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A negotiation-based algorithm to coordinate supplier development in decentralized supply chains

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A B S T R A C T

In this paper, we study supplier development in a decentralized supply chain with a single manufacturer and a single supplier. Because supplier development usually requires relationship-specific investments, the allocation of investment costs is a critical issue faced by participating firms. Referencing the relational view, we first investigate the effects of relationship-specific investments on the efficiency and effectiveness of supplier development. Next, we formulate and solve a continuous time optimal control model characterizing the decision to invest in supplier development and show that the supplier's incentive to participate in supplier development critically depends on the manufacturer's share of investment costs. The findings of our numerical analysis indicate that although the subsidy can lead to significant improvement in supply chain performance, subsidizing a constant share of investment costs is not always economically reasonable from the manufacturer's point of view. Thus, we provide a negotiation-based algorithm that assists the manufacturing firm in gradually increasing the share of investment costs to ensure an efficient level of subsidy, resulting in both perfect supply chain coordination and a win–win situation.

1. Introduction

Because manufacturing firms increasingly focus on their core competencies, capable supplier networks play a paramount role in generating competitive advantage. However, suppliers too often lack the capability to perform adequately. In response, manufacturers across a wide range of industries develop closer relationships with their suppliers and initiate supplier development programs (Wagner, 2010). Within the automotive industry, Toyota initially began providing on-site assistance to help supplying firms implement lean manufacturing concepts for technological and organizational changes (Marksberry, 2012; Sako, 2004). Other automobile manufacturers have followed this collaborative approach to improve supply chain performance, including Chrysler, Daimler, Ford, General Motors, Honda, Nissan, and Volkswagen (Praxmarer-Carus, Sucky, & Durst, 2013; Talluri, Narasimhan, & Chung, 2010). Further examples of supplier development programs applied by companies outside the automotive industry can be found, among others, at Boeing, Dell, General Electric, Hewlett-Packard, Motorola, Siemens, and Walmart (Routroy & Pradhan, 2013; Wagner, 2006a).

Supplier development is broadly defined as "any effort by a buying firm to improve a supplier's performance and/or capabilities to meet the manufacturing firm's short- and/or long-term supply needs" (Krause, 1999, p. 206). Following this definition, supplier development activities are typically initiated, designed, and administered by the manufacturing firm. Moreover, it is usually assumed that suppliers are eagerly willing to adapt and implement supplier development activities imposed by the manufacturer (Mortensen & Arlbjørn, 2012). However, despite the potential benefits resulting from such participation, supplier development may not always be a paying proposition for the supplier (Kim & Netessine, 2013; Krause, Handfield, & Tyler, 2007).

Indeed, there are sound arguments why suppliers might refrain from joining in supplier development. Because resources committed to supplier development are most often relationship-specific and therefore difficult or even impossible to redeploy outside the particular business relationship, suppliers may see such investments as vulnerable to opportunistic expropriation (Wang, Li, Ross, & Craighead, 2013; Williamson, 1979). Therefore, suppliers might be reluctant to modify or improve internal processes, and instead pursue their own objectives while participating in supplier

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development (Bai & Sarkis, 2014). Because supplier development is a reciprocal approach that requires mutual recognition, misaligned objectives and the hazards of opportunistic behavior could cause inefficiency in or, even worse, the premature abandonment of the supplier development process (Blonska, Storey, Rozemeijer, Wetzels, & de Ruyter, 2013; Iida, 2012).

Given this background, the purpose of our research is to examine the alignment of the supply chain partners' objectives to enhance the supplier development process. We seek to answer the following questions: How does the risk of partner opportunism affect the supplier's willingness to participate in manufacturer-initiated supplier development? Are bilateral relationship-specific investments a viable incentive to induce desirable supplier behavior, while simultaneously facilitating value generation within supplier development? Additionally, how should the mutual investment decision be arranged to improve supply chain coordination, while both the supplier and the manufacturer increase their respective profit?

By answering these questions, our paper makes a threefold contribution. First, in reference to the relational view as a theoretical framework, we investigate the effect of relationship-specific investments on the efficiency and effectiveness of supplier development and show that the deployment of bilateral relationship-specific investments might be an important source of competitive advantage. Second, considering a decentralized supply chain consisting of one manufacturer and one supplier, we formulate a continuous time optimal control model characterizing the supplier development investment decision. Using this model, we find that the supplier's incentive to participate in supplier development critically depends on the manufacturer's share of investment costs. We then carry out an extensive numerical analysis and demonstrate that although the manufacturer's subsidy leads to significant improvement in supply chain performance, subsidizing a constant share of investment costs is not always economically reasonable from the manufacturing firm's perspective. Given the fact that for an ongoing collaborative business relationship, supply chain coordination must result in enhancing the profitability of both the manufacturer and the supplier, we third present a negotiation-based algorithm that assists the manufacturing firm in gradually increasing the share of investment costs to ensure an efficient level of subsidy. The proposed coordination scheme can be employed as a guideline to realize perfect supply chain coordination while both the manufacturer and the supplier increase their respective profit in each iteration, leading to a win–win situation.

The remaining of this paper is structured as follows. First, the related literature is briefly reviewed in Section 2 before some theoretical background on the performance implications of supplier development is provided in the subsequent Section 3. Then, the basic optimal control problem is described in Section 4 before a reference solution is computed in Section 5 assuming a centralized decision-making process. Next, two cases of a decentralized decision-making process are considered: indirect supplier development in Section 6 and direct supplier development in Section 7. Subsequently, a negotiation-based coordination algorithm is proposed and numerically analyzed in Section 8. Finally, an extension to a scenario with multiple suppliers is briefly sketched before conclusions are drawn in Section 9.

2. Related literature

The topic of supplier development has received considerable attention from researchers in the past two decades (Talluri et al., 2010). Previous research on supplier development demonstrates that manufacturing firms use a variety of activities to develop suppliers' performance and/or capabilities. With few exceptions (e.g., Hartley & Jones, 1997; Sánchez-Rodríguez, Hemsworth, & Martínez-Lorente, 2005), supplier development activities are classified by the manufacturer's level of commitment to a specific supplier (e.g., Humphreys, Cadden, Wen-Li, & McHugh, 2011; Krause, 1997; Krause, Scannell, & Calantone, 2000; Monczka, Trent, & Callahan, 1993; Wagner, 2006b). Accordingly, we distinguish two types of supplier development activities in this paper, indirect and direct supplier development.

In the case of indirect supplier development, the manufacturing firm commits no or only limited resources to a specific supplier. Instead, indirect supplier development may encompass activities such as evaluating suppliers' operations, setting performance goals, providing performance feedback, instilling competitive pressure, promising future business based on goal attainment or recognizing suppliers' progress by designating them as preferred suppliers (Krause et al., 2000; Wagner, 2010). These activities might encourage suppliers to take additional efforts to better comply with the manufacturer's requirements, resulting in unilateral deployment of relationship-specific investments.

In contrast to indirect supplier development, the manufacturer plays a more active role in the case of direct supplier development. Direct supplier development might include activities such as training given to suppliers' personnel by manufacturing firm representatives, furnishing temporary on-site support to enhance further interaction, providing equipment and tools, or even dedicating capital resources to suppliers (Monczka et al., 1993; Wagner & Krause, 2009). Thus, direct supplier development presents a more collaborative approach based on frequent manufacturer-supplier exchanges, resulting in bilateral deployment of relationship-specific investments.

Empirical research generally supports the notion that supplier development plays a critical role in driving performance and/or capabilities improvement on the part of the supplier and contributes strategically to strengthen the manufacturer's competitiveness. However, Krause and Ellram (1997) note that manufacturers' success in supplier development varies and that those who are more satisfied with the outcome of supplier development activities appear to communicate more effectively with and invest more time and resources in suppliers than do less-satisfied companies. As indicated by Krause, Handfield, and Scannell (1998), suppliers are unlikely to embrace fully a set of changes required for improvement unless there is tangible evidence that the manufacturing firm will support the supplier's efforts with matched resources. Thus, successful supplier development apparently requires bilateral deployment of resources, not only inputs from the supplying firm (Krause, 1999). Similar results are found by Krause et al. (2000), Wen-li, Humphreys, Chan, and Kumaraswamy (2003), Humphreys, Li, and Chan (2004), Krause et al. (2007), Humphreys et al. (2011) and Wagner (2011), who all state that direct support by a manufacturing firm is of major significance in determining supplier performance and/or capabilities improvement, thus enhancing the manufacturer's competitiveness.

Although direct involvement by the manufacturing firm seems to be an important antecedent of successful supplier development, mounting anecdotal evidence indicates that the majority of manufacturers are generally very hesitant to commit considerable resources to external, independent suppliers. As Monczka et al. (1993) determine, manufacturers are reluctant to conduct direct supplier development activities when they fear that competitors may benefit from the supplier's capability improvements. Furthermore, Krause (1997) reports that relationship-specific investments in suppliers' operations are rarely used compared with indirect supplier development activities. In line with this, Krause and Scannell (2002) state that manufacturers' commitment appears to be non-existent when a need for direct investments arises in the context of supplier development. Similar results are found by Wagner (2006a), Carr and Kaynak (2007), and Wagner and Krause (2009).

There also have been some analytical, formal modeling-oriented studies of supplier development. Using rough set theory, Bai and Sarkis (2010) introduce a formal model to investigate relationships between organizational attributes, firms' involvement in supplier development, and performance outcomes. Using interpretative structural modeling, Govindan, Kannan, and Haq (2010) present a framework to analyze interactions among several critical success factors of supplier development. Furthermore, Talluri et al. (2010) present a set of optimization models proposed for assisting manufacturers in making optimal resource allocation decisions among different suppliers while minimizing the level of risk. Based on a profit-maximizing framework, Friedl and Wagner (2012) study a manufacturer's decision regarding whether to develop a deficient supplier or switch to an alternative source. Routroy and Pradhan (2013) propose a fuzzy analytic hierarchy process to evaluate the effect of critical success factors on the performance of supplier development. Focusing on green supplier development, Dou, Zhu, and Sarkis (2014) introduce a gray analytical network process-based model to identify supplier development activities that effectively improve suppliers' performance. Bai and Sarkis (2014) model cooperative and non-cooperative supplier development situations as a game-theoretic analytical evaluation and explore the effect of returns to scale on investment strategies. Recently, Bai, Dhavale, and Sarkis (2016) introduce a novel integration of rough set theory and fuzzy clustering means to provide a methodology for decision modeling in the context of green supplier development.

Both empirical evidence and analytical investigations agree that manufacturer's direct involvement is critical to the supplier's participation in supplier development. However, development of a theoretical understanding of the effect of bilateral relationship-specific investments on the performance of supplier development and the application of formal decision-making models proposed for assisting supply chain partners in balancing such investments in an appropriate manner have received limited attention in the supplier development literature.

In this paper, we consider a manufacturer's problem of incentivizing suppliers to participate in supplier development programs. We specifically focus on direct supplier development, i.e., bilateral relationship-specific investments, as incentive instrument to achieve supply chain coordination. Thus, our research also contributes to the stream of literature in operations research that examines the coordination of suppliers' cost-reduction efforts in decentralized supply chains.

Several aspects of cost reduction have been studied in the context of decentralized decision structures (Li & Wang, 2007). Kim (2000) considers a supply chain in which the manufacturer subsidizes supplier's innovation that can eventually lead to supply cost reduction and thereby increasing channel profit in a continuous time setting. Gilbert and Cvsa (2003) study the effect of price commitment to encourage downstream investments in cost-reduction initiatives under the assumption of demand uncertainty. Considering an assembly system with a single manufacturer and multiple suppliers, Bernstein and Kök (2009) examine the dynamics of suppliers' investments in cost reduction through process improvement efforts over the life cycle of a product. Kogan and Tapiero (2009) present an inter-temporal model of co-investment in the supply chain infrastructure and show that supply chain performance deteriorates if the firms do not cooperate. Lee, Palekar, and Qualls (2011) study coordination problems and corresponding incentive mechanisms between a retailer and a manufacturer for jointly investing in information technologies that have the potential to improve supply chain efficiency. Iida (2012) investigates two different types of agreements, namely effort sharing agreements and effort compensation agreements, to achieve supply chain coordination and advance cooperative cost-reduction activities. Using single-period oligopoly and Cournot duopoly models, Li, Wang, Yin, Kull, and Choi (2012) examine the impact of joint cost-reduction efforts on the equilibrium outcome. Kim and Netessine (2013) investigate how incentives to collaborate are impacted by information asymmetry and contracting strategies, considering a setting where both the supplier and the manufacturer exert collaborative efforts to reduce the unit cost of a critical component during product development. Recently, Bernstein, Kök, and Meca (2015) investigate the benefits and challenges of knowledge sharing activities in a decentralized assembly network in which suppliers invest in process improvement initiatives to reduce the fixed production costs.

In this context, our paper complements research that considers incentive instruments to induce desirable supplier behavior, e.g., pricing mechanism, contract design, and subsidies for cost-reduction initiatives. However, unique features of our study, e.g., the specific supplier development context and the introduction of a negotiation-based coordination algorithm that assists the manufacturing firm in gradually increasing the share of investment costs to ensure an efficient level of subsidy, differentiate this paper from the existing literature.

3. Theoretical background

Sources of economic rents and competitive advantage have received considerable attention in the strategic management literature. Whereas the industry structure view (e.g., Porter, 1980) suggests that economic rents are primarily a function of the structural characteristics of an industry, the resource-based view of a firm (e.g., Barney, 1991; Wernerfelt, 1984) argues that economic rents are fundamentally due to firm heterogeneity rather than industry structure. However, because critical resources may extend beyond firm boundaries, researchers have also adopted a relational approach to explain how business relationships can be a source of competitive advantage. According to the relational view as proposed by Dyer and Singh (1998), firms who combine, share and invest in relationship-specific assets, substantial knowledge, complementary resources, and effective governance may realize relational rents that cannot be generated by either firm in isolation. This suggests that activities of supplier development, in which firms convert general-purpose assets such as money, people skills or managerial knowledge into relationship-specific assets, obviously represent a rent-generating process in accordance with the relational view (Krause et al., 2007; Sánchez-Rodríguez, 2009).

However, in spite or even because of their relevance for companies, relationship-specific assets entail considerable risk and thus are two-sided. As proposed by transaction cost economics (e.g., Williamson, 1979), investments in specialization are difficult to redeploy outside the focal relationship because specializing a resource lowers its value for alternative uses (Crosno & Dahlstrom, 2008; Wang et al., 2013). As such, relationship-specific investments lock in the investor and enable the receiver to opportunistically exploit or expropriate the investments' value by using ex post bargaining or threats of termination (Lui, Wong, & Liu, 2009; Rokkan, Heide, & Wathne, 2003). Therefore, the investing firm sees high levels of unilateral relationship-specific investments as vulnerable to opportunistic expropriation, particular in a dynamic and uncertain business environment (Hawkins, Wittmann, & Beyerlein, 2008; Sambasivan, Siew-Phaik, Mohamed, & Leong, 2013).

Thus, in the case of unilateral relationship-specific investments, e.g., indirect supplier development, suppliers tend to assign considerable resources to eradicate or at least minimize the hazards of opportunistic behavior by the manufacturer. This in turn influences the supplier's transaction costs, e.g., ex ante costs of drafting, negotiating and safeguarding an agreement and ex post costs of adjusting contracts to respond to unexpected contingencies, resulting in decreased efficiency of supplier development activities

(Vázquez, Iglesias, & Bosque, 2007; Xie, Suh, & Kwon, 2010). Additionally, concerns about partner opportunism might also temper a supplier's incentive to contribute resources to manufacturer-initiated supplier development activities in the first place, a decision that might lead to underinvestment and thus potentially undermine the manufacturer's effort to improve supplier performance (Artz, 1999; Rokkan et al., 2003).

According to the relational view, the employment of effective governance may influence transaction costs and the willingness of firms to engage in supplier development initiatives, a condition that could be an important source of competitive advantage (Dyer & Singh, 1998; Li, Humphreys, Yeung, & Cheng, 2007). In the first case, firms achieve an advantage by incurring lower transaction costs to realize a given level of supplier development specificity. In the second case, appropriate safeguard mechanisms encourage companies to make higher investments in relationship-specific assets (Dyer, 1996b; Vázquez et al., 2007). Following this line of reasoning, firms' ability to align a considerable level of relationship-specific investments with an appropriate safeguard mechanism could enhance efficiency and effectiveness of supplier development activities and thereby should be critical to the success of supplier development.

Although firms can select a variety of safeguard mechanisms, legal contracts are typically considered the primary formal means for safeguarding transactions. Contracts are formalized, legally binding agreements that explicitly specify the obligations of each firm (Artz, 1999). If one firm violates the terms of the contract, the other has the right to go to a third party to impose corrective action. Thus, contracts can prevent opportunistic behavior through legal force (Liu, Luo, & Liu, 2009). The drawback to contractual mechanisms is that as the transaction becomes more complex, so too must the contract protecting the exchange – and the costs of writing, monitoring and enforcing the contract increase (Dyer, 1997).

Another approach to managing opportunistic behavior in manufacturer-supplier relationships is to design incentive structures that deter opportunistic behavior. In Telser's (1980) terminology, a strong disincentive for partner opportunism can be created by designing self-enforcing agreements that make long-term gains from the ongoing relationship exceed potential short-term payoffs from acting opportunistically, making the use of legal contracts redundant. Scholars usually argue that self-enforcing agreements are a less costly and more effective means of safeguarding relationship-specific investments (Artz, 1999; Dyer, 1996a). Within self-enforcing agreements, contracting costs are avoided because firms behave in a more trustworthy fashion. Therefore, specifying every detail of the agreement in a contract is not necessary. In addition, monitoring costs are lower because self-enforcement relies on self-monitoring rather than external or third party monitoring. Finally, self-enforcing agreements lower the costs associated with complex adaptation because firms are able to adjust the agreement in a straightforward manner to respond to unforeseen market changes (Dyer & Singh, 1998).

Several researchers suggest that firms can accomplish self-enforcing agreements by making bilateral relationship-specific investments (e.g., Anderson & Weitz, 1992; Gundlach, Achrol, & Mentzer, 1995; Jap & Anderson, 2003; Palmatier, Dant, & Grewal, 2007). It is argued that investments made by both sides of an exchange serve as mutual hostages or as credible commitments that motivate firms to make the relationship work. On the one hand, bilateral relationship-specific investments strengthen the bonds between companies and contribute to a stable relationship because reciprocal actions are considered indications of each firm's commitment to the relationship. On the other hand, bilateral credible commitments tend to diminish the potential threat of partner opportunism because opportunistic behavior by one party can be met by retaliation from the other, a situation that could lead to the forfeiture of both the buyer's and the supplier's investments' actual value (Xie et al., 2010).

Therefore, if both manufacturer and supplier invest in supplier development, a self-enforcing agreement will exist that should make the installation of an additional governance mechanism redundant. With fewer opportunism concerns and lower safeguarding costs, supplier development becomes more efficient, more prone to joint action and includes greater expectations of continuity, all of which contribute to enhanced performance. In other words, direct supplier development provides an incentive to the supplier to behave in a more trustworthy fashion to maintain and continue the relationship until the value of its investments is recouped.

4. Basic model

We consider a particular two-stage supply chain situation with a supplier S and a manufacturer M, in which M assembles components from S and sells the final product to the market. Let the price distribution function $p : \mathbb{R} \to \mathbb{R}$, which establishes a connection between the production quantity d and its sale price p, be given by $p(d) = a - bd$ where coefficients $a > 0$ and $b > 0$ denote the prohibitive price, e.g., the maximum willingness to pay, and the price elasticity of the commodity, respectively. This situation might be comparable with an oligopolistic or monopolistic market condition, in which a firm can increase market demand by lowering the sale price. Note that we do not distinguish market demand from the production quantity of the manufacturer because the market price is endogenous to the quantity sold. Ignoring fixed costs, the manufacturer's profit is

$$d \cdot (p(d) - c_M - c_{SC}). \tag{1}$$

Here, c_M denotes the manufacturer's unit production costs, whereas c_{SC} represents the supply costs per unit charged by S. Because the manufacturer's goal is profit maximization, the production quantity d chosen by M is determined by differentiating (1) w.r.t. d and setting the resulting expression equal to zero, i.e.,

$$p(d) - c_M - c_{SC} - bd \stackrel{!}{=} 0, \tag{2}$$

which yields the optimum production quantity $d^\star = \frac{a - c_M - c_{SC}}{2b}$ and the optimal sale price $p(d^\star) = \frac{a + c_M + c_{SC}}{2}$. Since (1) is a quadratic and concave function, (2) is a necessary and sufficient condition for profit maximization.

Typically, M is contractually obliged to S for a certain period, or T time units. Assuming that supply costs c_{SC} are constant over the contract period [0, T], the manufacturer's overall profit is

$$J_0^M := T \cdot (d^\star \cdot (p(d^\star) - c_M - c_{SC})) = \frac{(a - c_M - c_{SC})^2}{4b} \cdot T.$$

Furthermore, let us suppose that the supply costs consist of the supplier's fixed profit margin r and the supplier's unit production costs c_S, i.e., $c_{SC} = r + c_S$. Thus, M commits to pay a constant margin above the expected unit production costs of S, no matter what level of d is realized. Similar approaches to specify the supply costs have been proposed by Bernstein and Kök (2009), Li et al. (2012), and Kim and Netessine (2013). We do not consider the detailed negotiations of a particular profit margin and simply consider r as exogenously given. Moreover, the supplier produces the components to satisfy d; thus, S does not make a production quantity decision. Hence, the supplier's profit is

$$J_0^S := d^\star \cdot r \cdot T = \frac{a - c_M - (r + c_S)}{2b} \cdot r \cdot T,$$

and the overall profit of the supply chain is

$$J_0^{SC} := J_0^M + J_0^S = \frac{(a - c_M - c_S)^2 - r^2}{4b} \cdot T.$$

We further assume that M wants to decrease c_S by establishing supplier development projects on the supplier's side to increase the market share, which might lead to an increased overall profit of the supply chain. To this end, the sustainable effect of supplier development on the supplier's unit production costs c_S is modeled by $c_S(x) = c_0 x^m$, where $c_0 > 0$ denotes the supplier's unit production cost at the beginning of the contract period, m the supplier's learning rate, and x measures the undertaken effort, e.g., the cumulative number of realized supplier development projects. The effort is modeled as a time-dependent function $x : [0, T] \to \mathbb{R}_{\geq 0}$ governed by dynamics

$$\dot{x}(t) := \frac{d}{dt}x(t) = u(t), \qquad x(0) = x_0 = 1, \tag{3}$$

with u: $[0, T) \to [0, \omega]$ to reflect that x increases during the contract period. Indeed, the ordinary differential Eq. (3) is easy to solve, i.e., $x(t) = x_0 + \int_0^t u(s)\, ds$ assuming u to be sufficiently regular such that the solution of the differential equation uniquely exists and is (at least) absolutely continuous. Here, $u(t)$ represents the effort at time t, with a capacity limit of $\omega > 0$, e.g., the resource availability in terms of time, manpower or budget. Because an accurate determination of ω is not critical to our discussion, a presumption is made that ω is exogenously assessed to be feasible to the problem. The learning rate $m = \frac{\ln(1-\theta)}{\ln \chi}$, $\theta \in [0, 1)$ and $\chi > 1$, can be interpreted as follows. If, e.g., parameters $\theta = 0.05$ and $\chi = 2$ are used, the effort x must be doubled to reduce the supplier's production costs $c_S(x) = c_0 x^m$ per unit by 5 percent. Similar models of cost reduction through learning have been proposed by Yelle (1979), Fine and Porteus (1989), Kim (2000), Bernstein and Kök (2009), and Li et al. (2012).

In summary, $c_S(x(t)) = c_0 x(t)^m$ is time varying, continuously decreasing, strictly positive, and convex. It is important to realize that, consequently, not only the optimal quantity offered $d^\star(c_{SC})$ but also the respective optimal sale price and the profit become time dependent. Moreover, adding $c_{SD}u(t)$, $c_{SD} \geq 0$, to the overall profit of the supply chain allows for integrating the costs of supplier development into the proposed model. Hence, a central task is to understand how supplier development contributes to the total profit, i.e., whether improving the cost structure c_S to generate further revenues outweighs the additional costs of supplier development. Answering this question naturally leads to seeking the best solution under the guiding principle of profit maximization. In the subsequent section, an optimal control problem is formulated to rigorously deduce the solution.

5. Supplier development in a centralized supply chain

In this section, we assume the existence of a central entity managing the supply chain as an integrated system in which all parameters, e.g., the optimal amount of effort invested in supplier development, are simultaneously chosen. We call the resulting solution of the problem the *centralized solution* because it is based on a centralized decision-making process.

Employing the variables and parameters of the preceding section, the profit function $J^{SC} : \mathcal{L}^1([0, T), \mathbb{R}) \to \mathbb{R}$ defined as

$$J^{SC}(u) := \int_0^T \frac{(a - c_M - c_0 x(t)^m)^2 - r^2}{4b} - c_{SD}u(t)\, dt \tag{4}$$

must be maximized subject to the control constraints $0 \leq u(t) \leq \omega$, $t \in [0, T)$, and the system dynamics (3). $\mathcal{L}^1([0, T), \mathbb{R})$ is the set of measurable functions for which the condition $\int_0^T |u(t)|\, dt < \infty$ holds. Mathematically speaking, the central entity must solve an optimal control problem to determine the optimal control function $u^\star$, i.e., the centralized optimal collaboration strategy, such that the accumulated profit $J^{SC}(\cdot)$ is maximized.

Because investments $c_{SD}u(t)$ pay off over time due to an improved cost structure, the optimal control function $u^\star$ is structurally of the shape

$$u^\star(t) := \begin{cases} \omega & \text{if } t < t^\star \\ 0 & \text{if } t \geq t^\star \end{cases}, \tag{5}$$

with $t^\star \in [0, T]$ not yet determined. Here, $t^\star = 0$ corresponds to the case in which supplier development does not increase the accumulated profit, i.e., the considered time horizon T (contract period) is too short such that the achievable cost reduction does not outweigh the required capital effort $\int_0^T c_{SC}u(t)\, dt$. Hence, the optimal control problem to be solved corresponds to finding $t^\star$ such that the system-wide optimum is attained. The claims based on heuristic arguments can be deduced in a rigorous manner by using Pontryagin's maximum principle (see, e.g., Kim, 2000) and noting that $J^{SC}(\cdot)$ is continuous whereas parameter $t^\star$ is limited to a compact (closed and bounded) interval.

Note that the production quantity $d(t)$ at time t is solely chosen by M without considering any collaboration effects. This assumption on the decision-making process justifies the optimal sale price used in the above calculations. Albeit the phenomenon of a so-called double marginalization may lead to a suboptimal solution (Li, Li, & Cai, 2013), this assumption is made to assess the efficiency of the proposed coordination mechanism separately.

Remark 5.1. Although $J^{SC}(\cdot)$ is optimized w.r.t. $u \in \mathcal{L}^1([0, T), [0, \omega])$, i.e., it is a set of measurable and bounded functions, the optimal control function $u^\star(\cdot)$ is piecewise constant and bang-bang with one jump at $t^\star$. Hence, the resulting solution is easily implementable and corresponds to (full) cooperation in terms of supplier development until time $t^\star$. Then, the improved cost structure is exploited without making further investments.

Pontryagin's maximum principle is used to solve the optimal control problem (4). To this end, the so-called Hamiltonian $\mathcal{H}(\cdot)$, which is defined as

$$H(x, u, \lambda) := \frac{(a - c_M - c_0 x^m)^2 - r^2}{4b} - c_{SD}u + \lambda u,$$

is needed to formulate the necessary optimality conditions. This yields the system dynamics

$$\dot{x}^\star(t) = H_\lambda(x^\star(t), u^\star(t), \lambda(t)) = u^\star(t),$$

the so-called adjoint $\lambda : [0, T] \to \mathbb{R}$, which is characterized by

$$\dot{\lambda}(t) = -H_x(x^\star(t), u^\star(t), \lambda(t)) = \frac{mc_0 x^\star(t)^{m-1}(a - c_M - c_0 x^\star(t)^m)}{2b} \tag{6}$$

and the transversality condition

$$\lambda(T) = 0. \tag{7}$$

Solving the optimal control problem yields the structural property (5) of the optimal control function $u^\star$. Then, the (absolutely continuous) state trajectory

$$x^\star(t) = \begin{cases} 1 + \omega t & t \in [0, t^\star) \\ 1 + \omega t^\star & t \in [t^\star, T] \end{cases} \tag{8}$$

can be computed using the system dynamics (3) and the initial condition $x(0) = x_0 = 1$. In particular, $x^\star(t) \geq 1$ holds for all $t \in [0, T]$. Hence, Eq. (6) implies that the adjoint $\lambda(\cdot)$ exhibits a strictly negative derivative, i.e., $\dot{\lambda}(t) < 0$ since the inequalities $m < 0$ and $a > c_M + c_0$ imply $a > c_M + c_0 x^\star(t)^m$ for all $t \in [0, T]$. Moreover, using (8), the system dynamics of the adjoint (6), and the transversality condition (7) allow us to calculate the adjoint

$$\lambda(t) = \frac{mc_0(1 + \omega t^\star)^{m-1}(a - c_M - c_0(1 + \omega t^\star)^m)}{2b} \cdot (t - T)$$

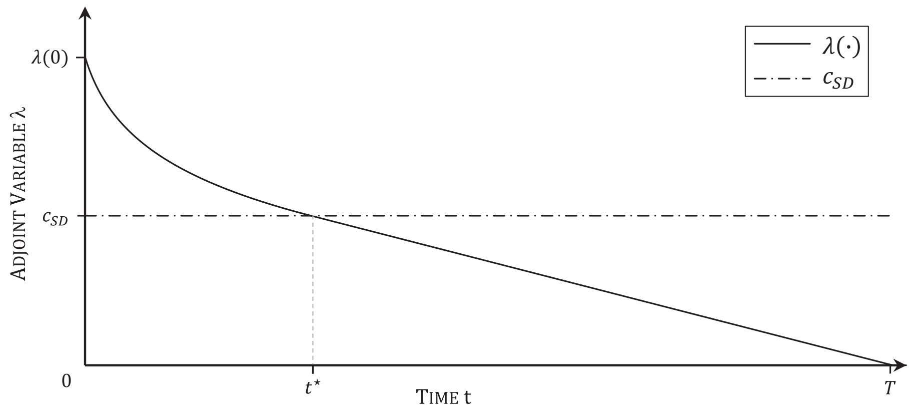

Fig. 1. Illustration of the switching condition (9).

for all $t \in [t^\star, T]$. Then, based on the fact that $m < 0$ holds, the adjoint Eq. (6) implies $\lambda(t)$, $t \in [0, t^\star]$,

$$\begin{aligned}\lambda(t) &= \lambda(t^\star) - \int_t^{t^\star} \dot{\lambda}(s)\,\mathrm{d}s \\ &= \lambda(t^\star) - \frac{mc_0(a-c_M)}{2b}\int_t^{t^\star} x(s)^{m-1}\mathrm{d}s + \frac{mc_0^2}{2b}\int_t^{t^\star} x(s)^{2m-1}\mathrm{d}s \\ &= \lambda(t^\star) - \frac{c_0(a-c_M)((1+\omega t^\star)^m - (1+\omega t)^m)}{2\omega b} \\ &\quad + \frac{c_0^2((1+\omega t^\star)^{2m} - (1+\omega t)^{2m})}{4\omega b}.\end{aligned}$$

Hence, the switching time $t^\star$ can be computed by solving the equation

$$H_u(x^\star(t), u^\star(t), \lambda(t)) = -c_{SD} + \lambda(t) = 0$$

and is thus given by the solution of the equation

$$\frac{mc_0(1+\omega t^\star)^{m-1}(a - c_M - c_0(1+\omega t^\star)^m)}{2b} \cdot (t^\star - T) = c_{SD} \qquad (9)$$

with respect to $t^\star$. Consequently, the optimal control function $u^\star$ and the resulting profit $J^{SC}(u^\star)$ are determined.

Economically, the adjoint variable λ can be interpreted as a shadow price that represents the rate of infinitesimal change of the performance measure, i.e., the marginal revenue, with respect to an infinitesimal change of the state variable $x(\cdot)$. Hence, by means of the adjoint variable λ and the supplier development costs c_{SD}, the economic efficiency (profitability) of further investments in supplier development can be assessed. As expressed by the switching condition (9), at time $t^\star$ the adjoint variable $\lambda(t^\star)$ equals the supplier development costs c_{SD}. Hence, cost-reduction efforts after time $t^\star$ are not economically reasonable, see Fig. 1 for an illustration.

Assumption 5.1. Throughout this paper it is tacitly assumed that supplier development can increase the supply chain profit. Furthermore, it is supposed that full cooperation, i.e., $\bar{u}(t) = \omega$ for all $t \in [0, T)$, is not the optimal solution. Mathematically speaking, this implies the existence of a collaboration strategy $u \in \mathcal{L}^1([0,T), \mathbb{R})$ satisfying $0 \le u(t) \le \omega$, $t \in [0, T)$, such that the inequality

$$J^{SC}(u) > \max\{J_0^{SC}, J^{SC}(\bar{u})\}$$

holds and thus ensures that the (global) maximum is attained for a switching time $t^\star$ located in the *open* interval (0, T). Here, J_0^{SC} and $J^{SC}(\bar{u})$ represent $t^\star = 0$ (no collaboration) and $t^\star = T$ (full collaboration), respectively.

Because an optimal solution exists and Assumption 5.1 holds, every optimal solution must satisfy the necessary optimality conditions resulting from Pontryagin's maximum principle. Furthermore, note that the solution of (9) is unique, because the adjoint and thus the left hand side of this equation are strictly monotonically decreasing. Hence, taking the structural property (5) into account, the switching time $t^\star \in (0, T)$ and the corresponding optimal control function $u^\star(\cdot)$ are uniquely determined.

In conclusion, considering the profit in dependence of the switching time t, the deduced qualitative behavior directly implies that the supply chain profit strictly increases for switching times $t \in [0, t^\star)$, which are smaller than the optimal switching time $t^\star$, and then strictly decreases for switching times $t \in (t^\star, T]$, see Fig. 2 for an illustration.

In short, an elementary proof showing that the necessary condition resulting from Pontryagin's maximum principle is also sufficient in the considered setting was presented. An alternative line of argumentation analogous to Chiang (1992), which structurally fits the optimal control problem to be solved and thus could be applied, would lead to the same conclusion.

The decision-making process in a centralized supply chain ensures system efficiency and opts for the optimum level of supplier development, i.e., maximizes the total (expected) profit of the supply chain. Thus, the *centralized solution* serves as a benchmark for the following analysis.

6. Indirect supplier development in a decentralized supply chain

Next, we consider the decision-making process in a decentralized supply chain, which differs from the centrally planned one in two fundamental aspects. First, there is no information exchange during the planning phase, resulting in asymmetrical distribution of information, e.g., information about the supplier's cost structure may be unknown to the manufacturer. Second, every decision maker in a supply chain typically has different objectives, which may lead to conflicting strategic orientations. The presence of both issues could cause inefficiency in the supply chain (Corbett, 2001; Iida, 2012). Consequently, the solution of the decision-making process in a decentralized supply chain could deviate from the *centralized solution*.

We first analyze the supplier's optimal decision-making process under the assumption of indirect supplier development, in which the supplier must bear the invested effort alone. Intuitively, S will determine the optimal supplier development level to reduce the unit production costs of the components, considering the manufacturer's optimal reaction in terms of procurement quantity. Then, the supplier's cost-reduction efforts are realized. Next, M chooses the optimal production quantity based on the resulting supply price. Our solution approach formalizes the above reasoning.

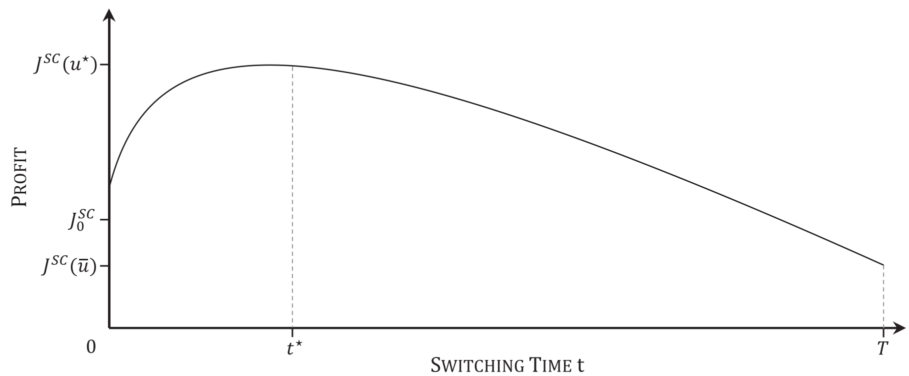

Fig. 2. The supply chain profit J^{SC} is depicted in dependence of the switching time t.

6.1. Indirect supplier development

In the case of indirect supplier development the supplier's profit $J^S : \mathcal{L}^1([0,T),\mathbb{R}) \to \mathbb{R}$, which is defined as

$$J^S(u_S) := \int_0^T \frac{a - c_M - (r + c_0 x(t)^m)}{2b} \cdot r - c_{SD} u_S(t)\,\mathrm{d}t, \tag{10}$$

is maximized subject to the system dynamics (3) and the control constraints $0 \le u_S(t) \le \omega$, $t \in [0, T)$, where the index S indicates that u_S represents the collaboration strategy from the supplier's point of view. Note that also the cumulative number of realized supplier development projects $x(\cdot)$ at time t depends of the chosen control function u_S in view of the differential equation (3). However, we dropped the index S in order to streamline the presentation. In summary, S solves an optimal control problem to determine the supplier's optimal control function $u_S^\star$ such that the supplier's profit $J^S(u_S^\star)$ is maximized.

Proceeding analogously to the centralized approach, the supplier's adjoint equation is characterized by

$$\dot{\lambda}_S(t) = \frac{rmc_0 x(t)^{m-1}}{2b}$$

and the corresponding adjoint is given by

$$\lambda_S(t) = \begin{cases} \frac{rmc_0(1+\omega t_S^\star)^{m-1}}{2b} \cdot (t - T) & t \in [t_S^\star, T] \\ \lambda_S(t_S^\star) - \frac{rc_0}{2\omega b}((1+\omega t_S^\star)^m - (1+\omega t)^m) & t \in [0, t_S^\star) \end{cases}.$$

Here, $t_S^\star$ must satisfy $\lambda_S(t_S^\star) = c_{SD}$, i.e.,

$$\frac{rmc_0(1+\omega t_S^\star)^{m-1}}{2b} \cdot (t_S^\star - T) = c_{SD}. \tag{11}$$

Hence, the supplier's optimal control function $u_S^\star$ and the supplier's profit $J^S(u_S^\star)$ are determined.

In the indirect supplier development case, it is implicitly assumed that the investment decision is solely up to the supplier. This assumption is justified, because S covers all supplier development costs $\int_0^T c_{SD} u_S(t)\,\mathrm{d}t$, whereas M benefits from the supplier's cost-reduction efforts by reduced supply costs without committing any resources to supplier development. Indeed, M would opt for full cooperation, i.e., $\bar{u}(t) = \omega$ for all $t \in [0, T)$. From the supplier's point of view, however, cost-reduction efforts after time $t_S^\star$ do not amortize during the contract period and thus are not economically reasonable, see Fig. 3. Hence, the collaboration stops after $t_S^\star$ time units.

Consequently, the corresponding manufacturer's profit is given by

$$J^M(u_S^\star) := \int_0^T \frac{(a - c_M - r - c_0 x(t)^m)^2}{4b}\,\mathrm{d}t.$$

Summing up $J^S(u_S^\star) + J^M(u_S^\star)$ yields $J^{SC}(u_S^\star)$.

6.2. Comparison with the centralized solution

We next compare the *centralized solution*, cf. Section 5, with the outcome of the decentralized decision-making process in the case of indirect supplier development. Here, it can be observed that the structural property (5) is maintained. However, the switching time $t_S^\star$ may change.

Proposition 6.1. *Let Assumption 5.1 hold. Then, the supply chain profit obtained in the centralized decision-making process characterized by $t^\star$ is superior in comparison to its counterpart obtained in the decentralized setting characterized by $t_S^\star$.*

Proof. Since it has been shown in Section 5 that the optimal solution is unique, showing that $t^\star \neq t_S^\star$ holds is sufficient to prove the assertion. Using Eqs. (9) and (11) leads to

$$r \cdot f(t_S^\star) = (a - c_M - c_0(1+\omega t^\star)^m) \cdot f(t^\star)$$

with strictly decreasing function $f : [0,T] \to \mathbb{R}_{\ge 0}$ defined as $f := t \mapsto \frac{mc_0(1+\omega t)^{m-1}\cdot(t-T)}{2b}$. Hence, if $r < (a - c_M - c_0(1+\omega t^\star)^m)$ holds, the switching time for the *centralized solution* $t^\star$ will be strictly larger than its counterpart $t_S^\star$ for the decentralized one.

Because the prohibitive price a is strictly larger than the costs per unit $c_M + c_{SC} = c_M + r + c_0$ without any supplier development – a necessary condition for the manufacturer – the inequality $a > c_M + c_{SC}(t) = c_M + r + c_0(1+\omega t)^m$ holds for all $t \in [0, T]$ and thus in particular for $t^\star \in (0, T]$, i.e., in the case that supplier development can contribute to the supply chain profit. Hence, the assertion follows. □

In other words, if the supplier defrays all supplier development costs, i.e., indirect supplier development, S will choose a smaller switching time $t_S^\star$, $t_S^\star < t^\star$, and thus will stop the collaboration "too early".

7. Direct supplier development in a decentralized supply chain

Next, we investigate the decentralized decision-making process under the assumption of direct supplier development. Hereto, we suppose that the manufacturer covers a certain share αc_{SD}, $\alpha \in (0, 1]$, of the supplier development costs c_{SD} to align potentially contradictory objectives and thus alleviate the inefficiencies occurring in the indirect supplier development case. This assumption is not completely new: within the automobile industry, for instance, manufacturers offer assistance by providing training, equipment and tools to their suppliers, or sharing the monetary costs of investments (Bernstein et al., 2015; Sako, 2004). Moreover, similar approaches to specify a subsidy for cost-reduction initiatives have also been proposed by Iida (2012), Li et al. (2012), and Bernstein and Kök (2009).

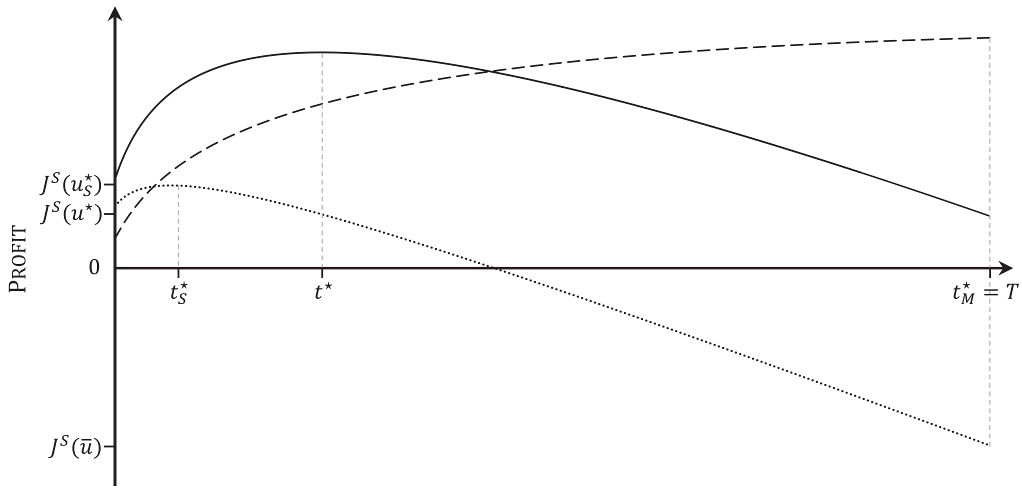

Fig. 3. The supply chain profit J^{SC} (solid line), the supplier's profit J^S (dotted line), and the manufacturer's profit J^M (dashed line) are depicted in dependence of the switching time t.

7.1. Direct supplier development

Incorporating the cost allocation factor α, the supplier's profit function (10) is changed to

$$J^S(u_S) := \int_0^T \frac{a - c_M - (r + c_0 x(t)^m)}{2b} \cdot r - (1-\alpha) c_{SD} u_S(t) \,\mathrm{d}t,$$

while the manufacturer's profit function is given by

$$J^M(u_M) := \int_0^T \frac{(a - c_M - r - c_0 x(t)^m)^2}{4b} - \alpha c_{SD} u_M(t) \,\mathrm{d}t,$$

where the index M indicates that $u_M(\cdot)$ represents the collaboration strategy from the manufacturer's point of view.

In the case of direct supplier development the manufacturer supports the supplier's cost-reduction efforts with, e.g., matched resources, and thus actively participates in the decentralized decision-making process. Hence, both the supplier *and* the manufacturer solve an optimal control problem to determine their optimal control functions $u_S^\star$ and $u_M^\star$ maximizing their individual profits $J^S(u_S^\star)$ and $J^M(u_M^\star)$, respectively.

Due to the adaptation of the cost functional J^S, the right hand side of the supplier's switching condition (11) is multiplied with the factor $(1-\alpha)$, i.e.,

$$\frac{rmc_0(1+\omega t_S^\star)^{m-1}}{2b} \cdot (t_S^\star - T) = (1-\alpha) c_{SD}, \qquad (12)$$

which yields $t_S^\star$ and, consequently, the supplier's optimal control function $u_S^\star$.

Applying the same reasoning as in the centralized approach, it can be observed that the structural property (5) also holds for M. Thus, the manufacturer's adjoint equation is characterized by

$$\dot{\lambda}_M(t) = mc_0 x(t)^{m-1} \cdot (a - c_M - r - c_0 x(t)^m)/(2b) \qquad (13)$$

and the manufacturer's adjoint is given by

$$\lambda_M(t) = \begin{cases} \frac{mc_0(1+\omega t_M^\star)^{m-1} \cdot (a - c_M - r - c_0(1+\omega t_M^\star)^m)}{2b} \cdot (t - T) & \text{for } t \in [t_M^\star, T] \\ \lambda_M(t_M^\star) - \frac{c_0(a - c_M - r)[(1+\omega t_M^\star)^m - (1+\omega t)^m]}{2\omega b} + \frac{c_0^2[(1+\omega t_M^\star)^{2m} - (1+\omega t)^{2m}]}{4\omega b} & \text{for } t \in [0, t_M^\star) \end{cases}. \qquad (14)$$

The manufacturer's optimal switching time $t_M^\star$ is determined by the switching condition $\lambda_M(t_M^\star) = \alpha c_{SD}$, i.e.,

$$\frac{mc_0(1+\omega t_M^\star)^{m-1} \cdot (a - c_M - r - c_0(1+\omega t_M^\star)^m)}{2b} \cdot (t_M^\star - T) = \alpha c_{SD}, \qquad (15)$$

which characterizes the manufacturer's optimal control function $u_M^\star$.

In general, $t_M^\star$ and $u_M^\star$ do not coincide with $t_S^\star$ and $u_S^\star$, respectively. However, direct supplier development is a reciprocal approach that requires a mutually agreed collaboration strategy between the participating firms. Consequently, M cannot pursue the manufacturer's optimal collaboration strategy without considering the supplier's optimal collaboration strategy, and vice versa. Here, we heavily exploit the structural property (5): both S and M monotonically increase their respective profit until $t = \min\{t_S^\star, t_M^\star\}$, because their respective investments in supplier development pay off during the considered time interval [0, T] due to an improved cost structure. Hence, both firms willingly collaborate until that time. However, for $t > \min\{t_S^\star, t_M^\star\}$ further cost-reduction efforts do not amortize during the contract period from the perspective of at least one firm, cf. the switching conditions (12) and (15). Because prolonging supplier development is not economically reasonable for at least one firm, the collaboration stops at $t = \min\{t_S^\star, t_M^\star\}$. Mathematically speaking, the (mutually agreed) collaboration strategy on supply chain level is limited by $\min\{t_S^\star, t_M^\star\}$. In conclusion, the (mutually agreed) optimal control function $u_{SC}^\star$ is structurally of shape

$$u_{SC}^\star(t) := \begin{cases} \omega & \text{if } t < \min\{t_S^\star, t_M^\star\} \\ 0 & \text{if } t \geq \min\{t_S^\star, t_M^\star\} \end{cases},$$

as illustrated in Fig. 4.

Accordingly, the individual firms' profits are now determined by $u_{SC}^\star$. Summing up $J^S(u_{SC}^\star) + J^M(u_{SC}^\star)$ yields the overall supply chain profit $J^{SC}(u_{SC}^\star)$.

Proposition 7.1. *Let Assumption 5.1 hold and let $\alpha \in [0, 1]$ be given. Then, if the individual firms' switching times $t_S^\star \in [0, T]$ and $t_M^\star \in [0, T]$ do not coincide, the centralized decision-making process characterized by $t^\star$ leads to a (strictly) higher supply chain profit $J^{SC}(u^\star)$ than its counterpart $J^{SC}(u_{SC}^\star)$ with switching time $t_{SC}^\star := \min\{t_S^\star, t_M^\star\}$ obtained in the case of (in)direct supplier development.*

Proof. For $\alpha = 0$, i.e., indirect supplier development, the assertion follows directly from Proposition 6.1. Hence, let α be contained in the interval $(0, 1]$. Since it has been shown in Section 5 that the optimal solution is unique, the equality $t^\star = \min\{t_S^\star, t_M^\star\}$ must hold. Without loss of generality, let us assume that $t^\star = t_S^\star$ holds; a similar argumentation proves the claim in case of $t^\star = t_M^\star$. Then, using the switching conditions (9) and (12) yields

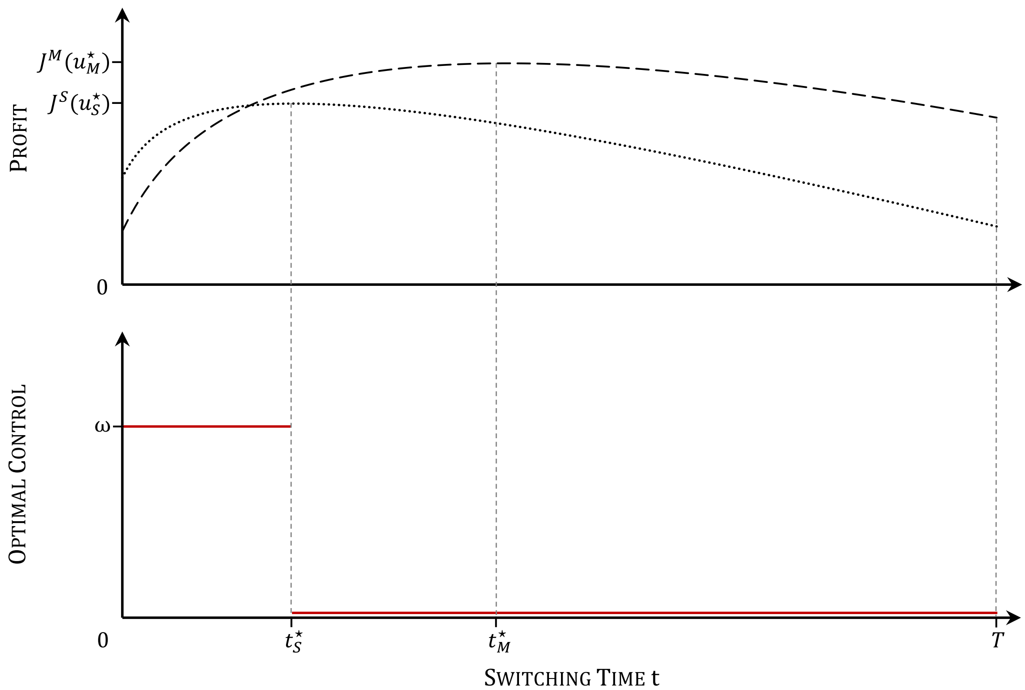

Fig. 4. The supplier's profit J^S (dotted line), the manufacturer's profit J^M (dashed line), and the (mutually agreed) collaboration strategy (solid line) – represented by the optimal control function $u_{SC}^\star$ – for $\alpha = 0.5$ using the parameter set introduced in Table 1.

$$2b \cdot \alpha c_{SD} = mc_0(1+\omega t^\star)^{m-1}(t^\star - T) \cdot (a - c_M - r - c_0(1+\omega t^\star)^m). \tag{16}$$

Because $t_S^\star \neq t_M^\star$ and $t^\star = \min\{t_S^\star, t_M^\star\}$ hold, the manufacturer's optimal switching time will be strictly larger than its counterpart for the *centralized solution*, i.e., $t_M^\star > t^\star$. Thus, the manufacturer's switching condition (15) implies

$$2b \cdot \alpha c_{SD} < mc_0(1+\omega t^\star)^{m-1}(t^\star - T) \cdot (a - c_M - r - c_0(1+\omega t^\star)^m),$$

a contradiction to (16). Hence, $t^\star \neq \min\{t_S^\star, t_M^\star\}$ follows, which completes the proof. □

By means of the firms' switching conditions (12) and (15), both the supplier and the manufacturer can assess the economic efficiency of further investments in supplier development. Based on these information and the mutually agreed switching time $t_{SC}^\star := \min\{t_S^\star, t_M^\star\}$, three cases can be distinguished:

(1) $t_S^\star < t_M^\star$, i.e., $\lambda_S(t_{SC}^\star) = (1-\alpha)c_{SD}$ and $\lambda_M(t_{SC}^\star) > \alpha c_{SD}$,
(2) $t_S^\star > t_M^\star$, i.e., $\lambda_S(t_{SC}^\star) > (1-\alpha)c_{SD}$ and $\lambda_M(t_{SC}^\star) = \alpha c_{SD}$, and
(3) $t_S^\star = t_M^\star$, i.e., $\lambda_S(t_{SC}^\star) = (1-\alpha)c_{SD}$ and $\lambda_M(t_{SC}^\star) = \alpha c_{SD}$.

Since $\lambda_M(t_{SC}^\star) + \lambda_S(t_{SC}^\star) > c_{SD}$ holds in the first two cases, further cost reduction efforts pay off during the contract period from the supply chain perspective, i.e., either the manufacturer M (Case 1) or the supplier (Case 2) is interested in extending the collaboration by adapting the α-value. In Case 3 neither firm has a profitable unilateral deviation from the (mutually agreed) collaboration strategy. Following this line of reasoning, we can even prove that the supply chain profit obtained in the centralized decision-making process characterized by $t^\star$, i.e., the *centralized solution*, coincides with its counterpart obtained in the decentralized setting characterized by $t_{SC}^\star$ for an appropriately chosen cost allocation factor.

Theorem 7.1. *Let Assumption 5.1 hold. Then, there uniquely exists a cost allocation factor $\alpha^\star \in (0, 1)$ such that $t_S^\star$ and $t_M^\star$, determined accordingly to the switching conditions (12) and (15), respectively, coincide, i.e., $t_S^\star = t_M^\star$. Moreover, the resulting (mutually agreed) switching time $t_{SC}^\star := \min\{t_S^\star, t_M^\star\}$ coincides with the optimal switching time $t^\star$ of the* centralized solution.

Proof. For $\alpha = 0$, the manufacturer's optimal switching time $t_M^\star$ equals the final time T of the contractual period and $t_S^\star < T$ holds in view of Assumption 5.1. Moreover, $t_M^\star < T$ holds for all $\alpha \in (0, 1]$ according to the manufacturer's switching condition (15). In addition, because the left hand side of (15) is strictly decreasing with respect to $t_M^\star$, the manufacturer's optimal switching time $t_M^\star = t_M^\star(\alpha)$ strictly decreases on the interval of admissible cost allocation factors $\alpha \in [0, 1]$. Similarly, in view of Assumption 5.1 and according to the supplier's switching condition (12), $t_S^\star = T$ holds if and only if $\alpha = 1$. Furthermore, because the left hand side of (12) is strictly decreasing in $t_S^\star$, the supplier's optimal switching time $t_S^\star = t_S^\star(\alpha)$ increases on the interval of admissible cost allocation factors $\alpha \in [0, 1]$.

Let us define the (allocation) function a_S: $[0, 1] \to [0, T]$ by $a_S(\alpha) = t_S^\star$ where $t_S^\star$ satisfies the supplier's switching condition (12). Analogously, a_M: $[0, 1] \to [0, T]$ is defined as $a_M(\alpha) = t_M^\star$ with $t_M^\star$ chosen in accordance with (15). The above reasoning shows that $a_S(1) = T$ and $a_M(0) = T$ hold and that a_S is strictly monotonically increasing on its domain [0, 1] while a_M is strictly monotonically decreasing on its domain [0, 1].

Hence, the continuous function $f: [0,1] \to \mathbb{R}$, $f(\alpha) \mapsto a_M(\alpha) - a_S(\alpha)$, is strictly monotonically decreasing with $f(0) > 0$ and $f(1) < 0$. Using the mean value theorem shows the existence of $\alpha^\star$ such that $f(\alpha^\star) = 0$ holds or, equivalently, $a_M(\alpha^\star) = a_S(\alpha^\star)$, i.e., the individual firms' switching times coincide for the cost allocation factor $\alpha^\star$.

Then, using this cost allocation factor and adding the switching conditions (12) and (15) shows that the resulting switching time $t_{SC}^\star = t_S^\star = t_M^\star$ satisfies the switching condition (9). Because $t^\star$ is uniquely determined by (9), $t_{SC}^\star = t^\star$ holds. Hence, the resulting control functions and the respective supply chain profits also coincide, which shows the assertion. □

Table 1
List of parameter values (basic scenario).

T	a	b	c_M	c_0	r	c_{SD}	ω	m
60	200	0.01	70	100	15	100,000	1	−0.1

As a conclusion that can be drawn from Proposition 7.1 and Theorem 7.1, it is desirable that the desired switching times $t_S^\star$ and $t_M^\star$ coincide in order to achieve the system-wide optimum, i.e., $t_S^\star = t_M^\star = t^\star$. To demonstrate the impact of direct supplier development on the individual firms' switching times, a numerical analysis is conducted in the subsequent section. □

7.2. Numerical analysis and managerial insights part I

The above reasoning shows that M can prolong the collaboration and thus increase the supply chain profit of the decentralized supply chain by subsidizing a certain share of the supplier development costs. We examine numerical examples using the parameter values in Table 1 to obtain more managerial insights.

Because we are interested in the dependence of the individual firms' switching times on the cost allocation factor α, we begin our numerical analysis by evaluating the switching conditions given by Eqs. (12) and (15) for all admissible α values, i.e., $\alpha \in [0, 1]$. Fig. 5 shows that both t_S^* and t_M^* change continuously *and* monotonically with respect to α. If $\alpha = 0$ holds, S covers the supplier development costs completely. Hence, M can exploit the achieved cost reductions for free, which implies $t_M^\star = T$. Conversely, for $\alpha = 1$, S benefits from the increasing quantity supplied at the market, whereas M bears all supplier development costs resulting in $t_S^\star = T$. We also integrated the supply chain profit $J^{SC}(u_{SC}^\star)$. Here, we observe that the system-wide optimum is attained for $t_S^\star = t_M^\star$. Given $0 < t_S^\star < t_M^\star = T$ for $\alpha = 0$, $0 < t_M^\star < t_S^\star = T$ for $\alpha = 1$ and the fact that $t_S^\star$ and $t_M^\star$ change continuously and monotonically with respect to α, the supply chain partners' objectives can be aligned, i.e., $t_S^\star = t_M^\star$, as shown in Theorem 7.1. Thus, the manufacturing firm can induce the *centralized solution* by choosing the cost allocation factor $\alpha \in (0, 1)$ appropriately.

To analyze the effect of direct supplier development on supply chain performance more deeply, we vary the parameters $b \in \{0.007, 0.008, 0.009, 0.01, 0.011, 0.012, 0.013\}$, $r \in \{12, 13, 14, 15, 16, 17, 18\}$, $c_{SD} \in \{70000, 80000, 90000, 100000, 110000, 120000, 130000\}$, and $m \in \{-0.13, -0.12, -0.11, -0.1, -0.09, -0.08, -0.07\}$, resulting in a total number of $7^4 = 2401$ instances. For each parameter combination, we compute both the supply chain profit $J^{SC}(u_{SC}^\star)$ resulting from direct supplier development ($\alpha = \alpha^\star$) and the corresponding profit $J^{SC}(u_S^\star)$ resulting from indirect supplier development ($\alpha = 0$), and then compare the respective profits. The depicted histogram in Fig. 6 shows the absolute frequency with which a percentage of profit increase is observed within our parameter set. For all computed instances, the ratios are positive. The arithmetic mean is 19.76 percent, with a standard deviation of 5.14 percent and a median of 19.12 percent, which shows that a direct involvement of the manufacturer leads to a significant improvement of supply chain performance.

According to Kim (2000), a system-wide optimum might not necessarily be optimal to each individual firm in a supply chain. Given this background, we also compute the individual firms' profits for the considered parameter set and compare the profits resulting from direct supplier development, i.e., $J^S(u_{SC}^\star)$ and $J^M(u_{SC}^\star)$, with the corresponding profits resulting from indirect supplier development, i.e., $J^S(u_S^\star)$ and $J^M(u_S^\star)$, respectively. At 6.38 percent, with a standard deviation of 8.18 percent and a median of 5.96 percent, the manufacturer's average-profit increase ratio is substantially lower than the corresponding ratio for the supplier (34.95 percent, with a standard deviation of 5.96 percent and a median of 34.85 percent). Moreover, although the supplier's ratios are strictly positive, the manufacturer suffers losses in 595 out of 2401 instances, cf. Fig. 7.

In conclusion, the results of our numerical analysis are twofold. On the one hand, supply chain coordination can be achieved by adopting direct supplier development, resulting in a possibly prolonged collaboration phase and the optimal system-wide profit corresponding to our benchmark – the *centralized solution*. This observation is clearly not a coincidence but is rather rigorously proved in Theorem 7.1. On the other hand, the results show that covering $\int_0^T \alpha^\star c_{SD} u_{SC}(t)\,dt$ of the supplier development costs is not always economically reasonable from the manufacturer's point of view. In other words, even though direct supplier development with a constant cost allocation factor $\alpha^\star$ leads to a significant improvement of the overall supply chain profit in comparison with indirect supplier development ($\alpha = 0$), i.e., the strict inequality $J^{SC}(u_{SC}^\star) > J^{SC}(u_S^\star)$ holds, the manufacturer's profit resulting from indirect supplier development, i.e., $J^M(u_S^\star)$, might be superior compared to its counterpart resulting from direct supplier development, i.e., $J^M(u_{SC}^\star)$, see the depicted histograms in Figs. 6 and 7, respectively.

Given the fact, that the mutually agreed collaboration strategy must increase the profitability of both firms, a possible remedy is based on the following idea: For $t \in [0, t_S^\star)$ the supplier invests in supplier development anyway ($\lambda_S(t) > c_{SD}$, $\alpha = 0$) and thus does not require further incentives (subsidies). This (simple) finding is the basic idea of the negotiation-based coordination algorithm developed in the subsequent section. Here, the manufacturer gradually increases the cost allocation factor α in order to ensure an efficient level of direct supplier development (subsidy) so as no firm

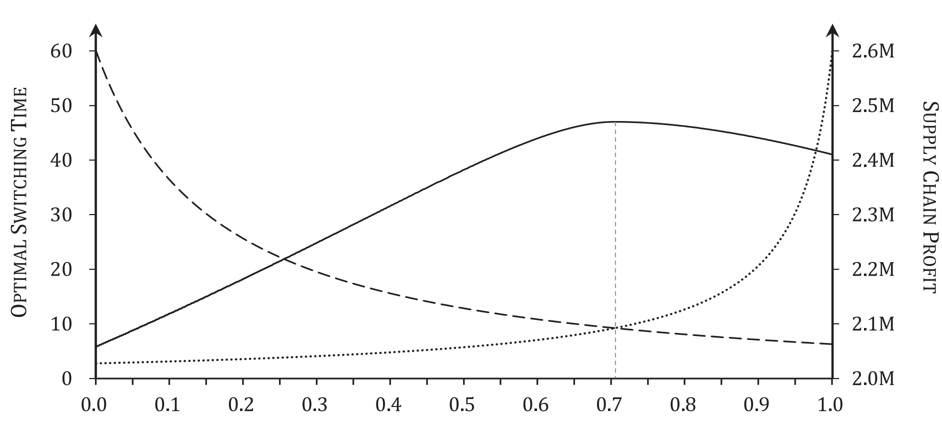

Fig. 5. Optimal switching times $t_S^\star$ (dotted line) and $t_M^\star$ (dashed line), and the supply chain profit (solid line) with respect to the cost allocation factor α.

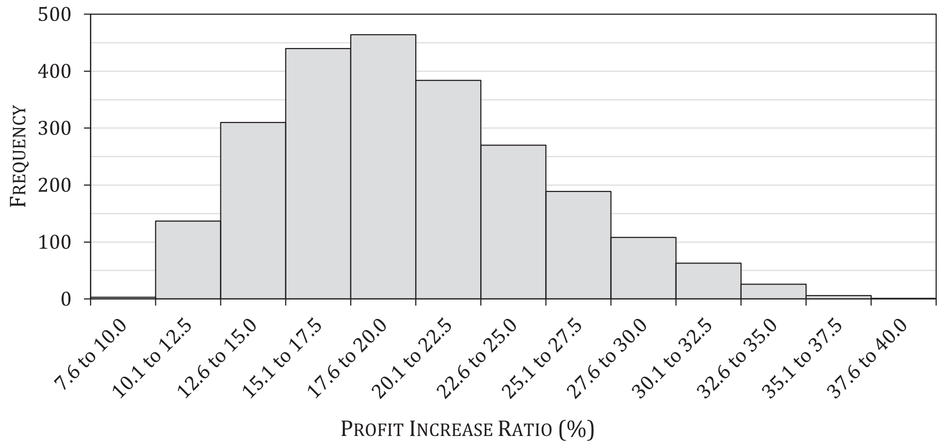

Fig. 6. Comparison of indirect and direct supplier development – supply chain profit.

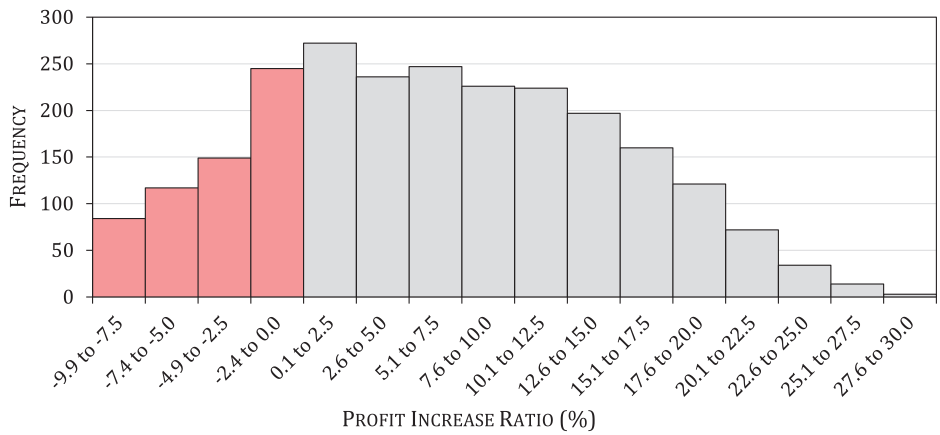

Fig. 7. Comparison of indirect and direct supplier development – manufacturer's profit.

has a profitable unilateral deviation from the set of system-wide optimal actions.

8. Coordinating supplier development

In this section, we propose a negotiation-based algorithm that can be employed as a guideline to realize (perfect) supply chain coordination while both the manufacturer and the supplier increase their respective profit in each iteration step, leading to a win–win situation. First, the sequence of events is described. Thereafter, the steps performed by the supplier and the manufacturer in each iteration are presented in more detail.

Starting from $\alpha = 0$, both S and M solve their optimal control problem to determine $t_S^\star$ and $t_M^\star$, respectively. Note that for $\alpha = 0$, $0 \le t_S^\star < t_M^\star = T$ is ensured in view of Assumption 5.1. Hence, both firms collaborate until time $t_S^\star = \min\{t_S^\star, t_M^\star\}$, i.e., they realize the outcome of the decentralized optimization corresponding to indirect supplier development, see Section 6. Next, based on the sensitivity information available from the adjoint and its derivative, M determines an adapted (increased) α-value. This newly set cost allocation factor holds for all supplier development costs from $t_S^\star$ onwards, i.e., M offers to increase the amount of effort invested in supplier development from $t_S^\star$ onwards to extend the collaboration. Then, the negotiation process starts again, resulting in a prolonged collaboration phase and thus increasing overall profit. With this overview in mind, we now present the coordination process in detail.

8.1. A negotiation-based algorithm

The proposed algorithm consists of the following six steps, which are repeated until a stopping criterion is satisfied. Each iteration step causes some additional expenses (negotiation costs), denoted by $\Xi > 0$. Moreover, the following (technical) condition is needed in order to ensure proper functioning of the proposed algorithm.

Assumption 8.1. Let $\bar{t} \in [0, t^\star)$ be the optimal switching time resulting from indirect supplier development, see Section 6. Moreover, let the optimal switching time of the centralized solution and the corresponding manufacturer's adjoint be denoted by $t^\star$ and $\lambda_M^\star$, respectively. Then, suppose that $\lambda_M^\star$ is strictly convex on $[\bar{t}, t^\star)$.

Remark 8.1. The manufacturer's adjoint $\lambda_M^\star$ is twice (infinitely many times) continuously differentiable on $[0, t_M^\star)$. Hence, Assumption 8.1 is equivalent to strict positivity of $\ddot{\lambda}_M^\star$ on $[\bar{t}, t^\star)$, i.e.,

$$\ddot{\lambda}_M^\star(t) = -\frac{mc_0\omega}{2b}((1-m)(a-c_M-r)(1+\omega t)^{-m} - c_0(1-2m)) \times (1+\omega t)^{2m-2} > 0.$$

This condition is satisfied if, and only if, $(1-m)(a-c_M-r)(1+\omega\bar{t})^{-m} > c_0(1-2m)$ holds. To this end, checking the inequality $(1-m)(a-c_M-r) > c_0(1-2m)$ suffices.

The algorithm is constructed such that, ignoring negotiation costs, i.e., $\Xi = 0$, the manufacturer's *and* the supplier's profit

Algorithm 1 Negotiation-based algorithm.

Initialization: set $i = 1$, $\alpha_0 = 0$, $t_0^\star = 0$, and $\hat{t} = T$.

(1) Solve the supplier's optimal control problem

$$\textit{Maximize} \quad \int_{t_{i-1}^\star}^{T} \frac{a - c_M - (r + c_0 x(t)^m)}{2b} \cdot r - (1 - \alpha_{i-1}) c_{SD} u_S(t)\, \mathrm{d}t$$

subject to the constraints $\dot{x}(t) = u_S(t)$, $u_S(t) \in [0, \omega]$ for all $t \in [t_{i-1}^\star, T]$, and $x(t_{i-1}^\star) = 1 + \omega t_{i-1}^\star$ to determine the optimal switching time $t_S^\star$. This can be done by solving Eq. (12) with $\alpha = \alpha_{i-1}$. Set $t_i^\star := \min\{\hat{t}, t_S^\star\}$.

(2) Compute the supplier's revenue Ψ_S^+ according to

$$\begin{aligned}\Psi_S^+ &= \int_0^{t_i^\star} \frac{a - c_M - (r + c_0(1 + \omega t)^m)}{2b} \cdot r\, \mathrm{d}t + \int_{t_i^\star}^{T} \frac{a - c_M - (r + c_0(1 + \omega t_i^\star)^m)}{2b} \cdot r\, \mathrm{d}t \\ &= \frac{r}{2b}\left(T \cdot (a - c_M - r) - c_0\left(\frac{(1 + \omega t_i^\star)^{m+1} - 1}{\omega(m+1)} + (T - t_i^\star)(1 + \omega t_i^\star)^m\right)\right),\end{aligned}$$

and $\Psi_S^- = c_{SD}\omega \cdot \sum_{k=1}^{i} (t_k^\star - t_{k-1}^\star)(1 - \alpha_{k-1})$, i.e., the supplier's effort invested in supplier development. Thus, the suppliers's profit is $\Psi_S(i) = \Psi_S = \Psi_S^+ - \Psi_S^-$.

(3) Compute the manufacturer's revenue Ψ_M^+ according to

$$\begin{aligned}\Psi_M^+ &= \int_0^{t_i^\star} \frac{(a - c_M - r - c_0(1 + \omega t)^m)^2}{4b} \mathrm{d}t + \int_{t_i^\star}^{T} \frac{(a - c_M - r - c_0(1 + \omega t_i^\star)^m)^2}{4b} \mathrm{d}t \\ &= \frac{1}{4b}\left(t_i^\star (a - c_M - r)^2 - 2(a - c_M - r)c_0 \frac{(1 + \omega t_i^\star)^{m+1} - 1}{\omega(m+1)} + c_0^2 \frac{(1 + \omega t_i^\star)^{2m+1} - 1}{\omega(2m+1)}\right) + (T - t_i^\star) \cdot \frac{(a - c_M - r - c_0(1 + \omega t_i^\star)^m)^2}{4b},\end{aligned}$$

and $\Psi_M^- = c_{SD}\omega \cdot \sum_{k=1}^{i} (t_k^\star - t_{k-1}^\star)\alpha_{k-1}$, i.e., the manufacturer's effort invested in supplier development. Thus, the manufacturer's profit is $\Psi_M(i) = \Psi_M = \Psi_M^+ - \Psi_M^-$.

(4) If $i > 1$: If one of the following two stopping criteria is satisfied, the algorithm is terminated:

- The incurred negotiation costs Ξ outweigh the manufacturer's additional profit, i.e., $\Psi_M(i) - \Psi_M(i-1) < \Xi$ holds.
- The supplier's desired collaboration time $t_S^\star$ is larger than its counterpart $\hat{t} = t_M^\star(\alpha_{i-1})$, i.e., $t_S^\star \geq \hat{t}$.

(5) Solve the manufacturer's optimal control problem

$$\textit{Maximize} \quad \int_{t_{i-1}^\star}^{T} \frac{(a - c_M - r - c_0 x(t)^m)^2}{4b} - \alpha_{i-1} c_{SD} u_M(t)\, \mathrm{d}t$$

subject to the constraints $\dot{x}(t) = u_M(t)$, $u_M(t) \in [0, \omega]$ for all $t \in [t_{i-1}^\star, T]$, and $x(t_{i-1}^\star) = 1 + \omega t_{i-1}^\star$ to determine the optimal switching time $t_M^\star$. This can be done by solving Eq. (15) with $\alpha = \alpha_{i-1}$. Then, evaluate the manufacturer's adjoint $\lambda_M(\cdot) = \lambda_M(\cdot; t_M^\star)$ and its derivative $\dot{\lambda}_M(\cdot)$ at $t_i^\star$ according to Eqs. (14) and (13), respectively, to compute

$$\hat{t} = t_i^\star + \frac{\alpha_{i-1} c_{SD} - \lambda_M(t_i^\star)}{\dot{\lambda}_M(t_i^\star)} \tag{17}$$

and α_i by plugging $\hat{t}$ into Eq. (15) instead of $t_M^\star$ and solving this equation for α, i.e.,

$$\alpha_i := \frac{m c_0 (1 + \omega \hat{t})^{m-1} \cdot (a - c_M - r - c_0(1 + \omega \hat{t})^m)}{2 b c_{SD}} \cdot (\hat{t} - T).$$

(6) Increment the iteration counter i, i.e., $i = i + 1$ and go to Step (1).

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increase in each iteration as shown in the corollary of the following preparatory lemma.

Lemma 8.1. *Let $t^\star$ denote the optimal collaboration time of the centralized solution. Suppose that indirect supplier development results in a collaboration time $\bar{t} > 0$, see Section 6, and let Assumption 8.1 hold. Then, Algorithm 1 yields a strictly increasing sequence of collaboration times $t_i^\star$, $i = 0, 1, 2, \ldots$, which is bounded by $t^\star$. Moreover, the sequence α_i, $i = 0, 1, 2, \ldots$, of cost allocation factors is also strictly increasing.*

Proof. Beforehand, note that $t_S^\star < t_M^\star = T$ holds for cost allocation factor $\alpha_0 = 0$ in view of conditions (12) and (15). Hence, $t_1^\star$ is set to $t_S^\star$ and $\hat{t}$ coincides with $t_M^\star$. Consequently, the relation

$$t_i^\star = \min\{t_S^\star, t_M^\star\} \leq t^\star \leq \max\{t_S^\star, t_M^\star\} \tag{18}$$

holds for $i = 1$ as shown in the proof of Theorem 7.1. In particular, the claimed upper bound for $t_1^\star$ is guaranteed. Note that both inequalities in (18) are strict provided $t_S^\star \neq t_M^\star$. The claimed monotonicity property $t_i^\star > t_{i-1}^\star = 0$ is satisfied in the first iteration ($i = 1$) by assumption. In addition, the inequality $\hat{t} - t_S^\star > 0$ holds, which is preserved during the following iterations until the algorithm is terminated due to the second stopping criterion of Step (4), i.e., it may only be violated after $\hat{t}$ and $t_S^\star$ are updated in the last iteration of Algorithm 1.

The *characteristic* equation (17) of Step (5) can be rewritten as

$$\lambda_M(t_i^\star) + \dot{\lambda}_M(t_i^\star)(\hat{t} - t_i^\star) = \alpha_{i-1} c_{SD} \tag{19}$$

where the manufacturer's adjoint λ_M depends on α_{i-1}. Hence, $\lambda_M(t_i^\star)$ minus the right hand side of Eq. (19) is strictly positive. In combination with $\dot{\lambda}_M(t_i^\star) < 0$ this implies that the *updated* $\hat{t}$ satisfies $\hat{t} > t_i^\star$. Since $t_M^\star > t_i^\star = t_S^\star \geq t_0^\star = \bar{t}$ holds, Assumption 8.1 implies strict convexity of λ_M on $[\bar{t}, t_M^\star)$. In combination with the fact that λ_M is linear after the switching time $t_M^\star$, the inequality $\hat{t} < t_M^\star$ can be concluded, see, e.g. Hiriart-Urruty and Lemaréchal (1993).

Hence, plugging $\hat{t}$ into Eq. (15) instead of $t_M^\star$ yields a strictly larger value for α_i. Consequently, the manufacturer's optimal switching time $t_M^\star$ strictly decreases (and coincides with $\hat{t} > t_i^\star$) while S computes a strictly larger optimal switching time $t_S^\star > t_i^\star$ in the successive iteration step. In summary, the claimed monotonicity of $t_i^\star$ and α_i is ensured. The boundedness now follows from the fact that $\min\{t_S^\star, t_M^\star\} \leq t^\star$ always holds according to Theorem 7.1, which completes the proof. □

The assumption with respect to indirect supplier development ($\bar{t} > 0$) essentially means that the supplier reacts sensitive to changes in the cost allocation factor α.

Corollary 8.1. *Let the assumptions of Lemma 8.1 hold. Then, ignoring negotiation costs Ξ, the manufacturer's and the supplier's profit increase in each iteration of Algorithm 1, i.e., the following inequalities hold*

$$\Psi_M(i) > \Psi_M(i-1) \quad \text{and} \quad \Psi_S(i) > \Psi_S(i-1) \quad \text{for } i = 0, 1, 2, \ldots.$$

Proof. Here, the successively adaptation of the cost allocation factor plays a major role. Both, the manufacturer and the supplier wants to prolong the collaboration until $\hat{t} = t_M^\star$ and $t_S^\star$, respectively, because their marginal profits (adjoints λ_M and λ_S) outweigh their marginal costs (αc_{SD} and $(1-\alpha)c_{SD}$) for the *updated* and increasing cost allocation factor, cf. Lemma 8.1. Hence, extending the collaboration until $\min\{t_S^\star, t_M^\star\}$ ensures that both entrepreneurs increase their profits, i.e., the assertion follows. □

We emphasize that monotonicity of the sequence α_i, $i = 0, 1, 2, \ldots,$ is an important property for the applicability of the proposed algorithm because it corresponds to successively increasing the manufacturer's share in the supplier development program. Moreover, the algorithm stops after a finite (small) number of iterations.

Proposition 8.1. *Let the assumptions of Lemma 8.1 be satisfied. Then, Algorithm 1 stops after a finite number of steps for negotiation costs $\Xi > 0$.*

Proof. If there exits an index $i \in \mathbb{N}$ such that $t_i^\star = \hat{t} \leq t_S^\star$ holds, the assertion trivially follows in view of the second stopping criterion formulated in Step (4) of Algorithm 1. Hence, let us suppose that $t_i^\star = t_S^\star < \hat{t}$ holds for all $i \in \mathbb{N}$. Then, the manufacturer's profit either increases at least by Ξ or Algorithm 1 stops due to the first stopping criterion. Since the manufacturer's profit is bounded by $J^M(u)$ with $u \equiv \omega$ evaluated for $\alpha = 0$, Algorithm 1 is terminated after at most $\lceil (J^M(u) - J^M(0))/\Xi \rceil < \infty$ steps where $J^M(0)$ denotes the manufacturer's profit without supplier development ($u \equiv 0$). In conclusion, the number of steps is uniformly bounded, which completes the proof. □

The outcome of Algorithm 1 is at least as good as its counterpart resulting from indirect supplier development, cf. Section 6. In contrast to Section 7.2, this claim holds from both the supplier's and the manufacturer's perspective. Indeed, the outcome even converges to the centralized solution, as shown in the following theorem.

Theorem 8.1. *Let the assumptions of Lemma 8.1 hold. Then, if $t_i^\star = t_S^\star \leq \hat{t}$ holds for all $i \in \mathbb{N}$, the sequence of switching times $(t_i^\star)_{i\in\mathbb{N}}$ converges to $t^\star$ for negotiation costs $\Xi = 0$.*

Proof. If, by chance, $(t_S^\star =)t_i^\star = \hat{t}(= t_M^\star)$ holds, the assertion follows in view of Theorem 7.1. Hence, the strict inequality $t_i^\star < \hat{t}$ is assumed without loss of generality. Since the sequence $(t_i)_{i\in\mathbb{N}_0}$ is strictly increasing and has the upper bound $t^\star$ according to Lemma 8.1, it converges to $\tilde{t}$, $\tilde{t} \leq t^\star$, for $i \to \infty$. Now, the assertion can be shown by contradiction. To this end, we show that the step size cannot be arbitrarily small if the switching times t_i are bounded away from $t^\star$.

Suppose that $\tilde{t} < t^\star$ holds. The one-to-one correspondence between switching time and cost allocation factor for each firm of the supply chain, implies the unique existence of a cost allocation factor $\tilde{\alpha}$ such that $\tilde{t} = t_S^\star(\tilde{\alpha})$ holds. For this cost allocation factor $\tilde{\alpha}$, the algorithm determines $\hat{t}$ such that Eq. (19) holds. Here, existence of (a sufficiently small) $\varepsilon > 0$ such that $\tilde{t}_M^\star - \varepsilon \geq \hat{t} \geq \tilde{t} + \varepsilon$ holds is directly implied by the proof of Lemma 8.1.

Since all considered expressions (in particular the adjoint λ_M as well as its derivative) are (uniformly) continuous with respective to their arguments *and* parameters, there exists a sufficiently small $\delta > 0$ such that $\tilde{t}_M^\star - \varepsilon/2 \geq \hat{t} \geq \tilde{t} + \varepsilon/2$ holds for all $t_i \in [\tilde{t} - \delta, \tilde{t}]$. Hence, the resulting change from α_{i-1} to α_i can also be uniformly estimated ensuring $t_{i+1} > \tilde{t}$. Since $\tilde{t}$ is the limit, the sequence t_i enters the set $[\tilde{t} - \delta, \tilde{t}]$ for sufficiently large iteration index $i^\star$, which leads to a contradiction to our assumption $\tilde{t} < t^\star$. In conclusion, $t_i \to t^\star$ for i approaching infinity. □

We like to point out that the additional assumption $t_i^\star = t_S^\star \leq \hat{t}$ for all $i \in \mathbb{N}$ is only incorporated to ensure monotonicity of the sequence $(\alpha_i)_{i\in\mathbb{N}_0}$ and thus to simplify Algorithm 1, which is preferable from the application's point of view. Details on the required modifications of the algorithm without this assumption are given in Appendix A. Moreover, Eq. (19) resembles the iteration of Newton's method. However, besides the fact that both the function λ_M and its derivative $\dot{\lambda}_M$ are *updated* in each iteration, also $t_i^\star$ is determined by the supplier's switching condition (11). Hence, the analysis of the proposed algorithm requires substantially different arguments.

In conclusion, the supply chain profit $\Psi_M(i) + \Psi_S(i)$ converges to its counterpart corresponding to the *centralized solution*; even though the profit is distributed differently in comparison to the approach pursued in Section 7. Indeed, the distance $t^\star - t_i$ (degree of suboptimality) tends to zero for $\Xi \to 0$, i.e., the algorithm yields a *near-optimal solution*.

8.2. Numerical analysis and managerial insights part II

The core of the proposed algorithm is the adaptation of the cost allocation factor α in Step (5). At this point, the manufacturer solves an optimal control problem to obtain sensitivity information from the adjoint variable $\lambda_M(\cdot)$, i.e., the value of further investments in supplier development, and its derivative $\dot{\lambda}_M(\cdot)$ and then sets α_i based on these data, see Fig. 8 for an illustration.

Mathematically speaking, M first determines an appropriate $\hat{t}$ by calculating the point of intersection of $\lambda_M(t_i^\star) + \dot{\lambda}_M(t_i^\star)(t - t_i^\star)$ and $\alpha_{i-1}c_{SD}$, cf. the black circle. Then, M computes α_i by solving the equation $\lambda_M(\hat{t}) = \alpha_i c_{SD}$, cf. the red square. This procedure is repeated until the manufacturer's additional profit is less than the negotiation costs Ξ.

We performed the first six iterations of the coordination algorithm for the basic scenario to illustrate the adaption of the α-value. The results show gradual adaption at each iteration and are listed in Table 2. The algorithm will stop if $\Psi_M(i) - \Psi_M(i-1) < \Xi$ holds, cf. Step (4). Thus, assuming negotiation costs of 5,000, the negotiation-based coordination ends with iteration 6 and can be interpreted as follows: For $t \in [0, 2.76)$, S must cover all supplier development costs. For $t \in [2.76, 4.815)$, M supports S by subsidizing a share of 40.32 percent of the investment costs. Similarly, for $t \in [4.815, 6.625)$, $t \in [6.625, 7.462)$, $t \in [7.462, 7.898)$ and $t \in [7.898, 8.162)$, M supports S by subsidizing a share of

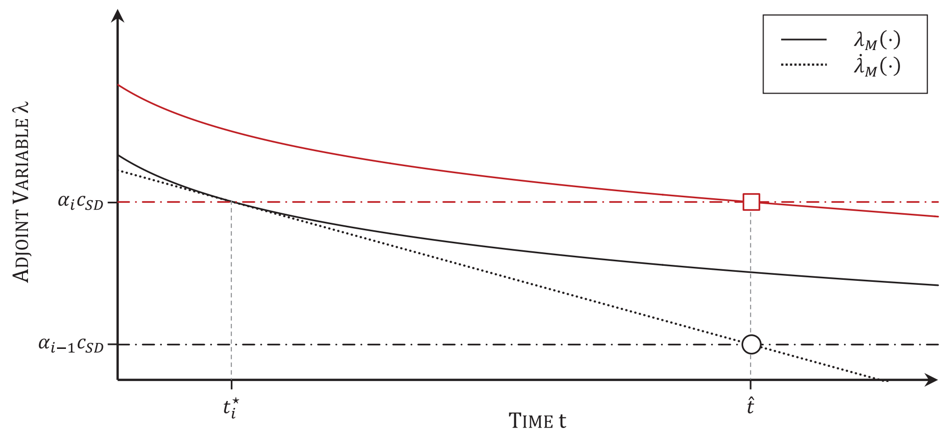

Fig. 8. Illustration of the manufacturer's approach showing the determination of the cost allocation factor α_i. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

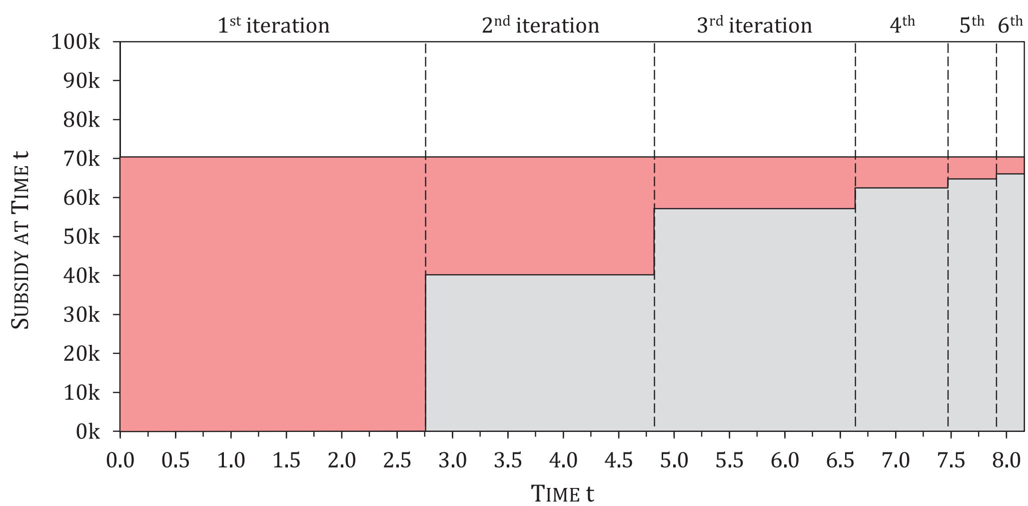

Fig. 9. Illustration of the manufacturer's total amount of subsidy in the case of gradual adaption of the cost allocation factor α_{i-1} (gray-colored area) and the additional savings (red-colored area) compared to the corresponding amount of subsidy in the case of a constant cost allocation factor $\alpha^\star$. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 2
Numerical results of the first six iterations of the proposed algorithm.

i	$t_M^\star$	$t^\star$	$t_S^\star$	α_{i-1}	$\Psi_M(i)$	$\Psi_S(i)$
1	60.000	9.212	2.760	0.0000	1,111,023.18	947,398.01
2	15.459	9.212	4.815	0.4032	1,335,958.88	982,524.83
3	11.326	9.212	6.625	0.5715	1,428,934.82	996,313.32
4	10.406	9.212	7.462	0.6239	1,452,416.18	998,424.42
5	10.037	9.212	7.898	0.6471	1,460,660.49	998,920.16
6	9.841	9.212	8.162	0.6599	1,464,420.04	999,088.17

57.15 percent, 62.39 percent, 64.71 percent, and 65.99 percent, respectively. In this manner M and S collaborate until time $t_6^* = 8.162$, resulting in a profit increase of 31.81 percent for M and 5.46 percent for S in comparison to indirect supplier development, i.e., $\alpha = 0$.

As illustrated in Fig. 9, in the case of gradual adaption of the cost allocation factor α_{i-1} for $i \in \{1, 2, 3, 4, 5, 6\}$, the manufacturer's subsidy is given by $\int_0^{t_i} \alpha_{i-1} c_{SD} u_{SC}(t)\,\mathrm{d}t$, cf. the gray-colored area, resulting in cumulative investment costs of 284,154.45. By contrast, in the case of a constant cost allocation factor $\alpha^\star$, cf. Section 7, the corresponding amount of subsidy is given by $\int_0^{t_i} \alpha^\star c_{SD} u_{SC}(t)^{\sim}\,\mathrm{d}t$ with $\alpha^\star = 0.7024$, resulting in substantially higher cumulative investment costs of 573,298.88. Thus, by gradually increasing the share of investment costs, the manufacturing firm can realize additional savings of 289,144.43, cf. the red-colored area.

Neglecting negotiation costs, i.e., $\Xi = 0$, we also performed the first six iterations of the proposed algorithm for all 2,401 instances of the parameter set considered in Section 7. We then compare the individual firms' profits resulting from gradual adaption of the cost allocation factor α_{i-1} for $i \in \{1, 2, 3, 4, 5, 6\}$ with the corresponding profits resulting from indirect supplier development ($\alpha = 0$). The depicted histogram in Fig. 10 shows that for all computed instances, the manufacturer's profit increase ratios are positive. The arithmetic mean of the ratios is 31.14 percent, with a standard deviation of 5.96 percent and a median of 30.46 percent. Although the supplier's average-profit increase ratio of 5.74 percent (with a standard deviation of 2.40 percent and a median of 5.33) percent is substantially lower, the ratios are strictly positive for all 2401 instances.

In conclusion, at each iteration step, both the supplier and the manufacturer increase their profit by collaborating until time t_i^*. Because neither the supplier nor the manufacturer has a profitable unilateral deviation from the set of system-wide optimal actions, the proposed coordination scheme always leads to a win–win situation.

8.3. Model extension: multiple suppliers

In the previous sections, we dealt with the coordination of supplier development, considering a decentralized supply chain with

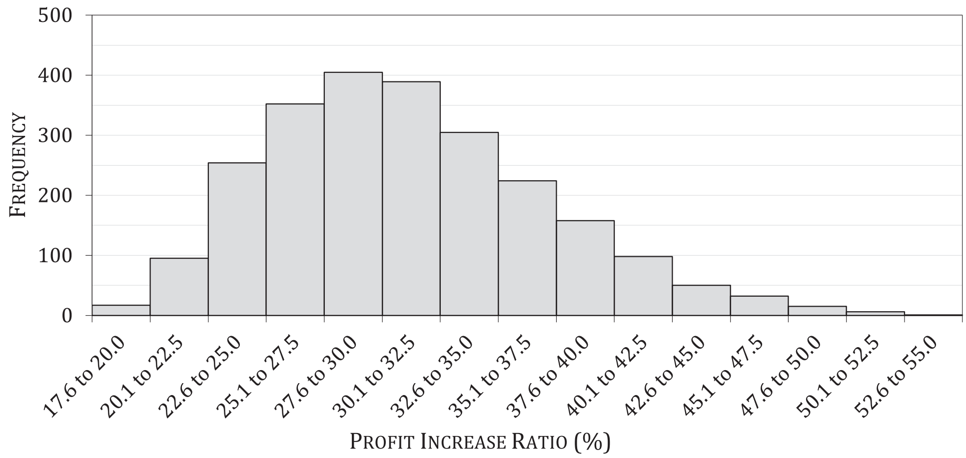

Fig. 10. Comparison of indirect and direct supplier development in the case of gradual adaption of the cost allocation factor α_{i-1} – manufacturer's profit.

a single manufacturer and a single supplier. However, the manufacturing firm may want to initiate supplier development programs with more than just one supplier. Given limited resources available, the allocation of supplier development investments among multiple suppliers is a critical issue from the manufacturer's point of view (Talluri et al., 2010). We briefly sketch an extension showing that the presented approach can be exploited in order to deal with this scenario.

The model extension is based on three key aspects of investments in supplier development: First, the manufacturer has a limited budget (resources) for supplier development efforts. Second, returns in terms of cost savings differ among suppliers depending, inter alia, on their current performance level c_0 and their learning rate m, i.e., the suppliers' innovation capabilities and competence. Thus, returns from supplier development investments vary. Third, the manufacturer's goal is to optimally allocate the budget (resources) among multiple suppliers so as to maximize return on investment.

Because the manufacturer is able to assess the value of further investments in supplier development by means of adjoint (14), we recommend the optimal allocation of supplier development investments by considering the manufacturer's adjoint and the respective investment costs (manufacturer's subsidy). Let us assume that $s \in \mathbb{N}_{\geq 2}$ suppliers are worthy of consideration for supplier development and let the manufacturer's adjoint and share of investment costs with respect to the nth supplier be denoted by $\lambda_M^n : [0, T] \to \mathbb{R}$ and $\alpha_{i-1}^n c_{SD}^n$, for all $n \in \{1, 2, \ldots, s\}$, respectively.

Setting the initial collaboration time $t_{0,n}^{\star} = 0$, and the initial cost allocation factor $\alpha_0^n = 0$, both the suppliers and the manufacturer solve their optimal control problems to determine the individual firms' switching times. Clearly, indirect supplier development ($\alpha_0^n = 0$) is always welcome from the manufacturer's point of view since all costs are covered by the respective supplier resulting in the (mutually agreed) switching time $t_{1,n}^{\star}$ according to the n-th supplier's switching condition (12) with $\alpha = \alpha_0^n$.

Then, the manufacturer selects supplier n (supplier development initiative) with the highest value according to $\lambda_M^n(t_{1,n}^{\star}) - \alpha_0^n c_{SD}^n$ and performs one iteration of the negotiation-based coordination algorithm for the selected supplier as presented in Section 8. This procedure is repeated until the manufacturer's (limited) resources are completely allocated *or* the incurred negotiation costs outweighs the manufacturer's additional profit, i.e., $\Xi^n > \Psi_M^n(i) - \Psi_M^n(i-1)$, for all $n \in \{1, 2, \ldots, s\}$.

Based on the parameter values of the basic scenario, cf. Table 1, we performed the first six steps of the proposed approach for a setting with two suppliers to make the basic idea more comprehensible. Both suppliers S^1 and S^2 differ in terms of their individual learning rate, i.e., $m^1 = -0.1$ and $m^2 = -0.13$, and the respective supplier development costs, i.e., $c_{SD}^1 = 100,000$ and $c_{SD}^2 = 70,000$. The results show the optimal allocation of the manufacturer's resources and are listed in Table 3. Neglecting negotiation costs, i.e., $\Xi = 0$, and assuming a manufacturer's budget for supplier development of $500,000$, the allocation process ends with Step IV and can be interpreted as follows: In Step I, the manufacturer selects supplier S^2 and performs one iteration of the negotiation-based coordination algorithm resulting in the (mutually agreed) switching time $t_{2,2}^{\star} = 10.14$ and cumulative investment costs of 193,561.71. Then, in Steps II and III, M selects supplier S^1 for direct supplier development resulting in the (mutually agreed) switching time $t_{2,1}^{\star} = 4.82$ and $t_{3,1}^{\star} = 6.63$, respectively, and cumulative investment costs of 379,462.37. Finally, in Step IV, M selects supplier S^2. However, with 120,537.63 of budget left for direct supplier development, the collaboration is prematurely stopped before $t_{3,2}^{\star} = 13.02$ is reached.

Hence, a model extension for assisting the manufacturing firm in making resource allocation decisions in supplier development initiatives is possible albeit a detailed study is left for future research.

9. Conclusions

This paper addresses the problem of coordinating supplier development in a decentralized supply chain. In particular, we examine the manufacturers problem of incentivizing suppliers to participate in manufacturer-initiated supplier development activities and provide an innovative application to coordinate the mutual decision to invest in supplier development. At this, we focus on one of the most important aspects of successful supplier development, namely, the allocation of costs and additional profits between supply chain partners.

To this end, we formulate and solve a continuous time optimal control model characterizing the decision to invest in supplier development. The detailed analysis of this model indicates that in the case of indirect supplier development, the optimum investment level, i.e., the *centralized solution*, is not achieved due to the supplier's tendency to underinvest in supplier development. The manufacturing firm can induce the *centralized solution* and intensify supplier's participation by subsidizing a share of the investment costs. Thus, direct supplier development provides a viable incentive instrument to induce desirable supplier behavior. Although the findings of our analysis indicate that direct supplier development leads to a significant improvement of supply chain

Table 3
Numerical results of the first six steps of the proposed approach for a setting with two suppliers.

	Supplier 1 ($m = -0.1$; $c_{SD} = 100,000$)						Supplier 2 ($m = -0.13$; $c_{SD} = 70,000$)				
	i	$t^\star_{i,1}$	α^1_{i-1}	Σ subsidy	$\lambda^1_M(t^\star_{i1})-\alpha^1_{i-1}c^1_{SD}$		$\lambda^2_M(t^\star_{i2})-\alpha^2_{i-1}c^2_{SD}$	Σ subsidy	α^2_{i-1}	$t^\star_{i,2}$	i
I	1	2.76	0.000	0.00	40,534.21	<	**47,333.50**	0.00	0.000	5.06	1
II	1	2.76	0.000	0.00	**40,534.21**	>	13,552.35	193,561.71	0.544	10.14	2
III	2	4.82	0.403	83,061.26	**14,602.19**	>	13,552.35	193,561.71	0.544	10.14	2
IV	3	6.63	0.572	185,900.66	6,766.40	<	**13,552.35**	193,561.71	0.544	10.14	2
V	3	6.63	0.572	185,900.66	**6,766.40**	>	5,500.85	328,404.85	0.669	13.02	3
VI	4	7.46	0.624	238,306.58	4,190.45	<	**5,500.85**	328,404.85	0.669	13.02	3

profit in comparison with indirect supplier development, subsidizing a constant share of supplier development costs is not always economically reasonable from the manufacturer's point of view.

Given the fact that for an ongoing collaborative business relationship, supply chain coordination must result in enhancing the profitability of both the supplier and the manufacturer, we introduce a negotiation-based algorithm that assists the manufacturing firm in gradually increasing the share of investment costs to ensure an efficient level of direct supplier development. We verify the reliability of our application by performing the first six iterations of the proposed algorithm for an extensive parameter set and show that for all 2,401 instances a win–win situation is achieved. Thus, the proposed coordination scheme can be employed as a guideline to achieve supply chain coordination while both the supplier and the manufacturer increase their respective profit in each iteration, resulting in a win–win situation.

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Appendix A. A technical comment

As shown in Theorem 8.1, the outcome of Algorithm 1 converges to the centralized solution, if negotiation costs are neglected, i.e., $\Xi = 0$. In addition, the numerical analysis in Section 8.2 demonstrates that Algorithm 1 can be employed as a guideline to achieve supply chain coordination for an extensive parameter set that covers most of the real-life scenarios. However, for (extremely) high learning rates the supplier's desired collaboration time $t^\star_S$ may be larger than its counterpart $\hat{t} = t^\star_M(\alpha_{i-1})$, i.e., $t^\star_S \geq \hat{t}$ and Algorithm 1 is terminated due to the second stopping criterion formulated in Step (4).

As a motivating example, let us consider the set of parameters given in Table 1 with learning rate $m = -0.27$. Starting from $\alpha = 0$, the firms solve their respective optimal control problems resulting in the (mutually agreed) switching time $t^\star_1 = t^\star_S \approx 5.61$ for $i = 1$. Next, based on the sensitivity information available from the adjoint and its derivative, M determines $\alpha_1 \approx 0.8428$. Then, both the supplier and the manufacturer perform the second iteration of Algorithm 1 resulting in $t^\star_S$ (≈ 20.90) and $t^\star_M$ (≈ 19.38), respectively. Note that, the manufacturer's optimal switching time $t^\star_M$ is smaller than its counterpart on the supplier's side, i.e., the algorithm is terminated due to the second stopping criterion formulated in Step (4).

Hence, for a mathematically sound analysis, a modification of Algorithm 1 is necessary in order to prove convergence without the assumption that $t^\star_i = t^\star_S < \hat{t}$ holds for all $i \in \mathbb{N}$. To be more precise, the roles of the manufacturer M and the supplier S are interchanged if the relation between their respective optimal switching times $t^\star_S$ and $t^\star_M$ is reversed.

Algorithm 2 Modified algorithm without Steps (2), (3), and (6) of Algorithm 1.

Initialization: set $i = 1$, $\alpha_0 = 0$, and $t^\star_0 = 0$.

(1a) Solve the supplier's optimal control problem

$$\textit{Maximize} \quad \int_{t^\star_{i-1}}^{T} \frac{a - c_M - (r + c_0 x(t)^m)}{2b} \cdot r - (1 - \alpha_{i-1}) c_{SD} u_S(t) \, \mathrm{d}t$$

subject to $\dot{x}(t) = u_S(t)$, $u_S(t) \in [0, \omega]$ for $t \in [t^\star_{i-1}, T]$, and $x(t^\star_{i-1}) = 1 + \omega t^\star_{i-1}$ to determine the optimal switching time $t^\star_S$.

(1b) Solve the manufacturer's optimal control problem

$$\textit{Maximize} \quad \int_{t^\star_{i-1}}^{T} \frac{(a - c_M - r - c_0 x(t)^m)^2}{4b} - \alpha_{i-1} c_{SD} u_M(t) \, \mathrm{d}t$$

subject to $\dot{x}(t) = u_M(t)$, $u_M(t) \in [0, \omega]$ for $t \in [t^\star_{i-1}, T]$, and $x(t^\star_{i-1}) = 1 + \omega t^\star_{i-1}$ to determine the optimal switching time $t^\star_M$.

(1c) Set $t^\star_i := \min\{t^\star_S, t^\star_M\}$. If $t^\star_S = t^\star_M$ holds, stop algorithm after Step (4).

(4) If $i > 1$: If the following stopping criterion is satisfied, the algorithm is terminated:

- The manufacturer's additional profit outweighs the incurred negotiation costs Ξ, i.e., $\Psi_M(i) - \Psi_M(i-1) < \Xi$ holds.

(5) If $t^\star_S < t^\star_M$, set $P = M$. Otherwise define $P := S$. Then, evaluate the adjoint $\lambda_P(\cdot) = \lambda_P(\cdot; t^\star_P)$ and its derivative $\dot{\lambda}_P(\cdot)$ at $t^\star_i$ to compute

$$\hat{t} = \begin{cases} t^\star_i + \frac{\alpha_{i-1} c_{SD} - \lambda_M(t^\star_i)}{\dot{\lambda}_M(t^\star_i)} & \text{if } P = M \\ t^\star_i + \frac{(1-\alpha_{i-1}) c_{SD} - \lambda_S(t^\star_i)}{\dot{\lambda}_S(t^\star_i)} & \text{if } P = S \end{cases} \tag{20}$$

and α_i by plugging $\hat{t}$ into (15) instead of $t^\star_M$ if $P = M$ or into (12) instead of $t^\star_S$ if $P = S$ and solving this equation for α_i.

Using the modifications presented in Algorithm 2, convergence to the supply chain optimum can be shown analogously to the proof of Theorem 8.1. The only change is the (technical) argument that the roles of S and M may be exchanged (and, thus, the sequence $(\alpha_i)_{i \in \mathbb{N}}$ may not be monotone). Note that the supplier's adjoint automatically satisfies the convexity assumptions exploited for λ_M.

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