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Dynamic Cost Reduction Through Process Improvement in Assembly Networks

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We consider a decentralized assembly system in which a buyer purchases components from several first-tier suppliers. We examine the dynamics of suppliers' investments in cost-reduction initiatives over the life cycle of a product under different procurement approaches. We model the suppliers' investment decisions under cost-contingent contracts, with wholesale prices determined on the basis of the prevailing component costs, as a dynamic game in closed-loop strategies. We show that there always exists an equilibrium in which the suppliers' investments are synchronized, that is, in each period either all suppliers invest in process improvement or no supplier does. We also consider target-price contracts, under which the assembler announces the rate of component cost reduction to be achieved over the product's life cycle at the beginning of the contractual relationship. We show that target-price contracts lead to higher investment levels and profits if the rates are properly specified. In general, the equilibrium investments of the suppliers are lower than those under centralized control. The buyer can eliminate this inefficiency by subsidizing a certain fraction of the costs of investments. We extend the model to a setting with two competing assemblers and knowledge spillover at the suppliers. We find that the level of inefficiency under decentralized control decreases with increased competition and spillover rate.

Key words: assembly systems; process improvement; dynamic games; procurement; supplier management
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1. Introduction

Process innovation plays a major role in reducing production costs over the life cycle of a product (Hatch and Mowery 1998). Original equipment manufacturers (OEMs) and their suppliers invest time and money in process-improvement activities such as lean production initiatives, inventory optimization, and quality-improvement projects. As a result, production costs typically decrease over the life cycle of a product. Some of this cost reduction is reflected in the suppliers' selling prices to the OEMs. This paper explores the dynamics of suppliers' investments in cost reduction over the life cycle of a product and how the extent of cost-reduction activities and the resulting firms' profits depend on the procurement strategy of the OEM.

We consider a decentralized assembly system in which a manufacturer purchases components from several first-tier suppliers over a finite horizon representing the life cycle of a product. We model the effect of cost-reduction initiatives by a learning model that is parameterized by a learning rate: the cost of a component in a given period is a decreasing convex function of the cumulative investment in process improvement achieved by its supplier. Specifically, we consider gradual investments in process improvement (as in Fine and Porteus 1989), a practice that is central to Lean Production and Six Sigma Programs, rather than a one-time large investment in technology resulting in radical change. Baily and Farrell (2006) investigate productivity growth in the U.S. auto industry from 1987 to 2002 and find that 45% of the growth was attributable to process improvement at assembly plants, notably the adoption of lean manufacturing practices. Andersson (2006) gives an example of cost reduction from a supplier of General Motors (GM). The supplier of a door hinge simplified the hinge design, allowing for a stamped hinge that did not need to be welded. This resulted in 35% savings in the cost of the hinges for GM. As in these examples, process improvement usually requires investment in the form of engineering hours and other managerial resources.

OEMs use different approaches for specifying how purchase prices should change over the years. Baron and Besanko (1984) identify two of these approaches—one in which the buyer adjusts the price it pays to its suppliers each year in response to the achieved cost improvements and another in which the buyer announces in advance the time path of target cost reductions based on a prediction of a "reasonable" rate of innovation and then keeps to this path. We refer to the first approach as *cost-contingent* contracts and to the second approach as *target-price* contracts. They differ in how they stimulate supplier investments and how they enable the assembler to extract the benefits achieved by the suppliers' cost-reduction activities. McMillan (1990) argues that, in the auto industry, North American manufacturers typically follow the first approach, extracting incremental price reductions through renegotiation despite preexisting long-term contracts. On the other hand, the author states that Japanese manufacturers tend to follow the second approach, setting a time path of target average cost/price reductions for each year over several years.

We investigate the effect of these procurement contracts on the dynamic investment-level decisions of the suppliers in a decentralized assembly network. Under cost-contingent contracts, the purchase prices in each period are determined in a Stackelberg game given the prevailing costs of the suppliers. We model the investment-level decisions by the suppliers as a dynamic game in closed-loop strategies. That is, each supplier chooses its investment level in each period to maximize its total profit over the remaining life cycle given the cumulative investments of all suppliers up to that period. We show that there exists an equilibrium to this game that is synchronized—that is, all suppliers make investments in process improvement in the same periods. This result is important not only because it facilitates computation of the equilibrium, but also because it conveys the insight that synergies in cost-reduction investment efforts are important in this setting. We also explore the factors that impact the dynamics of cost-reduction initiatives. We show that the timing of investments is determined not only by the pattern of market demand but also by the evolution of the product's price elasticity. We also describe how the rates of cost reduction are affected by the relative costs of the suppliers' components and by the total number of suppliers in the system.

Under a target-price contract, the buyer stipulates a time path of target cost reductions through the end of the horizon. The suppliers keep any amount of cost reduction beyond those stipulated in the contract. We show that target-price contracts may not necessarily induce higher levels of investments in process improvement than cost-contingent contracts. If the required rate of cost reduction is too high, the suppliers may struggle to meet the targets, hurting their profit performance. If the rate is too low, then production quantity and assembler profitability decline. We find that a target-price contract calibrated with the levels of cost reduction achieved under cost-contingent contracts results in higher investment levels and in higher profits for all firms. This suggests that an appropriately designed target-price contract should not set rates that are constant over the product's life cycle or equal for all suppliers, as is common in practice (for example, Milligan 2000 reports of an automaker requesting an across-the-board 5% cost reduction from all of its suppliers). Rather, the rates should reflect the evolution of demand and price elasticity, the size of the system, and the relative magnitude of each supplier's component (the same factors that affect the levels of cost reduction under cost-contingent contracts).

Squeezing the suppliers, extracting much of their achieved cost-reduction margin (as under cost-contingent contracts), is engrained in the culture of many auto manufacturers. This may be perceived as an effective practice to increase profitability—the manufacturer periodically renegotiates the contract terms based on the suppliers' achieved costs. However, implementing an appropriately designed target-price contract may result in higher profits for the manufacturer, increased investments in cost reduction, and a smoother relationship with the suppliers.

In general, we find that the equilibrium investments of the suppliers under both contract types are lower than the levels that arise when investment decisions are centralized. The buyer can eliminate this inefficiency by subsidizing a certain fraction of the costs of investments, a common practice in many industries. For example, Japanese car manufacturers assist their suppliers in planning for and realizing cost reductions (Chappell 2002), often providing them with free consulting services. Ford Co. has also begun to build a core network of strategic, long-term suppliers and to establish more collaborative relationships (Brown 2006). In contrast to findings in the economics literature, which suggest that fixed-price contracts achieve maximum cost reduction (Laffont and Tirole 1993), target-price contracts fail to achieve the centralized solution in our setting.

We also consider an extension to a system with two competing assemblers. We investigate the effect of competition and rate of knowledge spillover (transfer of knowledge on process improvement to the competitor's production lines) on our results. We show that although the structural results continue to hold, the level of inefficiency between the decentralized and centralized systems decreases as the rate of spillover, the degree of competition, or the size of the competitor's market increase.

It should be noted that we consider a stylized model of a decentralized assembly system, focusing on aspects of dynamic investment decisions and supplier management. In our setting the supply system is specified, so issues relevant to the selection of the supplier base, volume allocation among suppliers of the same component, and quality differentiation across suppliers do not arise in our model. In addition, when investments at one firm are specific to a particular relationship with a buyer, the buying firm may be able to hold up the other—i.e., capture some of the value of the other firm's investment. This leads to inefficiency in the form of underinvestment and spending on protection against being held up (Grossman and Hart 1986). In our setting, however, there is complete clarity regarding how payoffs will be determined at the time investment decisions are made. Therefore, the issues of ex post bargaining and holdup do not arise. Our model assumes complete information. Therefore, our findings apply to settings in which suppliers know about the cost of complementary assembly parts and the assembler has information about the suppliers' costs. This is the case, for example, in the automobile industry, in which suppliers need to share technical information while their parts are designed. Further research is needed to generalize the model to industries for which the assumption of complete information is not applicable (e.g., in the computer industry extreme modularity makes extensive interaction among the suppliers unnecessary).

The rest of this paper is organized as follows. Section 2 reviews the relevant literature. Section 3 describes the model, and §4 presents the analysis for the case of a single firm. Sections 5 and 6 present results for the assembly systems under decentralized and centralized investment decisions, respectively. Section 7 considers knowledge spillover in a setting with two competing assemblers. Section 8 concludes the paper. The e-companion[1] provides the appendices: Appendix A contains an algorithm to compute the investment decisions. Appendix B reports numerical examples that illustrate the types of investment equilibria that can arise under closed-loop strategies. All proofs and some intermediate results are provided in Appendix C. Appendix D contains a supplement to the numerical study.

2. Literature Review

Learning or increase in knowledge can stem from both production (learning by doing, autonomous learning) and process-improvement effort (induced learning). Hatch and Mowery (1998), in their empirical analysis of the semiconductor industry, show that learning in the early stages of manufacturing is a function of the allocation of engineering resources rather than an exogenous result of increasing production volume. Yelle (1979) reviews learning curve models and their applications.

Following this distinction, we review analytical models on dynamic cost reduction in two groups. The first group considers dynamic investment in process improvement by a single firm. Fine and Porteus (1989) partially characterize the optimal policy in a setting where a random amount of cost reduction is achieved as a result of the investment in each period. Kim (2000) studies the deterministic version of this problem in a continuous time setting. The second group considers dynamic production decisions with learning by doing in a single firm. Mazzola and McCardle (1997) show that, in the presence of learning by doing, the optimal production level generally exceeds the myopic production level. Fine (1986) considers a dynamic quality-based learning model—in which firms may learn faster at high quality levels than at low quality levels—to explain why high quality and low costs may be consistent. Fine (1988) studies the optimal machine inspection problem to improve quality. Li and Rajagopalan (1998) and Serel et al. (2003) consider deterministic models in which the firm benefits from learning by doing and process- and-quality improvement efforts. We do not consider quality as a different dimension in our model.

Long-term relationships with suppliers and assistance in the form of subsidies and engineering support help suppliers improve their processes. Dyer and Hatch (2006) discuss how process improvements achieved at a supplier are relation specific and cannot be easily transferable to other production lines. Several papers study supplier quality-development programs analytically through static models. Zhu et al. (2007) investigate whether the buyer or the supplier should invest in the supplier's quality improvement and how that affects the lot-sizing decisions. Iyer et al. (2005) analyze a model in which the buyer may allocate some resources to help the supplier reduce production costs but cannot observe the supplier's effort in cost reduction. Liu and Cetinkaya (2005) consider a similar model in which the buyer has incomplete information about the supplier's quality investment sensitivity.

Several economics papers (e.g., Lewis and Yildirim 2002) focus on how to regulate a monopolist with unknown costs in the presence of learning by doing. The buyer-supplier relationship has been studied by several researchers in the context of single-period models with cost reduction. Gupta and Loulou (1998) study the impact of upstream cost reduction on the equilibrium channel structures. Gupta (2008) extends this work to the case where there is knowledge spillover between the competitors. Gilbert et al. (2006) show that outsourcing to an external supplier mitigates the price competition between two manufacturers because it signals a credible commitment to not aggressively reduce costs. Gilbert and Cvsa (2003) consider whether a supplier should commit to a wholesale price before demand uncertainty is resolved in a setting with a downstream manufacturer that invests in cost reduction. Heese and Swaminathan (2006) examine the impact of cost-reduction efforts on a product line design problem with component commonality.

[1] An electronic companion to this paper is available as part of the online version that can be found at http://mansci.journal.informs.org/.

There is a significant body of literature on sourcing policies and supplier selection mechanisms. See Elmaghraby (2000) for a review. Elmaghraby and Oh (2004) consider a two-period model with asymmetric cost information, in which the first-period supplier's cost decreases because of learning by doing. The authors find that the buyer is better off holding auctions each period, rather than auctioning a long-term contract with predetermined price reductions as in a target-price contract.

Dynamic games have received limited attention in the operations management literature. For some recent work in this area, see Bernstein and Federgruen (2004) and the references therein. We refer the reader to Fudenberg and Tirole (2000) for an introduction to the extensive economics literature on dynamic games. Spence (1981) analyzes a dynamic game between competing firms and demonstrates that the learning curve creates entry barriers by conferring cost advantages on early entrants. Curtat (1996) proves the existence of Markov equilibria (players' actions at every period are a function of the current state variable only) for stochastic games that satisfy assumptions of complementarity and monotonicity.

Also related to our work are the papers exploring equilibrium production quantity, retail, and wholesale prices in supply networks with deterministic demand. Corbett and Karmarkar (2001) study serial systems with competing firms at each tier and characterize the equilibrium of a market entry game. Carr and Karmarkar (2005) study an assembly network in which a component can be supplied by several firms. The price and quantity determination in our model is similar to theirs, with the notable difference that the assembler is the Stackelberg leader in our model.

3. Model

We consider dynamic investment decisions over a finite horizon in a decentralized assembly network consisting of one assembler and M suppliers of complementary components. The time horizon represents the life cycle of the product. Periods are numbered $t = 1, \ldots, T$. (In the context of the auto industry, time periods may correspond to years.) A finished product requires one unit of a component (or a kit of components) from each supplier.[2] We assume that the suppliers contract to supply the component for T periods, and we do not take supplier cash-flow considerations or participation constraints into account.

[2] In our model, a single supplier sources each component throughout the life cycle of the product. This is indeed the case in many settings, for example, suppliers of critical components for Toyota (see Chozick 2007). In general, as long as the allocation among suppliers of the same component remains exogenous, our model can accommodate this situation by having the suppliers each provide a fraction of the demand of a component for each finished product.

The demand pattern evolves over time according to the different stages of the life cycle of a product: introduction, growth, maturity, and decline. We assume that demand is deterministic and linear in the price of the finished product. To capture the evolution of demand over the product's life cycle, we represent demand in period t as $d_t(p) = q_t = (a_t - p)/b_t$, where the values of a_t and b_t may vary across periods. The price elasticity of this demand model is $p_t/(a_t - p_t)$. Whereas b_t affects only the size of the market, a_t affects both the size of the market and its price elasticity. For most products, the market size increases in the introduction and growth stages, stabilizes during maturity, and decreases in the last stage. In addition, a product's price elasticity usually increases starting with the growth stage and increases further in the maturity and decline stages as the product loses its novelty and attracts mostly price-sensitive customers (Bijmolt et al. 2005). We restrict a_t to be nonincreasing in order to reflect a nondecreasing price elasticity. We present the analysis with the linear demand function for expositional simplicity. We also discuss which results continue to hold under the following commonly used nonlinear demand functions (see, e.g., Talluri and van Ryzin 2004): linear power $d_t(p) = ((a_t - p)/b_t)^\eta$, which is convex if $\eta < 1$ and concave if $\eta > 1$, isoelastic $d_t(p) = b_t^{-1} p^{-1/a_t}$ with $a_t < 1$, and exponential $d_t(p) = b_t^{-1} e^{-p/a_t}$. In all cases, demand elasticity is determined only by (and is decreasing in) a_t, whereas both b_t and a_t determine the market size in period t.

We denote by x_{it} the cumulative investment in process improvement for periods 1 through t made by supplier i, that is, $x_{it} - x_{i,t-1}$ is the incremental investment in period t, for $t = 1, \ldots, T$ and $i = 1, \ldots, M$, with $x_{i0} = 1$. The production cost in period t is a function of the cumulative investment level: $v_i(x_{it}) = v_{i0}(x_{it})^{-\beta_i}$, where v_{i0} is supplier i's component production cost before the beginning of the contractual relationship and $\beta_i > 0$ is supplier i's learning rate. The function $v_i(\cdot)$ is decreasing and convex. Specifically, $v_i'(x_{it}) = -\beta_i v_{i0}(x_{it})^{-\beta_i - 1} < 0$ and $v_i''(x_{it}) = \beta_i(\beta_i + 1) v_{i0}(x_{it})^{-\beta_i - 2} > 0$. (Similar models of cost reduction through learning have been proposed in Yelle 1979, Fine and Porteus 1989, and Mazzola and McCardle 1997.) In addition, each supplier i incurs a cost k_i per unit of incremental investment in process improvement made in any given period. (Investment costs, representing dollar engineering or consulting hours, do not vary significantly across periods. Nevertheless, it is possible to extend our results to time-dependent investment costs as long as k_{it}/k_{jt} does not change with t.) A linear investment cost coupled with a per-unit production cost that is convex decreasing results in decreasing returns to scale in the amount of investment, so the net effect is of the desired form. Finally, let $\delta < 1$ be the discount factor. Table 1 provides a summary of notation.

Table 1 Summary of Notation

x_{it}: Cumulative investment level of supplier i in period t.
$x_i = (x_{i1}, \ldots, x_{iT})$; $x_t = (x_{1t}, \ldots, x_{Mt})$; $x = (x_{it})_{i=1,\ldots,M,\, t=1,\ldots,T}$.

Single firm:

$\pi_t(x_t)$:	Firm profit in period t with cumulative investment x_t, not including investment costs.
$\pi_t^*(x_{t-1})$:	Optimal profit-to-go function in period t starting with cumulative investment x_{t-1}.
x_t^u:	Unconstrained maximum of the investment problem in period t.
x_t^*:	Optimal cumulative investment level in period t.
x_t^n:	Optimal cumulative investment level if the firm invests only in period t and for n periods.

Assembly system:

$v_i(x_{it})$:	Supplier i's component cost with cumulative investment x_{it}.
$\tilde{v}_{it}$:	Supplier i's target component cost under a target-price contract.
m_{it}:	Supplier i's margin in period t in the equilibrium of the Stackelberg game.
m_{At}:	Assembler's margin in period t.
w_{it}:	Wholesale price paid to supplier i in period t.
q_t:	Production quantity in period t.
$\pi_{it}(x_t)$:	Supplier i's profit in period t, not including investment costs.
$\pi_{At}(x_t)$:	Assembler's profit in period t.
$\hat{x}_t^n$:	Vector of equilibrium investment levels under a cost-contingent contract if all suppliers invest only in period t and for n periods.
x_t^c:	Vector of equilibrium investment levels in period t under a cost-contingent contract.
x_t^{tp}:	Vector of equilibrium investment levels in period t under a target-price contract.

4. Single Firm

We first consider a setting in which a single firm produces and sells a single component directly to the market. The results in this section will facilitate the analysis of the general assembly network. The firm first makes the investment decision and subsequently determines the retail price or selling quantity. Thus, there are no contracting issues in this setting. We omit subscript i. The dynamic investment decision problem can be formulated as follows. For $t = 1, \ldots, T$,

$$\pi_t^*(x_{t-1}) = \max_{x_t \geq x_{t-1}} \{\pi_t(x_t) - k(x_t - x_{t-1}) + \delta \pi_{t+1}^*(x_t)\}, \quad (1)$$

where $\pi_t(x_t) = \max_q (p_t(q) - v(x_t))q$, $x_0 = 1$, and $\pi_{T+1}^*(x) = 0$, for all x.[3] The optimal price and quantity in each period depend only on the cost and demand parameters in that period. That is, in period t, $p_t(q_t) = (a_t + v(x_t))/2$, $q_t = (a_t - v(x_t))/2b_t$, and the profit is given by

$$\pi_t(x_t) = (a_t - v(x_t))^2/4b_t.$$

[3] The terminal value can be specified to be a nonzero constant or an increasing concave function of x. This could change the magnitude and timing of investments, but it would not affect the structural results.

Differentiate $\pi_t(x_t)$ to obtain $\pi_t'(x_t) = -(a_t - v(x_t)) \cdot v'(x_t)/2b_t > 0$ and $\pi_t''(x_t) = \beta v_0 (x_t)^{-\beta-2}[\beta v(x_t) - (\beta+1) \cdot (a_t - v(x_t))]/2b_t$. The last expression is negative, guaranteeing strict concavity, if and only if $(1+\beta/(\beta+1))v(x_t) < a_t$. A sufficient condition for this inequality is that $2v_0 \leq a_t$. (Note that a_t is the largest possible price in period t—corresponding to zero sales—and v_0 is the initial cost of the component.) We assume, hereafter, that the latter inequality holds for all $t = 1, \ldots, T$. Note also that the one-period function $\pi_t(x_t)$ is increasing in x_t.

The following result characterizes the structure of the optimal profit-to-go function and optimal investment policy in each period t. We first define x_t^u as the unconstrained maximum of $\pi_t(x_t) - k(x_t - x_{t-1}) + \delta \pi_{t+1}^*(x_t)$. We denote by $\{x_t^*: t = 1, \ldots, T\}$ the optimal investment path.

Proposition 1. *For any t, $\pi_t^*(x_{t-1})$ is increasing and concave in x_{t-1}. In period t, it is optimal to invest up to $x_t^* = \max(x_t^u, x_{t-1})$. Moreover, $(\partial \pi_t^*/\partial x)(x) = k$ for $x \leq x_t^u$ and $(\partial \pi_t^*/\partial x)(x) < k$ for $x > x_t^u$.*

We next characterize the solution to the firm's investment problem. For $t_0 = 1, \ldots, T-1$, define $x_{t_0}^n$ to be the unique solution of

$$\sum_{t=t_0}^{t_0+n-1} \delta^{t-t_0} \pi_t'(x_{t_0}^n) = \begin{cases} (1-\delta^n)k & \text{if } 1 \leq n < T+1-t_0, \\ k & \text{if } n = T+1-t_0. \end{cases} \quad (2)$$

The quantity $x_{t_0}^n$ is the (optimal) cumulative investment level reached in period t_0 if no additional investments are made in the subsequent $n-1$ periods (the left-hand side in (2) is the marginal profit from sales over n periods, and the right-hand side is the marginal investment cost). Clearly, we have that $x_{t-1}^* \leq x_t^u$ if and only if $x_t^* = x_t^u$. The next result shows that, for each t, x_t^u is given by one of the cumulative investment levels defined in (2): $x_t^1, x_t^2, \ldots, x_t^{T+1-t}$.

Lemma 1. *Consider the optimal investment path $\{x_t^*: t = 1, \ldots, T\}$. If positive investments are made in periods t_0 and $t_0 + n \leq T$, but no investments are made in between those periods, then $x_{t_0}^* = x_{t_0}^u = x_{t_0}^n$. If t_0 is the last period of positive investment, then $x_{t_0}^* = x_{t_0}^u = x_{t_0}^{T+1-t_0}$. In addition, the following property holds*:

$$x_{t_0}^* = x_{t_0}^n \leq x_{t_0}^{n-l} \quad \textit{for } 1 \leq l \leq n-1. \quad (3)$$

The last statement in Lemma 1 is of interest. It states that if it is optimal to invest in periods t_0 and $t_0 + n$, but not in between, then investing in t_0 and in any of the intermediate periods would have resulted in overinvestment. This may initially seem counterintuitive, because one would expect x_t^n, the investment made at time t for the next n periods, to be higher than x_t^{n-l}, the investment made for the next $n-l$ periods. Although the marginal benefit of making an investment at time t increases with n, the cost of making a unit of investment at time t as opposed to making the investment n periods later, given by $(1-\delta^n)k$, also increases with n. The result in (3) states that, for the maximization problem in (1) at period t, the cost outweighs the benefit for x_t^{n-l}, $1 \le l \le n-1$, if x_t^n is the optimal solution of the dynamic program in that period.

Lemma 1 provides a partial characterization of the optimal investment path—it states what the optimal investment levels are given the optimal investment periods. The following result allows us to determine, inductively, the periods of investment in the optimal solution.

Proposition 2. *Suppose that x_{t+n}^* is the optimal investment level in period $t+n$ if the problem starts in that period, for each $n = 1, \ldots, T-t$. Then, at most one of the inequalities $x_t^n < x_{t+n}^*$, $n = 1, \ldots, T-t$, is satisfied. For a problem starting in period t, it is optimal to invest in periods t and $t+n_0$ if the inequality is satisfied for $n = n_0$. If no inequality is satisfied, then it is optimal to invest in period t and in no subsequent period.*

Proposition 2 states that, given solutions to the dynamic investment problems starting in periods $t+1, \ldots, T$, the problem starting in period t has a unique feasible solution in the set $\{x_t^1, \ldots, x_t^{T-t+1}\}$ that is also optimal. (This follows from (3) and the strict concavity of the one-period profit functions.) Appendix A discusses a simple algorithm, based on the result in Proposition 2, to compute recursively the optimal investment solution.

5. Assembly System

In the assembly system, there are M suppliers, each producing one component (or kit of components) used in the finished product. In §5.1, we explore settings with cost-contingent contracts, in which investments in cost reduction are made before the wholesale prices are established. Wholesale and retail prices and the sales quantity are determined in a Stackelberg game with the assembler as the leader. In §5.2, we consider target-price contracts. Under a target-price contract, the assembler stipulates a rate of cost reduction for each period and announces the path of wholesale prices over the length of the contract. Prices and production quantity are again determined according to a Stackelberg game with the assembler as the leader, based on the announced trajectory of component costs.

Let x_{it} denote the vector of cumulative investment level of supplier i in period t. Also, let $x_i = (x_{i1}, \ldots, x_{iT})$, $x_t = (x_{1t}, \ldots, x_{Mt})$, $x = (x_{it})_{i=1,\ldots,M,\, t=1,\ldots,T}$, and $x_{-i} = (x_j)_{j \ne i}$.

5.1. Cost-Contingent Contracts

Under cost-contingent contracts, purchase prices are determined contingent on the prevailing cost-reduction achievements. Specifically, suppliers determine, at the beginning of each period, the investment level for that period. This is followed by a Stackelberg pricing game with the assembler as the leader. The assembler moves first and sets its margin before the suppliers, ensuring that it gets a larger portion of the profit (this is consistent with the current balance of power in the automobile industry). The sequence of events in a period is as follows:

1. Suppliers select a level of investment in cost reduction.
2. The assembler establishes its margin over the variable production and procurement costs.
3. Suppliers determine their wholesale prices (by selecting their margins).

Stages 2 and 3 determine the retail price and sales quantity in each period. Given that a finished product requires one unit of each component, all suppliers produce and sell the same amount within each period. In stage 1, the suppliers select the period's level of investment in process improvement (or, alternatively, the cumulative level of investment up to and including that period) in anticipation of the subsequent price/quantity Stackelberg game. (Solution details are provided in Proposition 10 in Appendix C.) The resulting sales quantity and wholesale prices are

$$\begin{aligned} q_t &= \frac{1}{2(M+1)b_t}\Big(a_t - \sum_j v_j(x_{jt})\Big), \\ w_{it} &= v_i(x_{it}) + \frac{1}{2(M+1)}\Big(a_t - \sum_j v_j(x_{jt})\Big). \end{aligned} \tag{4}$$

The equilibrium wholesale prices reflect the assembler's response to cost reductions under a cost-contingent contract. A reduction in cost achieved through investment in process improvement is followed by a decrease in the wholesale price (note that w_{it} decreases if v_i does). The equilibrium profit expressions for the assembler and the suppliers are:[4]

$$\begin{aligned} \pi_{it}(x_t) &= \frac{1}{4(M+1)^2 b_t}\Big(a_t - \sum_j v_j(x_{jt})\Big)^2, \\ \pi_{At}(x_t) &= \frac{1}{4(M+1)b_t}\Big(a_t - \sum_j v_j(x_{jt})\Big)^2. \end{aligned} \tag{5}$$

[4] In equilibrium, all suppliers earn the same profit before investment costs (although the marginal benefit of an increase in the level of investment depends on each supplier's learning rate and initial component cost). This property is intrinsic to the assembly structure, and it arises in settings with stochastic demand and under different assumptions regarding the sequence of negotiations between the assembler and the suppliers (see, e.g., Nagarajan and Bassok 2002).

While the choice of prices and selling quantity under cost-contingent contracts is independent of any past prices or production quantities, the suppliers' investment decisions in stage 1 depend on the history of investments of all suppliers. In addition, a supplier's investment in cost reduction in a given period impacts the other suppliers' profits in that period (through the equilibrium selling quantity) and the future investments and profits of all suppliers. Thus, the investment/pricing game under cost-contingent contracts reduces to a supplier dynamic investment game in closed-loop strategies in which supplier i's profit in period t is given by $\pi_{it}(x) - k_i(x_i - x_{i,t-1})$.

In a dynamic game under closed-loop strategies, players condition their play at time t on the history of play until that date. That is, the state space at time t includes the history from periods $1, \ldots, t-1$. Under cost-contingent contracts, in every period t, supplier i makes an investment decision x_{it} with information about T, the demand trajectory, the initial component cost, learning rate and unit cost of investment of each supplier, and the history of investments of all suppliers, given by $\{x_{j1}, \ldots, x_{j,t-1}\}$, $j = 1, \ldots, M$. Supplier i's action space in period t is $\{x_{it} \geq x_{i,t-1}\}$.

In the game with closed-loop strategies under cost-contingent contracts, each firm chooses its investment level in period t given the other suppliers' investment levels $x_{-i,t}$ in that period and given the history of investments up to period t. An equilibrium in period t is determined by

$$\max_{x_{it} \geq x_{i,t-1}} \{\pi_{it}(x_t) - k_i(x_{it} - x_{i,t-1}) + \delta \pi^c_{i,t+1}(x_t)\} \quad \text{for all } i, \qquad (6)$$

where $\pi^c_{i,t+1}(x_t)$ is the equilibrium profit-to-go for supplier i in period $t+1$, with starting investment vector x_t. The boundary conditions are $x_{i0} = 1$ and $\pi^c_{i,T+1}(x) = 0$, for all i, x. Note that a closed-loop equilibrium is subgame perfect. That is, a supplier sets its investment level in period t with the expectation that all firms will respond with their state-dependent equilibrium strategies in period $t+1$. We denote this game by (C) to indicate that the assembler and the suppliers operate under cost-contingent contracts.

To guarantee strict concavity of $\pi_{it}(x_t)$ with respect to x_{it}, we assume that $a_t \geq 2\sum_j v_{j0}$ for all t (a similar assumption was made for the case of a single firm in §3, requiring that the consumers' willingness to pay for the first unit in the market be twice as large as the initial total cost of the components).

We first analyze the investment game in a single period. We drop the subscript t in this setting. The single-period profit function for supplier i is $\pi_i(x) - k_i(x_i - 1)$. Each supplier chooses an investment level to maximize its profit given the other suppliers' investment levels.

Proposition 3. *The single-period investment game is supermodular. Any equilibrium of the game satisfies the set of equations* $-(1/(2(M+1)^2 b))(a - \sum_j v_j(x_j))v_i'(x_i) - k_i = 0$ *for all i. If, in addition, the investment level for each supplier i is restricted to the interval*

$$1 \leq x_i \leq \frac{(1+\beta_i)a}{\sum_j (1+\beta_i+\beta_j)v_{j0}}, \qquad (7)$$

then there exists a unique equilibrium, which we denote by x^c. Otherwise, there is one equilibrium that is (component-wise) largest among all equilibria, which is preferred by all firms (the suppliers and the assembler). In that case, we denote that largest equilibrium by x^c. Finally, the equilibrium x^c is increasing in a and decreasing in b and k_i.

Note that the condition in (7) is sufficient to guarantee uniqueness of the equilibrium. Without this restriction, there may be multiple equilibria. In that case, the largest equilibrium Pareto-dominates all other equilibria because it results in higher profits for all firms. Therefore, if there are multiple equilibria, we restrict attention to the largest equilibrium.

The last statement in Proposition 3 is intuitive—the equilibrium investment levels decrease with the per-unit investment cost, whereas they increase in response to an increase in the level of demand (through either a larger a or a smaller b). In terms of comparative statics with respect to the initial component cost, an increase in v_{i0} results in an increase in supplier i's investment level and a decrease in the investment levels of all other suppliers. A larger v_{i0} means that supplier i supplies a larger portion of the necessary components for the finished product—therefore, an increase in this supplier's investment level makes sense. At the same time, a higher initial component cost translates into a higher retail price and thus a lower selling quantity, thus reducing the other suppliers' incentives to invest in cost reduction.

We now turn our attention to the multiperiod dynamic investment game. In contrast to the single-period game, which is supermodular, the multiperiod dynamic investment game fails to exhibit a structural property to guarantee the existence of a closed-loop equilibrium. In particular, the investment game in closed-loop strategies may not be supermodular. Proposition 11 in Appendix C shows that the last-period equilibrium profit is not supermodular as a function of the initial cumulative investment levels. We now consider a specific example of a system with two suppliers i and j, with $T = 2$, $\beta_i = 1.1$, and $\beta_j = 1.3$, $k_1 = k_2 = 4$, $\delta = 0.9$, $v_{0i} = v_{0j} = 1$, $a = (10, 10)$, and $b = (1, 0.09)$. There are three closed-loop equilibria in this example:

(i) $x_i = (1.121, 1.186)$, $x_j = (1.194, 1.257)$;
(ii) $x_i = (1.208, 1.208)$, $x_j = (1.198, 1.258)$;
(iii) $x_i = (1.125, 1.187)$, $x_j = (1.270, 1.270)$.

In equilibrium (i), both suppliers invest in both periods. In equilibria (ii) and (iii), there is one supplier that invests in both periods, whereas the other one invests in period 1 only. If the game were supermodular, then the set of equilibria would form a lattice (see Theorem 4.2.1. in Topkis 1998). However, the componentwise maximum of equilibria (ii) and (iii), i.e., $x_i = (1.208, 1.208)$ and $x_j = (1.270, 1.270)$, is not an equilibrium. Therefore, the game is not supermodular.

Despite the lack of structural properties of the dynamic game in closed-loop strategies, we next show that there always exists one closed-loop equilibrium that is characterized by synchronized investments. That is, depending on the market conditions, either all suppliers invest in cost-reduction initiatives in any given period or no supplier does. In the example above, equilibrium (i) is synchronized—both suppliers invest in both periods—whereas equilibria (ii) and (iii) are not. As we discuss below, the synchronized closed-loop equilibrium corresponds to an equilibrium in open-loop strategies. Note that other equilibria in closed-loop strategies may also exist, which are not in open-loop strategies (such as equilibria (ii) and (iii) above). We refer to Appendix B for examples that illustrate when multiple closed-loop equilibria may arise.

In an equilibrium under open-loop strategies, players choose time paths of actions that depend only on time. In the investment game, each supplier i makes its investment trajectory decision in the set $\Omega_i = \{x_i = (x_{i1}, \ldots, x_{iT})\colon 1 \le x_{i1} \le x_{i2} \le \cdots \le x_{iT}\}$ with information about T, the demand trajectory, and the initial component cost, learning rate, and unit cost of investment of each supplier. The next result shows that, in our setting, an equilibrium in open-loop strategies is also an equilibrium in closed-loop strategies.

Proposition 4. *In the dynamic investment game under cost-contingent contracts, an equilibrium in open-loop strategies is also an equilibrium in closed-loop strategies.*

Thus, we prove the existence of a closed-loop equilibrium by showing that one such equilibrium exists in open-loop strategies. We refer to x^c as the equilibrium of the investment game, implemented as an equilibrium in closed-loop strategies, that is also an open-loop equilibrium.

We now investigate the multiperiod game under open-loop strategies. An open-loop equilibrium $x^c = (x_1^c, \ldots, x_M^c)$ is such that supplier i's strategy $x_i^c \in \Omega_i$ is a best response to the other suppliers' strategies x_{-i}^c. The best-response function of supplier i to x_{-i} is obtained by solving

$$\max_{x_i \in \Omega_i} \sum_{t=1}^{T} \delta^{t-1}(\pi_{it}(x_t) - k_i(x_{it} - x_{i,t-1})), \tag{8}$$

where $x_{i0} = 1$ for all i.

Given the other suppliers' investment decisions x_{-i}, the optimization problem of supplier i in (8) is equivalent to the single firm's optimization problem in (1), with π_t replaced by π_{it} as defined in (5)—that is, the intercept of single firm i's problem is $a_t - \sum_{j\neq i} v_j(x_{jt})$. We established that, under a condition on the cost and demand parameters, supplier i's optimization problem is concave in x_i (for fixed investment paths x_{-i}). Therefore, an open-loop equilibrium exists. Furthermore, the investment game in open-loop strategies is supermodular. The next result shows that in any open-loop equilibrium path, suppliers' investments in process improvement are synchronized.

Theorem 1. *In an open-loop equilibrium of the suppliers' investment game, investments in cost reduction are synchronized. That is, for any given period, either all suppliers invest or no supplier does:* $(x_{it}^c > x_{i,t-1}^c) \Leftrightarrow (x_{jt}^c > x_{j,t-1}^c)$ *for all* i, j, *and* t.

The result in Theorem 1 shows that all suppliers make positive investments in process improvement in the same periods at equilibrium, although their actual investment-level decisions are not necessarily the same. This result conveys the insight that synergies in cost-reduction investment efforts are important in this setting. For example, synchronized investments allow suppliers to coordinate their efforts to permit technical changes that require coordination among suppliers. The literature on learning in organizations discusses other benefits to synchronous learning activities not captured in our model (see Zhao et al. 2004).

Synchronization arises because all suppliers face the same market conditions (i.e., if demand for the finished product goes up [down], then each component's demand increases [decreases]) and because there are positive externalities across their investment decisions. To illustrate, suppose that one of the suppliers sold components to another firm, thus benefiting from investments in cost reduction beyond those accrued in the assembly system. Then, this supplier may be willing to invest in cost reduction even toward the end of the product's life cycle, when demand is decreasing, provided that the supplier's second business benefits substantially from a lower cost. Other suppliers, however, may not enjoy the same benefits, and, consequently, synchronization may not hold. Note that facing equal market conditions alone does not imply synchronization—this can be seen in equilibria (ii) and (iii) above. Synchronization is also a result of the positive externalities present across the suppliers' decisions. That is, a supplier's benefit from investing in cost reduction increases if the other suppliers invest too. This may not be the case if the game is not supermodular. Synchronization holds even if the initial component costs, learning rates, and unit investment costs differ across suppliers.[5] In §7, we show that synchronization holds in settings with assembler competition and knowledge spillover, provided that the suppliers face the same market conditions and that the game is supermodular. We hereafter focus attention on the synchronized equilibrium as the solution to (C).

Theorem 1 is instrumental in the characterization of equilibria in the investment game. The property allows us to decompose the multiperiod investment game into several one-time investment games in which each supplier's profit is the sum of the discounted profits over a given time interval. Similar to the definition of $x_{t_0}^n$ for a single firm, we now consider the equilibria of the one-time investment game in which suppliers invest in period t_0 and do not make any additional investments in the subsequent $n-1$ periods ($t_0+n \le T$). The profit of supplier i as a function of the vector x, for starting investment level $x_{i,\,t_0-1}$, is given by

$$\sum_{t=t_0}^{t_0+n-1} \delta^{t-t_0}\pi_{it}(x) - k_i(x_{i,\,t_0} - x_{i,\,t_0-1}) + \delta^n k x_{i,\,t_0}. \tag{9}$$

As in the case of a single period, this game is also supermodular and any equilibrium x_{t_0} satisfies the equations

$$\sum_{t=t_0}^{t_0+n-1} \delta^{t-t_0}\frac{\partial \pi_{it}}{\partial x_i}(x_{t_0}) = -\sum_{t=t_0}^{t_0+n-1} \delta^{t-t_0}\frac{(a_t - \sum_j v_j(x_{j,\,t_0}))}{2(M+1)^2 b_t} v_i'(x_{i,\,t_0}) = (1-\delta^n)k_i \quad \text{for all } i.$$

Following a similar argument as in Proposition 3, it follows that the equilibrium is unique if the investment level for each supplier i is restricted to the interval

$$1 \le x_{it} \le \frac{(1+\beta_i)\min\{a_t\colon t=1,\ldots,T\}}{\sum_j (1+\beta_i+\beta_j)v_{j0}}. \tag{10}$$

Under the restriction in (10), we denote the unique equilibrium of the investment game (9) at period t_0 by $\hat{x}_{t_0}^n = (\hat{x}_{1t_0}^n, \ldots, \hat{x}_{Mt_0}^n)$. Without the restriction in (10), there may be multiple equilibria. In that case, as in Proposition 3, there is a largest equilibrium that is preferred by all suppliers and the assembler. Therefore, we restrict attention to the largest equilibrium and denote it also by $\hat{x}_{t_0}^n$.[6] (We similarly define $\hat{x}_{t_0}^n$ for $n = T - t_0 + 1$.)

[5] Note, however, that if investment costs change over time with k_{it}/k_{jt} *depending* on t, then synhronization may not hold. A supplier with increasing investment costs may prefer to invest early in the product's life cycle, whereas another supplier with decreasing costs would be better off investing toward the end of the product's life cycle.

[6] If the upper bounds in condition (10) are tight, then the suppliers that reached their maximum possible investment level would not invest any more through the end of the product's life cycle. These sufficient conditions to guarantee uniqueness are most useful when the bounds are not tight.

We use the vectors $\{\hat{x}_t^n\}_{t=1,\ldots,T,\,n=1,\ldots,T-t+1}$ to characterize the equilibrium of the multiperiod investment game (C). Making use of the result in Theorem 1, there are time periods $1 = t_1 < \cdots < t_m$ in which all suppliers make positive investments in the equilibrium path. These cumulative equilibrium levels are given by $x_{t_r}^c = \hat{x}_{t_r}^{n_r}$ for $r = 1, \ldots, m$, with $n_r = t_r - t_{r+1}$ for $1 \le r < m$ and $n_m = T - t_m + 1$. In what follows, we restrict attention to x^c, the largest (or unique, if (10) is satisfied) equilibrium path of the investment game (C). We next show that a condition analogous to (3) in Lemma 1 holds for the assembly system—the interpretation here is the same as for the case of a single firm.

Lemma 2. *If* $x_{t_0}^c = \hat{x}_{t_0}^n$, *then* $x_{t_0}^c = \hat{x}_{t_0}^n \le \hat{x}_{t_0}^{n-l}$ *for* $1 \le l \le n-1$.

The equilibrium investment levels x^c and the equilibrium investment periods can be determined recursively using a simple algorithm, presented in Appendix A. The algorithm produces the largest (or unique, if (10) is satisfied) synchronized equilibrium of the multiperiod investment game.

The following result allows us to compare, period by period, equilibria of investment games with different input parameters. Because these equilibria may be characterized by investments in different time periods (e.g., one in periods 1, 3, and 5 and the other one in periods 1, 4, 5, and 7, in a setting with $T = 7$), a direct comparison of the equilibrium levels in each period may not be straightforward. The result states that it is sufficient to compare the equilibrium levels arising from all possible one-time investment games.

Lemma 3. *Consider two M-supplier dynamic investment games with different input parameters. For* $t = 1, \ldots, T$ *and* $n = 1, \ldots, T-t+1$, *let* $\{\hat{x}_t^n\}$ *and* $\{\hat{y}_t^n\}$ *denote the resulting equilibria of all possible one-time investment games in each of the two problems, respectively. Furthermore, suppose that* $\hat{x}_t^n \le \hat{y}_t^n$, *for all* $t = 1, \ldots, T$ *and* $n = 1, \ldots, T-t+1$. *Then, the equilibrium path in the second problem is no smaller, period by period, than that in the first problem.*

Similar to the results shown for the single-period problem, each of the vectors $\hat{x}_{t_0}^n$ is increasing in a_t for $t = t_0, \ldots, t_0+n-1$, and decreasing in k_i and in b_t for $t = t_0, \ldots, t_0+n-1$. Lemma 3 implies the same comparative statics results for the equilibrium path. Also, an increase in v_{i0} increases supplier i's equilibrium investment path and reduces the investments of all other suppliers, implying a higher rate of cost reduction for the larger component suppliers and a lower rate for the smaller component suppliers. These observations enable us to understand how the magnitude and timing of the equilibrium investments are affected by changes in the input parameters.

The following result shows that it is not optimal to invest in cost reduction as the product approaches the end of its life cycle. Furthermore, positive investments occur in any two periods if a weighted average of the demand levels (as measured by the a_t- and b_t-values) is higher in the later of the two periods. This result assumes that investment costs do not depend on time. If investment costs decrease significantly over time, then suppliers may choose to invest even while demand is decreasing.

Proposition 5. *In the equilibrium investment path, investments are made in periods t_0 and t_0+n, for the length of n and m periods, respectively, if*

$$\sum_{t=t_0}^{t_0+n-1} \frac{\delta^{t-t_0}}{1-\delta^n}\frac{1}{b_t} \le \sum_{t=t_0+n}^{t_0+n+m-1} \frac{\delta^{t-t_0-n}}{1-\delta^m}\frac{1}{b_t} \quad \text{and}$$

$$\sum_{t=t_0}^{t_0+n-1} \frac{\delta^{t-t_0}}{1-\delta^n}\frac{a_t}{b_t} \le \sum_{t=t_0+n}^{t_0+n+m-1} \frac{\delta^{t-t_0-n}}{1-\delta^m}\frac{a_t}{b_t},$$

where $t_0+n+m<T$. In addition, if $a_t=a$ for all t, then all suppliers invest in process improvement as the market is expanding and will all stop investing in the same time period.

To illustrate this result, we consider a setting with two suppliers and five time periods. Fixing $a_t=20$ for all t, $b_1=1$, $b_4=0.5$, and $b_5=1$, we let b_2 and b_3 vary so that $b_3\le b_2\le b_1=1$ and $0<b_3\le b_4=0.5$, thus ensuring a demand pattern in which demand increases over the first three periods and decreases thereafter. The three possible equilibrium paths involve investments in period 1 only, in periods 1 and 2 only, and in periods 1–3. The case with investments in all three periods requires a low value of b_3, which corresponds to a high demand level in the third period. We also note that, for any fixed value of b_2, the frequency of investments increases as b_3 decreases (e.g., from investments in periods 1 and 2 to investments in periods 1–3). If b_2 and b_3 are both large, then demand is relatively flat over the product's life cycle and suppliers invest only in the first period.

As reported in Bijmolt et al. (2005), some products experience increased price elasticity as they enter the maturity and decline stages of their life cycles. If that is the case, then more irregular equilibrium investment patterns may emerge as compared to settings with constant price elasticity. Indeed, when demand elasticity increases over the product's life cycle, investments in process improvement may not occur continuously over periods of increasing market demand. Consider, for example, the following setting: $\delta=0.9$, $k_1=k_2=10$, $v_{10}=v_{20}=5$, $\beta_1=\beta_2=1.2$, $a=(20,18,16,14,14)$, and $b=(1,0.88,0.05,0.5,1)$. Here, demand increases over periods 1–3 and decreases in the remaining two periods, whereas price elasticity increases over the product's life cycle. In equilibrium, suppliers invest in process improvement in period 1, do not invest in period 2, resume process improvement activities in period 3, and stop investing thereafter. In this example, demand increases slowly over the first two periods and steeply in the third period. That is, a modest increase in demand may be offset by increasingly price-sensitive customers, and an investment may therefore not be profitable.

Proposition 5 suggests that only the market size and discount factor affect the timing of investment decisions when price elasticity is constant. When price elasticity is not constant, however, factors like investment costs or learning rates may affect not only the magnitude of investments, but also their timing. In particular, to make projections regarding cost reductions over the product's life cycle, firms need to be aware of the prospects for market expansion and of the possible changes in the product's price elasticity.

We now explore how the size of the supplier base affects the equilibrium investment levels and the resulting rate of cost reduction. To analyze the effect of the number of suppliers, we assume that all suppliers are symmetric. Let v_0 be the total initial cost of components. As the number of suppliers (M) changes, we assume that each supplier incurs an initial cost of v_0/M. In other words, each supplier manufactures an equal-sized portion of the finished product. There are two elements that play a role in the equilibrium investment levels and resulting cost reduction rates. As can be verified from (5), the extent of double marginalization increases with the number of suppliers, thus reducing the incentives to invest in cost-reduction initiatives. At the same time, there are diseconomies of scale in the investment levels. To see this, consider the cases with one and two suppliers and suppose that in both settings total investments (across all components) in cost reduction equal x. Comparing the resulting total component costs, we have $v_0(x)^{-\beta}<(v_0/2)(x/2)^{-\beta}+(v_0/2)(x/2)^{-\beta}=v_0(x/2)^{-\beta}$, implying a larger amount of component cost reduction in the system with one supplier, for the same aggregate level of investment x. As a result of these two effects, equilibrium investment levels decrease as the number of suppliers increases.

Before proceeding to the analysis of target-price contracts, we note that all of the structural results in this section continue to hold for general demand functions as long as the single-period profit $\pi_{it}(x_t)$ is strictly concave in x_{it}. Under linear power $d_t(p)=((a_t-p)/b_t)^\eta$, supplier i's equilibrium profit is strictly concave in x_{it} if $(\eta+1)\sum_j v_{j0}\le a_t$. For the isoelastic demand function, $d_t(p)=b_t^{-1}p^{-1/a_t}$ with $a_t<1$, the condition is $\beta_i/(\beta_i-1)\le a_t/(1-a_t)$ for all i. For the exponential demand $d_t(p)=b_t^{-1}e^{-p/a_t}$, the condition is

$v_{i0} \le a_t$ for all i. The parameter conditions that guarantee uniqueness of an equilibrium and the parametric monotonicity results in Proposition 5 are specific to the linear demand function.

Many car manufacturers employ cost-contingent contracts. Although this procurement arrangement may seem beneficial to the buyer, renegotiation of wholesale prices in each period can have a negative impact on the suppliers' profitability. Indeed, Clanton (2005) reports that, in the automobile industry, excessive cost-cutting pressures have forced some suppliers into bankruptcy. As a result, as reported in a recent article in the *Wall Street Journal* (McCracken and Glader 2007), some suppliers are refusing to go along with the additional cost reductions required by some auto manufacturers. We next explore target-price contracts as an alternative approach to procurement. The implementation of appropriately designed target-price contracts may increase profitability for all firms and facilitate a smoother relationship with the suppliers.

5.2. Target-Price Contracts

We now consider an alternative approach to procurement, in the spirit of Toyota's target-price contracts (McMillan 1990). Under this arrangement, the time path of wholesale prices is determined in advance based on a stipulated rate of process improvement and cost reduction. Specifically, the assembler announces the time path of production costs $\{\tilde{v}_{it}\}$ that it expects from each supplier i; i.e., supplier i's unit cost in period t must be no larger than $\tilde{v}_{it}$. The wholesale prices, margins, and production quantity are then determined according to a Stackelberg game with the assembler as the leader, based on the stipulated component costs $\{\tilde{v}_{it}\}$. Consequently, for period t, the base margin of supplier i is $m_{it} = (1/(2(M+1))) \cdot (a_t - \sum_j \tilde{v}_{jt})$, its wholesale price is $\tilde{w}_{it} = m_{it} + \tilde{v}_{it}$, and the production quantity is $q_t = (1/(2(M+1)b_t)) \cdot (a_t - \sum_j \tilde{v}_{jt})$. (The *actual* unit cost achieved by supplier i in period t, $v_i(x_{it})$, depends on the supplier's cumulative investment up to that period and may be larger or smaller than $\tilde{v}_{it}$. Thus, its true margin may be different from m_{it}.) This formulation is equivalent to one in which the assembler announces a time path of wholesale prices $\{\tilde{w}_{it}\}$ because there is a one-to-one correspondence between the wholesale prices and the suppliers' production costs in the equilibrium of the Stackelberg game.

Because wholesale prices are determined in advance, the suppliers' investment decisions decouple. That is, each supplier's profit is independent of the other suppliers' actions. Supplier i chooses x_{it} in period t in order to maximize its profit:

$$\pi^{tp}_{it}(x_{i,t-1}) = \max_{x_{it} \ge x_{i,t-1}} (\tilde{w}_{it} - v_i(x_{it}))q_t - k_i(x_{it} - x_{i,t-1}) + \delta \pi^{tp}_{i,t+1}(x_{it}),$$

where $\pi^{tp}_{i,t+1}(x_{it})$ is the profit-to-go for supplier i in period $t+1$, with initial investment level x_{it}. The results for the single firm developed in §4 apply to the optimization problem of each supplier. In addition, the synchronization result in Theorem 1 holds for target-price contracts.

In practice, target-price contracts typically set the time path of wholesale prices based on a cost trajectory that follows a constant percentage cost reduction in each period.[7] These rates are independent of the prevailing market characteristics (e.g., demand volume) and of the configuration of the system (e.g., number of suppliers). That is, the unit cost in time period t is expected to decrease by a certain percentage ρ from that in period $t-1$, leading to

$$\tilde{v}_{it} = (1-\rho)^{t-1}\, v_{i0}, \quad \rho \in (0, 1]. \qquad (\mathrm{TP}(\rho))$$

Under a target-price contract, each supplier keeps all of the savings from cost reduction beyond those stipulated in the contract, as opposed to keeping only a fraction of the cost savings under cost-contingent contracts. This suggests that the investment levels resulting from a target-price contract should be higher than those under cost-contingent contracts. We show below that this intuition does not always hold. In particular, whether target-price contracts lead to higher investment levels depends on the demand model and on the specific contract parameters.

Proposition 6. *For linear and linear-power demands, the equilibrium investment path under* (TP(ρ)) *is higher than the one that arises under cost-contingent contracts for any* ρ. *For isoelastic and exponential demands, the equilibrium investment path under* (TP(ρ)) *is higher* [*lower*] *than that under cost-contingent contracts for sufficiently high* [*low*] ρ.

In addition to its impact on the investment levels, the specific rate of cost reduction has implications for the profit performance of all firms. Low values of ρ lead to high wholesale prices and low sales quantities—this may hurt the assembler and the suppliers. Indeed, if the target rate of cost reduction is not high enough, the assembler's profit may be lower than under cost-contingent contracts. On the other hand, high values of ρ (i.e., aggressive cost-reduction requirements) result in significantly lower wholesale prices, allowing the assembler to charge a low retail price and thus increase sales. This may cause deterioration in the suppliers' performance and may even result in negative profits for some of them.

Depending on the cost trajectory and on the suppliers' ability to reduce costs through process improvement, target-price contracts may hurt the profit

[7] In the automobile industry, the rate is typically anywhere between 3% and 7% (see Clanton 2005).

performance of the suppliers, the assembler, or the whole supply chain. Thus, the choice of the time path of cost reductions is critical for a successful implementation of target-price contracts. (McMillan 1990 argues that firms should specify target-price contracts based on a "reasonable" rate of cost reduction.) We next propose an alternative approach for specifying the trajectory of suppliers' cost reductions that favors all firms—a target-price contract in which the stipulated rates of cost reduction are calibrated with those that arise under cost-contingent contracts. We denote this contract as (TP), under which the target costs are specified as $\tilde{v}_{it} = v_i(x^c_{it})$. The resulting wholesale price and quantity equal those that are the outcome of the Stackelberg game under the cost-contingent contract. Here, in contrast to (C), the path of wholesale prices is determined at the beginning of the contractual relationship. We next show that (TP) is more efficient than a cost-contingent contract for all firms in the system.

Proposition 7. *For any of the demand models considered, the equilibrium investment path and all firms' profits under* (TP) *are greater than or equal to those under cost-contingent contracts.*

Setting the rates of cost reduction equal to those that arise under cost-contingent contracts ensures that the wholesale prices and assembler's profit are the same under (TP) and (C). At the same time, the wholesale prices under (TP) are not contingent on the actual component costs, so suppliers earn any incremental benefits of investment. The result is that (TP) leads to strictly higher investment levels and profits for all suppliers under all demand functions, except for the exponential model (in that case, investment levels and profits remain equal to those under (C)). Therefore, a target-price contract stipulating somewhat higher cost reduction rates than those arising under (C) would result in higher investment levels, a higher sales volume, and higher profits for all firms. This is the case even for the exponential demand model because the effect of a decrease in wholesale prices is offset by a larger increase in the sales volume.

Consequently, target price paths calibrated with the levels of cost reduction achieved under cost-contingent contracts can serve as a guideline for the efficient design of target-price contracts. This suggests that target-price contracts should not require the same cost-reduction rates for all suppliers or be constant throughout the product's life cycle. Because the rate of cost reduction under a cost-contingent contract depends on the evolution of demand over the product's life cycle (market size and price elasticity), target cost reductions should evolve in a similar way (as opposed to being constant over the product's life cycle). In particular, under cost-contingent contracts, suppliers invest in process-improvement activities as demand increases. Therefore, the target cost-reduction rates should typically be higher in earlier periods and decrease toward the end of the product life cycle. As discussed in §5.1, there are a number of factors that affect the equilibrium investment levels and the resulting rate of cost reduction under cost-contingent contracts. In particular, equilibrium investment levels decrease as the number of suppliers increases. Also, the rate of cost reduction of a relatively larger component supplier is higher than that of a smaller component supplier. These observations suggest that a properly specified target-price contract must consider the dynamic effects of cost-reduction initiatives along the product's life cycle, stipulating rates that evolve according to market demand and that are sensitive to changes in the product's price elasticity. Also, the rates should depend on the number of suppliers in the system and on their individual characteristics (e.g., relative cost of components, investment costs).

6. Centralized Investment Decisions

We now consider a system in which investment levels are chosen to maximize total supply chain profit. The problem consists of

$$\max_{x_i \in \Omega_i} \sum_{t=1}^{T} \delta^{t-1} \left(\pi_{\mathrm{A}\,t}(x_t) + \sum_{i=1}^{M} (\pi_{it}(x_t) - k_i(x_{it} - x_{i,\,t-1})) \right).$$

Let x^* denote the vector of optimal centralized investment levels. The conditions (10) guarantee joint concavity of the total supply chain profit. We assume that these conditions hold. We compare the optimal investment levels that arise under centralized decision making with the equilibrium investment levels in the decentralized systems under cost-contingent and target-price contracts.

Theorem 2. (i) $x^* > x^{tp} \geq x^c$, *where* x^{tp} *and* x^c *are the equilibrium investment paths under* (TP) *and* (C), *respectively.*

(ii) *If* $a_t = a$ *for all* t, *then the timing of investments is the same under centralized and decentralized control.*

Theorem 2 holds for linear as well as for the nonlinear demand models considered earlier. Because the suppliers' profits are only a fraction of the total supply chain profit, the decentralized equilibrium investment levels never reach those that are optimal when investment decisions are centralized.[8] One

[8] Laffont and Tirole (1993) argue that, in a setting with a single supplier producing an indivisible project, fixed-price contracts (similar to target-price contracts) induce the centralized investment levels. In their model, the production quantity is the same under a fixed-price contract and under centralized control. In contrast, in our setting, the production quantity depends on the wholesale prices and is therefore different under target-price contracts and under centralized investment decisions.

way to achieve the centralized investment levels in a decentralized setting is to offer assistance to the suppliers in the form of subsidies for cost-reduction initiatives. In the automobile industry, for example, many car manufacturers offer assistance by providing free consulting services (see Chappell 2002). Specifically, under cost-contingent contracts and for linear demand, by subsidizing a $2M/(2M+1)$ fraction of each supplier's expenses in cost-reduction initiatives, each supplier incurs a share of its investment costs that equals its share of supply-chain profit before investment costs. Thus, the equilibrium investment levels with subsidies equal the optimal investment levels. (The optimal subsidy rates for the nonlinear demand models are also constant over time and depend only on the number of suppliers.)

Not all subsidies are equally effective. Whereas sharing the monetary costs of investments (e.g., with a reimbursement mechanism) would lead to increased supplier investments, providing consulting time for free without tying it to a proportional effort by the supplier would not. In this case, a subsidy would serve only as a substitute for a supplier's own cost-reduction efforts. In our setting, the assembler should require a supplier to supplement every hour spent by the consultants with at least $1/2M$ hours of the supplier's own engineers and managers.

To compare the firms' performance across the three regimes, we conducted a set of experiments with linear demand and the following 96 parameter combinations: $M \in \{2, 3\}$, $T \in \{3, 4, 5\}$, $\delta \in \{0.9, 0.95\}$, $a_t = 20$, or $a_t = 20 - 2(t-1)$ for all t, $b = (1, 0.1, 0.5)$, $b = (1, 0.5, 0.1, 0.5)$, or $b = (1, 0.5, 0.1, 0.1, 0.5)$, $k_1 = k_2 = k \in \{2, 5\}$ for all i, $v_{0i} = 5$ for all i and $\beta_i = 1.1$ or $\beta_i = 1 + 0.1i$ for all i. These parameters describe settings with two and three suppliers, various lengths of the product's life cycle, and various discount rates. In addition, the numerical study considers both the cases of constant and increasing price elasticity, as well as symmetric and asymmetric learning rates. In all cases, demand increases in the first few periods and decreases toward the end of the product's life cycle. Finally, we consider both low and high investment costs.

We find that, on average, total supply chain profit under cost-contingent contracts is 16.4% lower than under centralized investment decisions. Target-price contracts reduce this gap to an average of 11.3%. In addition, supplier profits are, on average, 16% higher under (TP) than under (C). Factors that tend to exacerbate the inefficiency of cost-contingent contracts are a higher number of suppliers, higher values of k_i, and increases in demand price elasticity over the product's life cycle. In addition to comparing the investment levels, Theorem 2 states that the timing of investments is the same across the three regimes when the price elasticity of demand is constant. This may not be the case in settings with increasing price elasticity. We find that in four scenarios with increasing price elasticity, suppliers invest more frequently under centralized decisions than under either decentralized regime. For example, for $M = 3$, $T = 3$, $k = 2$, $\delta = 0.9$, $\beta_i = 1.1$, $i = 1, 2, 3$, $a = (20, 18, 16)$, and $b = (1, 0.1, 0.5)$, optimal centralized investments occur in periods 1 and 2, whereas suppliers invest only in period 1 under (TP) and (C). This is a manifestation of double marginalization specifically related to the multiperiod setting.

7. Competing Assemblers and Knowledge Spillover

In this section, we consider a system in which there are two competing assemblers purchasing from the same suppliers with knowledge spillover between the suppliers' production lines. Assemblers A and B compete in the same market with demand functions $q_{jt}(p_A, p_B) = (a_{jt} - p_j + c_t p_i)/b_t$, $i, j \in \{A, B\}$, $j \neq i$, where $c_t < 1$ and the values of a_{jt}, b_t, and c_t may vary across periods.

We assume that two components are required to assemble each final product, i.e., $M = 2$. A supplier's cost for the same component may be different for each assembler. (In the auto industry, for example, the suppliers of subassemblies and major components have separate production lines for each manufacturer.) The suppliers engage in process-improvement activities for the production line corresponding to Assembler A. Some of this knowledge may spill over to the production line for Assembler B. This is modeled by introducing a parameter $\alpha \in [0, 1]$ to reflect the fraction of cost reduction achieved for Assembler A's component that spills over to Assembler B's component. (Dyer and Hatch 2006, argue that, in the automobile industry, process-improvement efforts at a supplier's production line are usually not transferable from another production line because of the relationship-specific nature of the investments and other barriers to knowledge transfer. Then, presumably, the value of α may be quite low in practice. Here, we allow for any value $0 \leq \alpha \leq 1$.)

The component production cost for supplier i in period t is a function of the cumulative investment level in the production line of Assembler A, $v_{iA}(x_{it}) = v_{i0}(x_{it})^{-\beta_i}$ and $v_{iB}(x_{it}) = v_{i0} - \alpha(v_{i0} - v_{iA}(x_{it}))$. We assume that $a_{jt} \geq v_{10} + v_{20}$ for $j = A, B$ and all t. The sequence of decisions in each period under cost-contingent contracts is similar to that with a monopolist assembler. First, suppliers make their investment decisions, which determine the costs of the components. Second, the assemblers announce their m_{At} and m_{Bt} margins simultaneously. Third, the suppliers announce their margins (m_{1At}, m_{1Bt}) and (m_{2At}, m_{2Bt}). The sum of costs and margins determines the equilibrium prices and quantities.

We also consider settings in which Assembler A establishes target-price contracts with the suppliers while Assembler B continues to operate under cost-contingent contracts. Assembler A initially stipulates target cost-reduction rates based on the equilibrium path that arises under cost-contingent contracts. In each period, the suppliers first make investment decisions. Then, the assemblers announce their margins m_{At} and m_{Bt} simultaneously. Finally, the suppliers announce their margins for product B, m_{1Bt} and m_{2Bt}. In the decentralized setting, each supplier makes investment decisions to maximize her profit including investment costs. The centralized investment levels maximize total profits related to Assembler A's production line.

Proposition 8. (i) *Under cost-contingent contracts, the cost-reduction investment game is supermodular. In addition, the synchronization result holds.*

(ii) *Under both cost-contingent and target-price contracts, the suppliers' investment levels increase as the spillover rate α increases.*

(iii) *If $c_t > 0$, then the centralized investment levels are strictly decreasing in α.*

Because of the additional benefits of investing in process improvement in one production line, a supplier's investment level increases as the spillover rate increases. From Assembler A's centralized perspective, however, an increase in α results in a further decrease in the production cost of product B, reducing the marginal benefit of making an investment. The result in Proposition 8(i) may not hold if a supplier sold components to both assemblers while the other supplier sold components to only one of the assemblers. In that case, the suppliers' investment decisions may no longer be strategic complements. Moreover, the timing of the suppliers' investments may not be synchronized if the assemblers' demand patterns differ significantly.

We replicate the 48 cases with $M = 2$ in the numerical study reported in §6 for the following parameter combinations: $\alpha \in \{0, 0.2, 0.4\}$, $c_t = c \in \{0, 0.3\}$, $a_{At} = a_t$, where the a_t-values are as specified earlier, and $a_{Bt} = \{0.8, 1, 1.2\} \times a_{At}$ to represent symmetric and asymmetric market sizes for the two assemblers. In this study, increased α results in higher profits for the suppliers and Assembler B because of the additional reduction in the suppliers' component costs, but lower profit for Assembler A because Assembler B can produce a more cost-competitive product.

We also compare the level of inefficiency in the decentralized system (with respect to centralized investment decisions) to the case of a monopolistic assembler. In that setting (i.e., $\alpha = 0$, $c = 0$, and $M = 2$), target-price contracts are more efficient than cost-contingent contracts: the average gap with the profit of the centralized system is 5.4% under (TP) and 8.1% under cost-contingent contracts. As α and c increase, the level of inefficiency decreases. For example, the inefficiency gaps under target-price and cost-contingent contracts are, respectively, 4.8% and 7.0% for $\alpha = 0.2$, $c = 0$, 2.6% and 3.6% for $\alpha = 0.2$, $c = 0.3$, and 2.2% and 2.8% for $\alpha = 0.4$, $c = 0.3$. For a given α, an increase in c implies stronger competition downstream, so each unit of cost reduction is followed by a steeper decrease in retail prices and, therefore, incrementally higher sales volumes. For a given c, an increase in α translates into lower costs for Assembler B's production line and therefore increased marginal benefits for the suppliers, increasing their investment levels (see Proposition 8). At the same time, centralized investment levels decrease with α, so the gap narrows. While the incremental benefit of target-price contracts over cost-contingent contracts, relative to the centralized system, declines as α and c increase, subsidies remain as an alternative to further increase investment levels.

The subsidy rates that induce centralized investment decisions exhibit significantly different properties in this setting. Recall that the subsidy rate in the case of a monopolist assembler with two suppliers is 80% (i.e., $2M/(2M+1)$) throughout the product's life cycle. In a setting with competing assemblers, if either $\alpha > 0$ or $c_t > 0$, then the subsidy rate varies across periods and depends on the demand trajectory (described by a_{At}, a_{Bt}, b_t, c_t) and the spillover rate α. In the numerical study, we find that the subsidy rate decreases with factors that increase the competitor's benefits from process improvement, such as higher values of α, c_t, and a_{Bt}/a_{At}. If a_{Bt}, α, or c_t increase, then the suppliers' profits from selling to Assembler B increase and so do their investment levels, which in turn reduces the need for subsidies by Assembler A. In the numerical study, subsidies in this setting varied from as low as 60% to up to 80%, indicating the importance of understanding the market dynamics in designing subsidies for more complex systems.

8. Conclusions

This paper presents a novel framework to investigate the dynamics of cost reduction in decentralized supply networks, in which suppliers invest in process-improvement activities. We consider two approaches to procurement. In the first one, the wholesale prices in each period are determined contingent on the cost of components in that period. In the second one, under so-called target-price contracts, the assembler announces a priori a periodic rate of cost reduction that it expects from its suppliers, and the wholesale prices are determined based on this rate.

In settings with cost-contingent contracts, we show that there exists an equilibrium in closed-loop strategies that is synchronized—that is, all suppliers invest in cost reduction in the same periods. In addition, we explore the factors that impact the dynamics of cost-reduction initiatives. In particular, we show that the timing of investments is determined by the evolution of market demand and the product's price elasticity. We also find that the levels of cost reduction and the associated cost-reduction rates are affected by the number of suppliers and their relative initial component costs. Under target-price contracts, it is important to establish an appropriate rate of cost reduction that is supplier specific and that evolves over time according to the various stages of the product's life cycle. Overly aggressive target rates may hurt the supplier's profitability, whereas low rates result in smaller production quantity and lower profit for the assembler. We find that a target-price contract calibrated with the levels of cost reduction achieved under cost-contingent contracts results in higher investment levels and in higher profits for all firms. Therefore, the observations regarding the factors that affect the magnitude and timing of cost reductions under cost-contingent contracts can serve as a guideline for the design of target-price contracts.

We then compare the levels of cost reduction achieved under both contracts with those under centralized decision making. In the decentralized system, suppliers underinvest in cost-reduction initiatives and may invest less frequently. The assembler can alleviate these inefficiencies by subsidizing a certain portion of the investment activities. We finally consider a system with two competing assemblers and knowledge spillover. Although system inefficiency is lower with increased competition and increased knowledge spillover, the latter has a negative impact on the profit of the assembler involved in cost reduction. In this setting, designing subsidies to induce centralized investment levels requires a careful analysis of the market dynamics. In general, understanding the behavior of complex supply networks in a dynamic setting is relevant for the management of supplier relationships in all industries.

9. Electronic Companion

An electronic companion to this paper is available as part of the online version that can be found at http://mansci.journal.informs.org/.

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