)**		
50000000	36.5%	32.85%	29%	29%	29%	29%		

Solution results

This section presents the results of solving the proposed models in Section "Model description and solution approach". The results are reported in two tables in the form of non-dominated solutions. Table 5(a) and (b) show the costs of the members and the total cost of the supply chain according to different service levels in both scenarios, and Table 6 presents the quantities of the problem's decision variables.

The OEM is faced with capital shortage and financing limitations, that is, it cannot obtain more than M units of cash from external financial institutions such as banks (M is the maximum limit for external financing). As explained earlier, this limitation may have some consequences such as the inability to satisfy all of the auto manufacturer's demand and losing part of the OEM's market share.

According to the numerical results, in the non-coordinated scenario with this circumstance (Table 5(a)), the OEM is not able to satisfy more than about 50% of the demand, as the quantity of required external financing for 60% of the auto manufacturer's demand

Table 5 (a) Supply chain costs in the non-coordinated scenario (italics shows the infeasible solutions for the main problem). (b) Supply chain costs in the coordinated scenario

α	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1
(a) Non-coordinated supply chain										
C^0_{chain}	45,798,900	91,555,500	137,307,000	183,058,000	228,805,000	*274,552,000*	*320,298,000*	*366,045,000*	*411,793,000*	*457,530,000*
OEM	13,348,000	26,663,000	39,975,000	53,286,000	66,594,000	*79,903,000*	*93,211,000*	*106,520,000*	*119,830,000*	*133,130,000*
AM	27,750,000	55,500,000	83,250,000	111,000,000	138,750,000	*166,500,000*	*194,250,000*	*222,000,000*	*249,750,000*	*277,500,000*
S_1	302,100	602,970	903,640	1,204,200	1,504,700	*1,805,100*	*2,105,600*	*2,405,900*	*2,706,300*	*3,006,600*
S_2	501,440	1,002,000	1,502,500	2,002,900	2,503,200	*3,003,500*	*3,503,800*	*4,004,100*	*4,504,300*	*5,004,600*
S_3	250,850	501,200	751,470	1,001,700	1,251,900	*1,502,100*	*1,752,200*	*2,002,400*	*2,252,500*	*2,502,700*
S_4	151,170	301,660	452,030	602,340	752,620	*902,870*	*1,053,100*	*1,203,300*	*1,353,500*	*1,503,700*
S_5	962,050	1,922,900	2,883,600	3,844,100	4,804,600	*5,765,000*	*6,725,400*	*7,685,800*	*8,646,200*	*9,606,500*
S_6	651,300	1,301,800	1,952,300	2,602,600	3,252,900	*3,903,200*	*4,553,400*	*5,203,700*	*5,853,900*	*6,504,100*
S_7	901,680	1,802,400	2,702,900	3,603,400	4,503,700	*5,404,100*	*6,304,400*	*7,204,700*	*8,105,000*	*9,005,300*
S_8	326,640	652,330	977,850	1,303,300	1,628,700	*1,954,000*	*2,279,400*	*2,604,700*	*2,929,900*	*3,255,200*
S_9	351,760	702,480	1,053,000	1,403,500	1,753,900	*2,104,300*	*2,454,600*	*2,805,000*	*3,155,300*	*3,505,600*
S_{10}	301,880	602,660	903,260	1,203,800	1,504,200	*1,804,600*	*2,105,000*	*2,405,300*	*2,705,700*	*3,006,000*
(b) Coordinated supply chain										
C^0_{chain}	44,857,600	89,684,400	134,479,000	179,293,000	224,102,000	268,910,000	313,718,000	358,535,000	403,295,000	447,762,000
OEM	9,269,000	18,515,000	27,758,000	37,000,000	46,241,000	55,482,000	64,722,000	73,962,000	80,152,000	89,052,000
AM	30,892,000	61,783,000	92,646,000	123,530,000	154,410,000	185,290,000	216,170,000	247,060,000	277,940,000	308,820,000
S_1	301,350	601,900	902,330	1,202,700	1,503,000	1,803,300	2,103,600	2,403,800	2,866,600	3,166,800
S_2	501,230	1,001,700	1,502,100	2,002,500	2,502,700	3,003,000	3,503,200	4,003,500	4,935,500	5,435,700
S_3	250,690	500,960	751,180	1,001,400	1,251,500	1,501,700	1,751,800	2,001,900	2,436,400	2,686,500
S_4	150,860	301,220	451,490	601,720	751,920	902,110	1,052,300	1,202,400	1,466,800	1,616,900
S_5	961,310	1,921,900	2,882,300	3,842,600	4,802,900	5,763,200	6,723,500	7,683,700	9,086,000	10,046,000
S_6	651,060	1,301,500	1,951,800	2,602,100	3,252,400	3,902,600	4,552,800	5,203,000	6,320,100	6,970,300
S_7	901,260	1,801,800	2,702,200	3,602,500	4,502,800	5,403,100	6,303,300	7,203,600	8,644,400	9,544,600
S_8	326,220	651,730	977,120	1,302,400	1,627,700	1,953,000	2,278,200	2,603,500	3,125,300	3,450,500
S_9	351,280	701,810	1,052,200	1,402,600	1,752,900	2,103,100	2,453,400	2,803,600	3,489,700	3,839,900
S_{10}	301,340	601,890	902,320	1,202,700	1,503,000	1,803,300	2,103,500	2,403,800	2,832,400	3,132,600

is 55,479,000 (Table 6), which is more than the maximum limit of external financing (M = 50,000,000). Therefore, the problem is infeasible for $\alpha \geq 0.6$ (italics in Tables 5(a) and 6) for the non-coordinated structure in accordance with the financing limitations (For $\alpha \geq 0.6$, the problem is solved by eliminating constraint (5), which is related to the financing limitations, to track the amount of required loan from financial institutions.). The proposed coordination mechanism is developed to deal with these kinds of difficulties. Table 5(b) shows that in the coordinated scenario, all of the demand can be satisfied despite the financing limitations because of internal financing. Figure 3 illustrates the differences between the costs of the OEM, auto manufacturer, and the supply chain for the two scenarios for different service levels.

The numerical results indicate that the proposed coordination mechanism leads to cost reduction for the whole supply chain as compared with the non-coordinated scenario. As seen in Table 5(b), the supply chain cost is reduced in the coordinated scenario, as compared with the non-coordinated one, for all service levels (According to the results, for $\alpha > 0.5$, the problem is infeasible for the non-coordinated scenario, i.e., the costs become infinity.). Moreover, through coordination, the OEM can order in larger quantities and larger periods than in the non-coordinated case (Table 6). In the coordinated scheme, the OEM takes advantage of the prepayment option and avoids external financing for all service levels in this example. As explained later in Lemma 3 in section "Sensitivity analysis", the reason is that in this example, the interest rate of external financing is larger than the opportunity cost of the auto manufacturer. Consequently, the auto manufacturer's loss due to the prepayment to the OEM is less than the interest paid to the external institution for the loan at the end of the time horizon. It is also observed that for service levels of 0.9 and 1, the OEM takes advantage of both options: trade credit and prepayment of the auto manufacturer.

Cost-sharing mechanism

As previously mentioned, the supply chain benefits from the proposed coordination scheme through cost reduction. In the process of coordination, it is normal that some of the members face increased costs and others, reduced costs. As seen in Fig. 3, through coordination, the OEM's costs decrease but those of the auto manufacturer increase.

In such cases, to persuade members whose costs increased to accept the coordination scheme, the last step is sharing the gains and losses among all members of the supply chain so that all the parties benefit equally from the coordination. In this regard, we apply a cost-sharing mechanism to the coordination scheme, as adopted by Moussawi-Haidar et al. (2014), wherein the gains and losses are shared according to the ratio of the individual cost per unit time with respect to the chain's non-coordinated cost per unit time. Let C_{chain} and C^0_{chain} be the total unit cost of a coordinated supply chain and the total unit cost of a non-coordinated supply chain, respectively, and C^0_x the cost per unit time of member x of the non-coordinated supply chain. x is a member of set M_x = OEM, auto manufacturer, $S_1, S_2, \ldots, S_K$. We get the following ratios:

$$Z_x = \frac{C^0_x}{C^0_{chain}} \; with \sum_{M_x} Z_x = 1 \tag{17}$$

Table 6 The value of decision variables in both scenarios; italics shows the infeasible solutions for the main problem

α	D_k	Coordinated supply chain							Non-coordinated supply chain			
		β	Debt	λ_k	d_k	t_k	T_k	Q_k	Debt	λ_k	T_k	Q_k
0.1	5000	0.334	0	1	0	0	62	854.01		1	40	547.65
	5000			1	0	0	59	814.63	9,267,600	2	42	577.24
	5000			1	0	0	100	1369.86		1	82	1117.72
	5000			1	0	0	68	929.96		1	50	683
	20,000			1	0	0	58	3204.29		2	36	1998.89
	10,000			1	0	0	58	1597.61		2	46	1264.56
	10,000			1	0	0	52	1431.49		1	39	1073.74
	5000			1	0	0	60	817.72		1	44	608.21
	5000			1	0	0	50	682.73		1	40	547.65
	5000			1	0	0	49	627.57		2	42	577.24
0.2	10,000	0.334	0	1	0	0	44	1207.75		1	28	774.49
	10,000			1	0	0	42	1152.06	18,513,000	2	30	816.35
	10,000			1	0	0	72	1979.36		1	58	1580.70
	10,000			1	0	0	48	1315.16		1	35	965.91
	40,000			1	0	0	41	4531.55		2	26	2826.86
	20,000			1	0	0	41	2259.37		2	33	1788.36
	20,000			1	0	0	37	2024.43		1	28	1518.49
	10,000			1	0	0	42	1156.43		1	31	860.14
	10,000			1	0	0	35	965.53		1	26	704.68
	10,000			1	0	0	35	951.15		2	25	675.71
0.3	15,000	0.333	0	1	0	0	36	1479.19		1	23	948.55
	15,000			1	0	0	34	1410.98	27,756,000	2	24	999.82
	15,000			1	0	0	59	2424.21		1	47	1935.95
	15,000			1	0	0	39	1610.73		1	29	1183
	60,000			1	0	0	34	5549.99		2	21	3462.18
	30,000			1	0	0	34	2767.14		2	27	2190.28
	30,000			1	0	0	30	2479.41		1	23	1859.76
	15,000			1	0	0	34	1416.33		1	26	1053.45
	15,000			1	0	0	29	1182.52		1	21	863.05
	15,000			1	0	0	28	1164.92		2	20	827.57
0.4	20,000	0.333	0	1	0	0	31	1708.02		1	20	1095.29
	20,000			1	0	0	30	1629.26	36,997,000	2	21	1154.49
	20,000			1	0	0	51	2799.23		1	41	2235.45
	20,000			1	0	0	34	1859.91		1	25	1366.01
	80,000			1	0	0	29	6408.57		2	18	3997.78
	40,000			1	0	0	29	3195.22		2	23	2529.12
	40,000			1	0	0	26	2862.97		1	20	2147.47
	20,000			1	0	0	30	1635.44		1	22	1216.42
	20,000			1	0	0	25	1365.46		1	18	996.57
	20,000			1	0	0	25	1345.13		2	17	955.60

Table 6 (continued)

α	D_k	Coordinated supply chain							Non-coordinated supply chain			
		β	Debt	λ_k	d_k	t_k	T_k	Q_k	Debt	λ_k	T_k	Q_k
0.5	25,000	0.333	0	1	0	0	28	1909.62		1	18	1224.58
	25,000			1	0	0	27	1821.57	46,238,000	2	19	1290.76
	25,000			1	0	0	46	3129.64		1	36	2499.31
	25,000			1	0	0	30	2079.44		1	22	1527.24
	100,000			1	0	0	26	7165		2	16	4469.65
	50,000			1	0	0	26	3572.37		2	21	2827.64
	50,000			1	0	0	23	3200.90		1	18	2400.94
	25,000			1	0	0	27	1828.47		1	20	1360
	25,000			1	0	0	22	1526.63		1	16	1114.20
	25,000			1	0	0	22	1503.90		2	16	1068.39
0.6	30,000	0.333	0	1	0	0	25	2091.89		*1*	*16*	*1342.45*
	30,000			1	0	0	24	1995.43	*55,479,000*	*2*	*17*	*1413.95*
	30,000			1	0	0	42	3428.35		*1*	*33*	*2737.85*
	30,000			1	0	0	28	2277.92		*1*	*20*	*1673.01*
	120,000			1	0	0	24	7848.87		*2*	*15*	*4896.26*
	60,000			1	0	0	24	3913.33		*2*	*19*	*3097.53*
	60,000			1	0	0	21	3506.41		*1*	*16*	*2630.10*
	30,000			1	0	0	24	2002.99		*1*	*18*	*1489.0*
	30,000			1	0	0	20	1672.34		*1*	*15*	*1220.54*
	30,000			1	0	0	20	1647.44		*2*	*14*	*1170.36*
0.7	35,000	0.333	0	1	0	0	24	2259.50		*1*	*15*	*1448.94*
	35,000			1	0	0	22	2155.31	*64,719,000*	*2*	*16*	*1527.24*
	35,000			1	0	0	39	3703.04		*1*	*31*	*2957.22*
	35,000			1	0	0	26	2460.43		*1*	*19*	*1807.06*
	140,000			1	0	0	22	8477.75		*2*	*14*	*5288.57*
	70,000			1	0	0	22	4226.88		*2*	*17*	*3345.71*
	70,000			1	0	0	20	3787.36		*1*	*15*	*2840.83*
	35,000			1	0	0	23	2163.48		*1*	*17*	*1609.17*
	35,000			1	0	0	19	1806.33		*1*	*14*	*1318.34*
	35,000			1	0	0	19	1779.44		*2*	*13*	*1264.14*
0.8	40,000	0.333	0	1	0	0	22	2415.51		*1*	*14*	*1548.98*
	40,000			1	0	0	21	2304.12	*73,958,000*	*2*	*15*	*1632.69*
	40,000			1	0	0	36	3958.72		*1*	*29*	*3161.40*
	40,000			1	0	0	24	2630.31		*1*	*18*	*1931.83*
	160,000			1	0	0	21	9063.09		*2*	*13*	*5653.72*
	80,000			1	0	0	21	4518.73		*2*	*16*	*3576.72*
	80,000			1	0	0	18	4048.85		*1*	*14*	*3036.98*
	40,000			1	0	0	21	2312.86		*1*	*16*	*1720.27*
	40,000			1	0	0	18	1931.05		*1*	*13*	*1409.36*
	40,000			1	0	0	17	1902.30		*2*	*12*	*1351.42*

Table 6 (continued)

α	D_k	Coordinated supply chain							Non-coordinated supply chain			
		β	Debt	λ_k	d_k	t_k	T_k	Q_k	Debt	λ_k	T_k	Q_k
0.9	45,000	0.333	0	1	40	40	21	2562.22		*1*	*13*	*1642.94*
	45,000			1	70	70	20	2444.37	*83,197,000*	*2*	*14*	*1731.73*
	45,000			1	60	60	34	4199.48		*1*	*27*	*3353.7*
	45,000			1	50	50	23	2790.15		*1*	*17*	*2049.01*
	180,000			1	40	40	19	9615.73		*2*	*12*	*5996.67*
	90,000			1	60	60	19	4793.97		*2*	*15*	*3793.68*
	90,000			1	60	60	17	4294.89		*1*	*13*	*3221.20*
	45,000			1	60	60	20	2453.30		*1*	*15*	*1824.63*
	45,000			1	90	90	17	2048.29		*1*	*12*	*1494.85*
	45,000			1	40	40	16	2017.80		*2*	*12*	*1433.39*
1	50,000	0.333	0	1	40	40	20	2700.82		*1*	*13*	*1731.81*
	50,000			1	70	70	19	2576.59	*92,436,000*	*2*	*13*	*1825.40*
	50,000			1	60	60	32	4426.64		*1*	*26*	*3534.55*
	50,000			1	50	50	21	2941.07		*1*	*16*	*2159.85*
	200,000			1	40	40	18	10,135.87		*2*	*12*	*6321.05*
	100,000			1	60	60	18	5053.29		*2*	*15*	*3998.89*
	100,000			1	60	60	17	4527.21		*1*	*12*	*3395.45*
	50,000			1	60	60	19	2586.01		*1*	*14*	*1923.33*
	50,000			1	90	90	16	2159.09		*1*	*12*	*1575.71*
	50,000			1	40	40	16	2126.95		*2*	*11*	*1510.93*

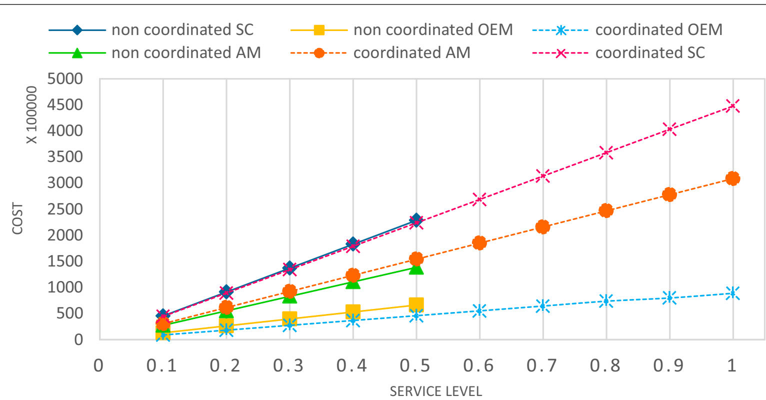

Fig. 3 The differences between the costs of OEM, AM, and the supply chain in two scenarios for different service levels. *Note*: For the service levels more than 0.5, the problem is infeasible for the non-coordinated scenario, that is, infinity costs

We can calculate the cost of each member by:

$$\text{Cost of member x} = Z_x C_{chain} \tag{18}$$

Table 7 shows the results of sharing the costs among members. As seen in Table 7, compared with the non-coordinated case, the costs of all members in the coordinated scenario are reduced for all service levels (Table 5(a)) after applying the cost-sharing mechanism.

Figure 4 shows the difference between the costs of the OEM, auto manufacturer, and supply chain in the non-coordinated and coordinated scenarios after applying the cost-sharing mechanism. A comparison between Fig. 3 and Fig. 4 indicates the fair distribution of gains and losses among supply chain members as a result of applying the cost-sharing mechanism.

Figure 5 shows the difference between the costs of the OEM and auto manufacturer before and after applying the cost-sharing mechanism in the coordinated scenario.

Sensitivity analysis

In this section, we analyze the sensitivity of the system's costs and model variables to the fluctuations in both the operational and financial parameters. To avoid excessive calculations, the analysis is only performed for the case with $\alpha = 1$.

Sensitivity analysis for the operational parameters

A sensitivity analysis regarding inventory-related parameters, A_k, S_k, A'_k, and S'_k, is provided. To this end, for simplicity, we define a coefficient denoted by ω to make changes in the parameters. For instance, for parameter A_k, if $\omega = 2$, this means that for all k, A_k is multiplied by 2. The results are illustrated in Fig. 6. As expected, the results indicate that the impact of changes in A_k and S_k on the order quantities and the total cost is similar to the classical EOQ model (see Fig. 6a, b). Moreover, by decreasing A_k or increasing S_k, the average amount of λ_k increases (see Fig. 6c) because of the reduction in the OEM's order quantities (Fig. 6a).

Any changes (increase or decrease) in A'_k has a direct effect on the order quantities at the OEM (see Fig. 6a). Furthermore, by increasing A'_k or decreasing S'_k the average amount of λ_k increases. In this case, the suppliers tend to order in larger quantities to support more than one order at the OEM every time and store the remaining inventory for the next orders. According to the results shown in Fig. 6a, the average order quantity at the OEM decreases by decreasing S'_k. This can be justified according to the model. As seen in Fig. 6c, d, by increasing S'_k (for $\omega < 1$) the average amount of λ_k decreases until it equals 1 (the lot-for-lot policy). In this situation, if the average order quantity also decreases, the average amount of $\lambda_k * Q_k$ will largely decrease and cause a large increase in the total cost. Therefore, to avoid this large loss, the OEM increases the order quantities. (The order quantities of the OEM and the total cost do not change by increasing S'_k from its values in the main example, that is, where $\omega = 1$ in the horizontal axis, because of the lot-for-lot policy of suppliers).

Sensitivity analysis for financial parameters

A sensitivity analysis is provided with respect to some important financial parameters namely, i, r_{OEM}, r_{AM} *, and* r_k. The results are presented in Tables 8, 9, 10 and 11. Note that the rates in the tables are daily rates. The analysis of the results is summarized in the form of some lemmas.

Table 7 Results of applying the proposed cost-sharing mechanism

α	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1
C_{chain}	44,857,600	89,684,400	134,479,000	179,293,000	224,102,000	268,910,000	313,718,000	358,535,000	403,295,000	447,762,000
OEM	13,073,660	26,118,094	39,151,668	52,190,053	65,225,186	78,261,006	91,296,132	104,334,571	117,357,118	130,287,752
AM	27,179,657	54,365,758	81,535,368	108,717,035	135,898,046	163,078,451	190,259,451	217,445,314	244,596,014	271,575,536
S_1	295,891	590,647	885,028	1,179,433	1,473,771	1,768,005	2,062,344	2,356,539	2,650,451	2,942,412
S_2	491,134	981,522	1,471,554	1,961,706	2,451,748	2,941,778	3,431,820	3,921,949	4,411,347	4,897,755
S_3	245,694	490,957	735,993	981,098	1,226,168	1,471,232	1,716,204	1,961,317	2,206,016	2,449,269
S_4	148,063	295,495	442,720	589,951	737,150	884,316	1,031,466	1,178,612	1,325,568	1,471,597
S_5	942,277	1,883,602	2,824,209	3,765,037	4,705,843	5,646,530	6,587,238	7,528,113	8,467,772	9,401,407
S_6	637,914	1,275,195	1,912,090	2,549,072	3,186,038	3,822,990	4,459,858	5,096,938	5,733,095	6,365,241
S_7	883,148	1,765,565	2,647,230	3,529,288	4,411,128	5,293,047	6,174,886	7,056,884	7,937,740	8,813,042
S_8	319,926	638,998	957,710	1,276,495	1,595,223	1,913,846	2,232,573	2,551,260	2,869,437	3,185,703
S_9	34,450	688,123	1,031,312	1,374,634	1,717,849	2,061,057	2,404,174	2,747,451	3,090,185	3,430,757
S_{10}	295,675	590,343	884,656	1,179,041	1,473,282	1,767,516	2,061,756	2,355,951	2,649,864	2,941,824

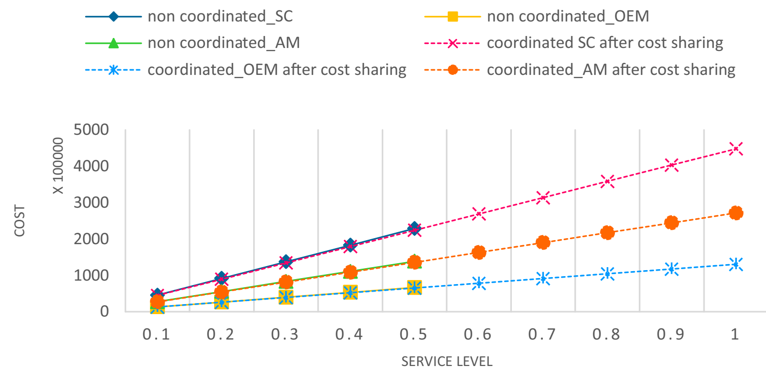

Fig. 4 The differences between the costs of OEM, AM, and the supply chain in the non-coordinated scenario and the coordinated scenario after applying the cost-sharing mechanism. Note: For the service levels more than 0.5, the problem is infeasible for the non-coordinated scenario, that is, infinity costs)

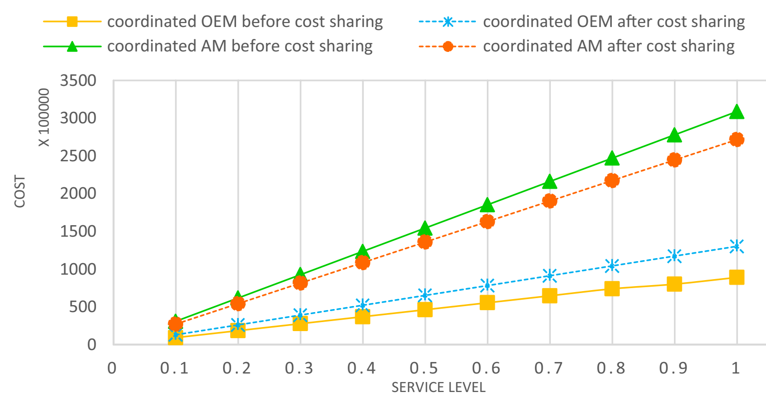

Fig. 5 The differences between the costs of OEM and AM before and after applying the cost-sharing mechanism in the coordinated scenario

Lemma 3 *When $i < r_{AM}$, the OEM borrows from the external financial institution as much as possible, that is, the maximum debt limit (Table 8(a)). Conversely, when $i \geq r_{AM}$, the OEM obtains financing from its internal source, the auto manufacturer's prepayment (Table 8(b), (c) and (d)).*

Proof $i < r_{AM}$ means that the interest rate of the loan is less than the opportunity cost of the auto manufacturer, such that the interest paid to the external institution for the loan at the end of the time horizon is less than the auto manufacturer's loss arising from its prepayment to the OEM. This is why the OEM uses the maximum limit of the loan in this situation. By contrast, when $i > r_{AM}$, the OEM uses internal financing from the auto manufacturer (Table 8(c), (d)). For the equality mode, $i = r_{AM}$, no difference is expected between external and internal financing, but by making the debt equal to zero, constraint (12) becomes less constrictive. Therefore, in this case, internal financing is preferred (Table 8(b)). □

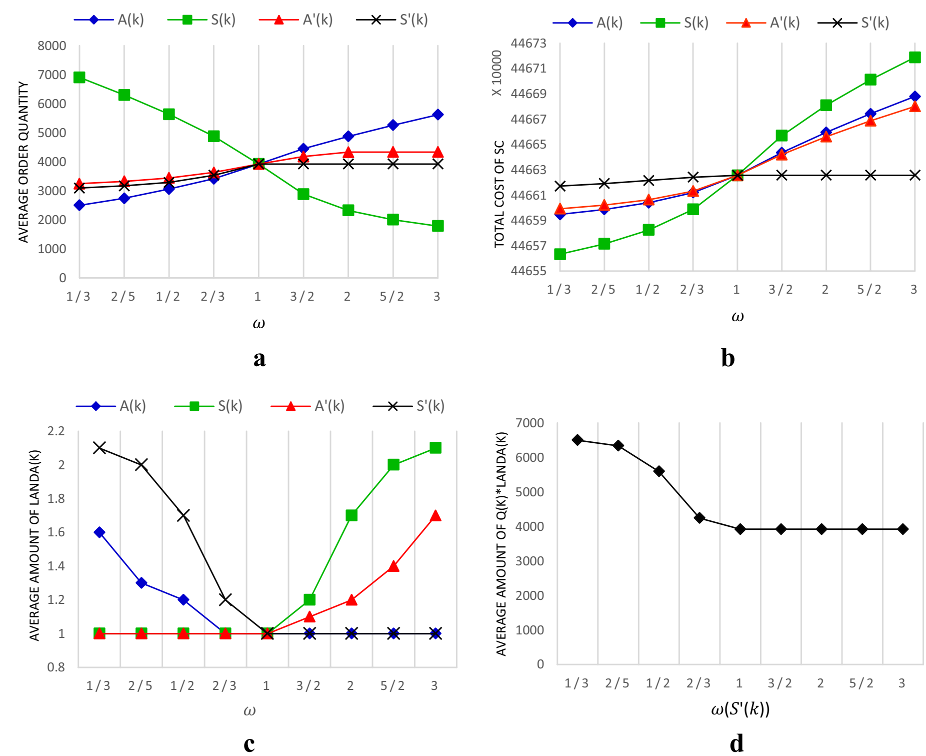

Fig. 6 The results of the sensitivity analysis for the operational parameters. *Note*: In the vertical axis, the average amount of each variable is defined on k, where k = 1,2, …, K. For instance, for the order quantity, it is defined as $\frac{\sum_k Q_k}{K}$

Lemma 4 *If $r_k < r_{OEM}$ then the OEM delays its payments until the maximum limit (Table 9(c), (d)) is reached, and if $r_k > r_{OEM}$ the OEM pays at the time of ordering ($t_k = 0$; Table 9(a)).*

Proof To prove this lemma, we consider Z' (Eq. 25 in "Appendix 2") because the rest of the cost function does not affect the process of proving. According to Z', we get the following rule:

The smaller the Z' the better is the objective function. Therefore, if $r_k > r_{OEM}$, the greater the t_k, the greater is the Z' and consequently, the worse is the objective function. From a mathematical viewpoint, we prove the proposition below:

Proposition 1: If $r_k > r_{OEM} > 0$ and assuming we have t'_k such that $t'_k > t_k > 0$; then:

$$(1 + r_k)^{t'_k} - (1 + r_{OEM})^{t'_k} > (1 + r_k)^{t_k} - (1 + r_{OEM})^{t_k} \tag{19}$$

Proof of proposition 1

This inequality implies that under this circumstance, the lower the t_k, the better is the objective function. To prove this, we write the inequality below:

$$\left[(1 + r_k)^{t_k} - (1 + r_{OEM})^{t_k}\right](1 + r_{OEM})^{t'_k - t_k} > \left[(1 + r_k)^{t_k} - (1 + r_{OEM})^{t_k}\right] \tag{20}$$

Table 8 The results of sensitivity analysis for various quantities of *i*

Parameters	C_{chain}	β	Debt	λ_k	t_k	Q_k	Parameters	C_{chain}	β	Debt	λ_k	t_k	Q_k
(a)							(b)						
$i=0.0007$ $r_{OEM}=0.0009$ $r_{AM}=0.0008$ $r_k=0.0008$	4.4538E+08	0.153	M	1	40	2700.818	$i=0.0008$ $r_{OEM}=0.0009$ $r_{AM}=0.0008$ $r_k=0.0008$	4.4777E+8	0.333	0	1	40	2700.818
				1	70	2576.594					1	70	2576.594
				1	60	4426.639					1	60	4426.639
				1	50	2941.071					1	50	2941.071
				1	40	10,135.871					1	40	10,135.871
				1	60	5053.293					1	60	5053.293
				1	60	4527.207					1	60	4527.207
				1	60	2586.005					1	60	2586.005
				1	90	2159.088					1	90	2159.088
				1	40	2126.946					1	40	2126.946
(c)							(d)						
$i=0.0009$ $r_{OEM}=0.0009$ $r_{AM}=0.0008$ $r_k=0.0008$	4.4777E+08	0.333	0	1	40	2700.818	$i=0.001$ $r_{OEM}=0.0009$ $r_{AM}=0.0008$ $r_k=0.0008$	4.4777E+08	0.333	0	1	40	2700.818
				1	70	2576.594					1	70	2576.594
				1	60	4426.639					1	60	4426.639
				1	50	2941.071					1	50	2941.071
				1	40	10,135.871					1	40	10,135.871
				1	60	5053.293					1	60	5053.293
				1	60	4527.207					1	60	4527.207
				1	60	2586.005					1	60	2586.005
				1	90	2159.088					1	90	2159.088
				1	40	2126.946					1	40	2126.946

Table 9 The results of sensitivity analysis for various quantities of r_{OEM}

Parameters	C_{chain}	β	Debt	λ_k	t_k	Q_k	Parameters	C_{chain}	β	Debt	λ_k	t_k	Q_k
(a)							(b)						
$i = 0.001$ $r_{OEM} = 0.0007$ $r_{AM} = 0.0008$ $r_k = 0.0008$	4.4816E+08	0.333	0	1	0	2700.818	$i = 0.001$ $r_{OEM} = 0.0008$ $r_{AM} = 0.0008$ $r_k = 0.0008$	4.4816E+08	0.333	0	1	20	2700.818
				1	0	2576.594					1	19	2576.594
				1	0	4426.639					1	32	4426.639
				1	0	2941.071					1	22	2941.071
				1	0	10,135.871					1	19	10,135.871
				1	0	5053.293					1	19	5053.293
				1	0	4527.207					1	17	4527.207
				1	0	2586.005					1	19	2586.005
				1	0	2159.088					1	16	2159.088
				1	0	2126.946					1	16	2126.946
(c)							(d)						
$i = 0.001$ $r_{OEM} = 0.0009$ $r_{AM} = 0.0008$ $r_k = 0.0008$	4.4777E+08	0.333	0	1	40	2700.818	$i = 0.001$ $r_{OEM} = 0.001$ $r_{AM} = 0.0008$ $r_k = 0.0008$	4.4739E+08	0.333	0	1	40	2700.818
				1	70	2576.594					1	70	2576.594
				1	60	4426.639					1	60	4426.639
				1	50	2941.071					1	50	2941.071
				1	40	10,135.871					1	40	10,135.871
				1	60	5053.293					1	60	5053.293
				1	60	4527.207					1	60	4527.207
				1	60	2586.005					1	60	2586.005
				1	90	2159.088					1	90	2159.088
				1	40	2126.946					1	40	2126.946

Table 10 The results of sensitivity analysis for various quantities of r_j

Parameters	C_{chain}	β	Debt	λ_k	t_k	Q_k	Parameters	C_{chain}	β	Debt	λ_k	t_k	Q_k
(a)							(b)						
$i = 0.001$ $r_{OEM} = 0.0009$ $r_{AM} = 0.0007$ $r_k = 0.0008$	4.4334E+08	0.333	0	1	40	2730.191	$i = 0.001$ $r_{OEM} = 0.0009$ $r_{AM} = 0.0008$ $r_k = 0.0008$	4.4777E+08	0.333	0	1	40	2700.818
				1	70	2625.402					1	70	2576.594
				1	60	4456.308					1	60	4426.639
				1	50	2966.118					1	50	2941.071
				1	40	10,250.184					1	40	10,135.871
				1	60	5110.175					1	60	5053.293
				1	60	4563.827					1	60	4527.207
				1	60	2607.373					1	60	2586.005
				1	90	2177.746					1	90	2159.088
				1	40	2146.422					1	40	2126.946
(c)							(d)						
$i = 0.001$ $r_{OEM} = 0.0009$ $r_{AM} = 0.0009$ $r_k = 0.0008$	4.5237E+08	0.333	0	1	40	2672.195	$i = 0.001$ $r_{OEM} = 0.0009$ $r_{AM} = 0.001$ $r_k = 0.0008$	4.5714E+08	0.333	0	1	40	2644.307
				1	70	2532.026					1	70	2491.177
				1	60	4397.845					1	60	4369.905
				1	50	2916.719					1	50	2893.048
				1	40	10,024.429					1	40	9915.803
				1	60	5000.214					1	60	4950.592
				1	60	4491.619					1	60	4457.041
				1	60	2565.236					1	60	2545.053
				1	90	2140.947					1	90	2123.309
				1	40	2095.624					1	40	2061.816

Table 11 The results of sensitivity analysis for various quantities of r_k

Parameters	C_{chain}	β	Debt	λ_k	t_k	Q_k	Parameters	C_{chain}	β	Debt	λ_k	t_k	Q_k
(a)							(b)						
$i=0.001$ $r_{OEM}=0.0009$ $r_{AM}=0.0008$ $r_k=0.0007$	4.4739E+08	0.333	0	1	40	2700.818	$i=0.001$ $r_{OEM}=0.0009$ $r_{AM}=0.0008$ $r_k=0.0008$	4.4777E+08	0.333	0	1	40	2700.818
				1	70	2576.594					1	70	2576.594
				1	60	4426.639					1	60	4426.639
				1	50	2941.071					1	50	2941.071
				1	40	10,135.871					1	40	10,135.871
				1	60	5053.293					1	60	5053.293
				1	60	4527.207					1	60	4527.207
				1	60	2586.005					1	60	2586.005
				1	90	2159.088					1	90	2159.088
				1	40	2126.946					1	40	2126.946
(c)							(d)						
$i=0.001$ $r_{OEM}=0.0009$ $r_{AM}=0.0008$ $r_k=0.0009$	4.4816E+08	0.333	0	1	20	2700.818	$i=0.001$ $r_{OEM}=0.0009$ $r_{AM}=0.0008$ $r_k=0.001$	4.4816E+08	0.333	0	1	0	2700.818
				1	19	2576.594					1	0	2576.594
				1	32	4426.639					1	0	4426.639
				1	22	2941.071					1	0	2941.071
				1	19	10,135.871					1	0	10,135.871
				1	19	5053.293					1	0	5053.293
				1	17	4527.207					1	0	4527.207
				1	19	2586.005					1	0	2586.005
				1	16	2159.088					1	0	2159.088
				1	16	2126.946					1	0	2126.946

The inequality above is true because $r_{OEM} > 0$ and $t'_k - t_k > 0$; consequently, $(1 + r_{OEM})^{t'_k - t_k} > 1$; therefore, we reach:

$$(1 + r_k)^{t_k}(1 + r_{OEM})^{t'_k - t_k} - (1 + r_{OEM})^{t'_k} > \left[(1 + r_k)^{t_k} - (1 + r_{OEM})^{t_k}\right] \tag{21}$$

If $r_k > r_{OEM} > 0$, then $(1 + r_k)^{t'_k - t_k} > (1 + r_{OEM})^{t'_k - t_k}$; thus, we can substitute $(1 + r_k)^{t'_k - t_k}$ with $(1 + r_{OEM})^{t'_k - t_k}$ in the inequality (22). Then we get:

$$(1 + r_k)^{t_k}(1 + r_k)^{t'_k - t_k} - (1 + r_{OEM})^{t'_k} > \left[(1 + r_k)^{t_k} - (1 + r_{OEM})^{t_k}\right] \tag{22}$$

which is equal to $(1 + r_k)^{t'_k} - (1 + r_{OEM})^{t'_k} > (1 + r_k)^{t_k} - (1 + r_{OEM})^{t_k}$.

This is why the OEM should pay at the beginning of the period when $r_k > r_{OEM}$.

Lemma 5 *The lower the r_{AM}, the lower is the total cost of the supply chain* (*Table* 10).

Proof Taking the derivative of the cost function with respect to r_{AM}, we get $T\beta\left(\sum_n p_n \alpha_n D_n\right)(1 + r_{AM})^{T-1}$, which is greater than or equal to zero. Thus, the total cost function is increasing in r_{AM}.

Lemma 6 *If $r_k \geq r_{OEM}$ (Table 11(c), (d)), then the total cost of the supply chain becomes greater than the total cost in the case where $r_k < r_{OEM}$ (Table 11(a), (b)), that is, $Z_{r_k \geq r_{OEM}} > Z_{r_k < r_{OEM}}$.*

Proof Again, we consider only Z' (Eq. 25 in "Appendix 2") because the other parts do not have any effect on the proof of this theorem. According to Z', it is obvious that the greater *the* r_{OEM} from r_k, the lesser is the Z', which means the lesser is the cost function of the supply chain.

Conclusion

In this study, we exploited two vital issues in supply chain management—coordination between supply chain members and integration of the supply chain's physical and financial flows—to improve system performance and service level.

As previously mentioned, combining supply chain coordination and financial decisions is a relatively new research area and needs more attention and extensions to real-world assumptions. In this stream of literature, some important financial issues, such as budget constraints and different financing options, have not been addressed in many of the existing works. Moreover, the idea of considering financing limitations and lost sales as a consequence of financing limitations is novel in the supply chain coordination literature. Meanwhile, most of the previous works have been limited to the relationships in a single buyer–single vendor with a single product scenario. To fill these gaps in the literature, we proposed a coordination scheme that is based on joint decision-making and that coordinates the operational (inventory–production) and financial decisions of the members of a capital-constrained supply chain (with financing limitations) in the automotive industry. To the best of our knowledge, this is the first work to address supply chain coordination together with financing issues for maximizing service level and minimizing operational–financial costs.

The proposed supply chain model consists of three levels and multiple products. Two scenarios were developed according to the different structures of the supply chain: i) non-coordinated supply chain and ii) coordinated supply chain. In the first scenario, the members optimize their own costs without considering the benefits and costs of others, but in the second one, all the members work in a way that optimizes the supply chain costs.

The models were solved using the ε-constraint method, applying GAMS based on data from an automotive supply chain in Iran. The results indicate that in the non-coordinated scenario, the OEM cannot satisfy all of the auto manufacturer's demand and faces lost sales. This happens because of the capital shortage and limitations in external financing. As observed in Table 5(a) (italics), the OEM is not able to satisfy more than about 50% of the auto manufacturer's demand in the non-coordinated scenario. However, in the coordinated scenario, all of the auto manufacturer's demand can be satisfied through the OEM's internal financing.

The advantages of this coordination scheme are twofold: (1) By applying the proposed coordination scheme, the total cost of the supply chain decreases compared with the non-coordinated scenario; and (2) The scheme makes it possible to satisfy all of the auto manufacturer's demand despite the capital shortage and financing limitations of the OEM. In other words, by adopting this coordination scheme, the supply chain manager can finance the supply chain operations and still ensure the service level for the auto manufacturer.

In such coordination methods, some of the members take advantage of the coordination more than others, and some of them may even lose a fraction of their profit. To avoid this inequity and motivate the members that lose a portion of their profits because of the coordination, a cost-sharing mechanism was applied to the coordination scheme. The results demonstrate that after applying the cost-sharing mechanism, the costs of all members are lower than their costs in the non-coordinated scenario. Thus, the proposed coordination scheme is beneficial to all members of the supply chain. Finally, to validate the proposed coordination model, a sensitivity analysis for the financial parameters was conducted to measure the sensitivity of the model variables and cost function to the fluctuations of these parameters.

Our results provide the following managerial insights for manufacturers that face financial constraints such as insufficient capital and limitations on external financing. First, the supply chain manager should integrate the operational and financial decisions of the firm. Second, he/she should entice the upstream and downstream partners to adopt operational–financial coordination. Furthermore, some detailed managerial insights after adopting the proposed coordination scheme are listed below.

- If the interest rate of the loan is more than the downstream partner's rate of return (ROR), the manufacturer should finance all the required working capital from the downstream partner. Conversely, it should borrow from the external source as much as it needs until the maximum limit of the external financing is reached.

- If supplier k's ROR is less than the manufacturer's ROR, supplier k should offer a credit period (interest-free period) to the manufacturer for its payment, and the manufacturer should delay its payment to supplier k until the maximum deadline. Conversely, it should pay at the time of ordering.

We end this paper with two remarks. First, we have modeled the deterministic state of the problem based on an EOQ policy. However, sometimes in the real world, firms face fluctuations in demand. Thus, this research can be extended to the case with stochastic demand, which calls for a new coordination scheme. Second, we used trade credit and prepayment of the auto manufacturer as two options for internal financing. Adopting other options to finance the capital-constrained member is another avenue for further research.

Abbreviations

AM: Auto manufacturer; EOQ: Economic order quantity; GAMS: General algebraic modeling system; OEM: Original equipment manufacturer; ROR: Rate of return; SC: Supply chain; SCC: Supply chain coordination; SCF: Supply chain finance; TCF: Trade credit financing.

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Authors' contributions

FE helped to conceive and design the study, conducted the data collection and analysis and drafted the manuscript. NN helped to conceive and design the study and coordinated the research activities. FM helped to conceive and design the study. All authors read and approved the final manuscript.

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The authors declare that they have no competing interests.

Appendix 1

The proof of lemma 1

As mentioned in section "The mathematical formulation of the non-coordinated supply chain", this paper has assumed that the total holding cost is a composite of two cost components, one associated with the opportunity cost of capital, while the other is the cost of stocking one unit of an item. Since the suppliers offer the OEM to settle his/her accounts by the time t_k (t_k is in terms of days) after the shipment receives, the OEM's holding cost will be different from the case that the OEM settles his/her accounts at the time of receiving the shipments. We have considered two cases: 1) $t_k \leq T_{OEM_k}$ and 2) $t_k > T_{OEM_k}$. In case 1, the holding cost of the OEM with respect to the cost of capital ($H(k)$) is calculated as $h_k \frac{(Q_k - t_k D_k)\left(T_{OEM_k} - t_k\right)}{2}$ according to Fig. 7. Where $\frac{(Q_k - t_k D_k)\left(T_{OEM_k} - t_k\right)}{2}$, is the area of shaded triangle and h_k is the unit holding cost of component k for the OEM, representing the cost of capital, excluding the storage cost. We substitute $T_{OEM_k} = Q_k / D_k$ in the above statement and reach $H(k) = h_k \frac{(Q_k - t_k D_k)^2}{2D_k}$.

In case 2, since the OEM settles his/her account for component k after T_{OEM_k}, i.e., $t_k > T_{OEM_k}$, his/her inventory level of component k will be zero and subsequently $H(k) = 0$. We have merged these two cases as bellows:

$$H(k) = h_k \frac{\left((Q_k - t_k D_k)^+\right)^2}{2D_k} \quad \text{where} \quad (x)^+ = \max(x, 0).$$

Appendix 2

The proof of lemma 2

The total system cost function (23) is as follows:

$$\begin{aligned} Z = &\sum_k A_k \frac{\sum_n N_{nk}\alpha_n D_n}{Q_k} + \sum_k s_k \frac{Q_k}{2} + \sum_k H(k) \frac{\sum_n N_{nk}\alpha_n D_n}{Q_k} + \sum_n (F_n + v_n \alpha_n D_n) \\ &+ \sum_k w_k * \left(\sum_n N_{nk}\alpha_n D_n\right) + Dbt\left((1+i)^T - 1\right) \\ &- \sum_k w_k * \left(\sum_n N_{nk}\alpha_n D_n\right) * \left[(1+r_{OEM})^{t_k} - (1+\gamma_k)^{(t_k-d_k)^+}\right] \\ &+ \sum_k \left[c_k \left(\sum_n N_{nk}\alpha_n D_n\right) + A'_k \frac{\sum_n N_{nk}\alpha_n D_n}{\lambda_k Q_k} + (s'_k + h'_k) \frac{Q_k(\lambda_k - 1)}{2}\right] \\ &+ \sum_k w_k \left(\sum_n N_{nk}\alpha_n D_n\right) \left[(1+r_k)^{t_k} - (1+\gamma_k)^{(t_k-d_k)^+}\right] \\ &+ \sum_n p_n \alpha_n D_n + \beta \left(\sum_n p_n \alpha_n D_n\right) \left(\left(1+r_j\right)^T - 1\right) \end{aligned} \tag{23}$$

In the above cost function, we consider only the parts containing t_k and d_k as the other parts do not have any influence on our process of proving. We have shown this part by Z':

$$\begin{aligned} Z' = &-\sum_k w_k * \left(\sum_n N_{nk}\alpha_n D_n\right) * \left[(1+r_{OEM})^{t_k} - (1+\gamma_k)^{(t_k-d_k)^+}\right] \\ &+ \sum_k w_k \left(\sum_n N_{nk}\alpha_n D_n\right) \left[(1+r_k)^{t_k} - (1+\gamma_k)^{(t_k-d_k)^+}\right] \end{aligned} \tag{24}$$

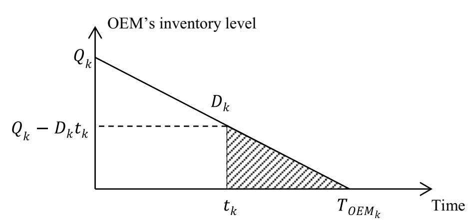

Fig. 7 The behavior of the inventory in an OEM's cycle

By simplification of (Eq. 24) we have:

$$Z' = \sum_k w_k \left(\sum_n N_{nk} \alpha_n D_n \right) \left[(1 + r_k)^{t_k} - (1 + r_{OEM})^{t_k} \right] \tag{25}$$

We can see that $(t_k - d_k)^+$ is omitted from the objective function. Therefore, we need to check these two variables only in the constraints (11) and (12).

If $t_k > d_k$ then it exacerbates these two constraints, on the contrary, putting $t_k \leq d_k$ meliorates the two constraints. So in the optimal solution, we will have $t_k \leq d_k$.

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