The Economics of Agricultural Supply Chain Design: A Portfolio Selection Approach

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November 26, 2015

Invited Paper prepared for presentation at the 2016 Allied Social Science Associations Annual Meeting, San Francisco, CA, January 3-5

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Abstract

Agrifood firms in the modernizing/globalizing world, both in developing and developed countries, regularly need to undertake innovations. They develop supply chains to accommodate the nature of the innovations. In this paper we analyze an innovator's supply chain design problem. The design of the supply chain may include allocating resources between production of feedstock (agricultural products) and processing and marketing, and determining the amount of feedstock to be obtained through contracts. We show that the innovator determines its overall level of production taking advantage of its monopoly power in the output market, and behaves as a monopsony in buying feedstock from contractors. These decisions are constrained by the marginal cost of capital and the properties of production and marketing technologies. When the innovator is risk averse, risk considerations in production processing and marketing and the correlation between risks will affect both overall production and share of input purchased through contracts.

Keywords: Supply Chain, Agricultural Contracts, Innovation.

JEL Classification Numbers: Q12, Q16.

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Grateful acknowledgment is made to the Energy Biosciences Institute, and the USDA National Institute of Food and Agriculture for funding.

Xiaoxue Du, Liang Lu and David Zilberman gratefully acknowledge support from the Energy Biosciences Institute.

Introduction

There are various studies that comment on the rapid evolution of agribusiness (Boehlje et al. 1998). Agrifood firms in the modernizing/globalizing agrifood system, both in developing and developed countries, regularly need to undertake innovations. New innovations are induced both by new technological developments and by the structural and behavioral change on the demand side. The firm has then to adjust its supply side practices to the above innovation(s). These adjustments are "derived" from the nature of the innovation. The changes in practices include its production technology and its arrangements for procurement of inputs and marketing of output. These adjustments may lead to establishment of new multilevel supply chains including production of raw materials, refining, processing, and marketing.

This adjustment occasions tensions that need to be resolved for the innovation to succeed. There are two sources of tension: (a) capital constraints faced by the firm for its own technology change; (b) risks from its input suppliers; (c) risks from its output marketers. The firm chooses recursively the extent it wants to outsource production, input supply, and output marketing. Conditional on that choice, it chooses the design of the contract, subject to its capital constraints, and in order to maximize profit and minimize risk. The degree of monopsony and monopoly power of the firm conditions the volume of production and reliance on contracts. This is the first paper that systematically models the above points in a model of determining the overall utilization of a new innovation and allocation of resources between outsourcing and contract choice.

According to Porter (1990), innovation is a new way of doing things that is commercialized. New patterns of trade are established, new technologies of production and marketing are introduced and adopted, and new products are marketed. The innovator is challenged to designing an appropriate supply chain structure to accommodate the introduction of the new innovation. For example, should the innovator that identifies new markets or differentiated products produce these by themselves through vertically integrated operations? Or should they establish contracts with or purchase from upstream suppliers? There are many examples showing that supply chains play a key role in production in many industries: Tyson adopts production contracts to secure the chicken

for processing; Indeed, contract farming adopted by Tyson is related to the innovation in food processing. Sunkist forms a growers cooperative to stabilize market conditions. The new wave of supermarkets introduced in developing countries uses contractors frequently to supply their products (Reardon et al. 2003). The introduction of contracts by supermarkets is originated from their introducing new marketing tools to the developing countries.

With the fast pace of technology innovation and product differentiation, designing a good business model and contracting with upstream suppliers have become indispensable elements of modern agriculture. MacDonald and Korb (2011) note that the percentage of contract farming in total U.S. agricultural value product was 11 percent in 1969 and 39 percent in 2008. Moreover, the commodities with a higher percentage under contracts, such as poultry, sugar beets, and fruits and vegetables, are often the ones that require further steps of processing.

Supply chains may vary in complexity, but frequently combine farming activities with processing. They may also embody innovations in terms of a differentiated product, introduction of a crop to a new location, or production or processing technologies. The economics of supply chains emphasizes choices about organizational structure-activities can be contained within a vertically integrated firm or to different extents can be dispersed through contracting or trading between processors and farmers. The growing role of supply chains may lead to non-competitive behavior, both in the input and output markets, because the integrators may have monopolistic power when it comes to project differentiation and monopsonistic power with respect to the upstream supplier. Reardon (2015) documented the rise of the "hidden middle" noting that the midstream segments of supply chains (processors, wholesalers, logistics firms and warehouse companies) in developing countries account for about 35 percent of value added and costs in the value chain. The organization of supply chains also has significant distributional effects and can be affected by government policies. Furthermore, supply chains evolve as demand and supply forces affecting them evolve, and we will identify some of the dynamic patterns of output and prices that may emerge as supply chains evolve. Key elements that will determine the

There are several bodies of literature that our work is related to.

The first strand of literature relevant to our modeling is, Coase's theory of the firm (Coase 1937). Coase examined the determinants of the boundary of the firm: what activities will be done within the firm and what will be purchased in the market. He used minimization of transaction costs as a criterion for resource allocation. In our model below, in the line of Coase's reasoning, we model the decision on the size of operation and the allocation of resources inside and outside the firm. Our detailed assumptions allow us to have specific decision rules to answer these questions. The choices are determined by the nature of factor markets-imperfect factor markets (land, labor, capital) and constrained access to these factors.

Evolving from Coase, transaction cost theory holds that firms use different governance strategies (market, intermediate, or hierarchical) to deal with different kinds of exchanges so that the threat of opportunism is minimized. This threat is more likely if either end of the transaction has to make a transaction-specific investment, which has little value in its second best use. Consequently, when transaction-specific investment is high, intermediate or hierarchical governance is used in the form of vertical coordination to mitigate opportunistic behavior (Allen and Lueck 1995, Hennessy and Lawrence 1999, and Franken 2008).

The second strand of literature relevant to our modeling is Zusman's work on contracts, and the importance and evolution of contracts in agricultural economics (Bell and Zusman 1976, Zusman 1982). He emphasized the importance of relationships between parties and how contracts are established. His work provides a strong foundation for the economics and political economics of contract cooperatives. Literature such as Knoeber and Thurman (1995), Goodhue (2000), and Hueth and Ligon (2002) analyze the contractual relationship between integrators and farmers. A key issue these studies emphasize is that one party in the contract often does not have perfect information about its counterpart (e.g. a manufacturer may not know a producer's productivity or land quality), which is known as the asymmetric information problem. Using contract theory tools, this line of research often looks into the of contract terms where information rent plays an important role. In terms of the agricultural sector, there are many studies related to this theme: e.g., Alexander et al. (2000) and Hueth and Ligon (2002) on tomato contracts; Knoeber and Thur-

man (1995) and Goodhue (2000) on contracts in broiler industry. MacDonald and Korb (2011)) note that the perishability of certain crops, where number of potential buyers and sellers is small, may induce contract farming as it could stabilize the supply chain. Relating contracting and product innovation, Boehlje et al. (1998) note that modern industrial agriculture is associated with the use of contract farming by agribusiness firms that introduce differentiated products. These firms develop new technologies and have to allocate their physical, human, and managerial capital, as well as other scarce resources, between investment in processing and marketing and in-house farm production, securing the residual feedstock through contract farming. These forms of organization were associated with the introduction of new models of agribusiness like the production and processing of broilers, swine, or biofuel, as well as rubber and palm oil in Africa (Ruf 2009).

The main objective of this article is to provide a static theoretic framework to analyze an innovator's supply chain design problem. We investigate an innovator's decision on resource allocation when it has the option of acquiring the feedstock through upstream suppliers and own-production. The capital can be allocated to building a larger processing facility or to producing the feedstock on its own. If the innovator is short of capital, and when the innovator is inclined to expand its business by building larger processing capacity, then it may well produce less feedstock by itself and rely on upstream suppliers to acquire the remainder of the feedstock. For example, the common practice for the broiler processing industry in the US is that processors provide hatched eggs and other necessary inputs for contracted farmers to raise the chicken (Goodhue 2000). We will present a model of supply chain design and depict how a processor's monopoly or monopsony power may affect its decision on resource allocation.

The rest of the article is arranged as follows. In section 2, we introduce the supply chain design model under static conditions and discuss the implications of monopoly downstream or monopsony upstream. In section 3, we will investigate the optimal supply chain design problem under uncertainty. In section 4, we provide concluding remarks and suggest future directions.

Static Model

Consider a firm that introduces an innovative product which requires intermediate input processing. Let x denote the final output. There is various ways to model the innovator's processing investment problem. We follow Spence (1977) and assume that the innovator use capital, denoted by k, to construct the processing capacity. (Note that we made a simplifying assumption: for each unit of processing capacity, one must use one unit of capital to match it. Hence, capital and processing capacity are the same thing as long as all the capital is used to build the processing capacity.) Moreover, k, which is measured in x, must at least match the output level, i.e., $k \geq x$. The innovator could either produce the raw (intermediate) input in-house (denoted by x_1), or purchase it from upstream producers (denoted by x_2). One must have $x = x_1 + x_2$. We use $r(k)$ and $C(x_2)$ to denote the cost of capital function and cost of input purchase from upstream, respectively. It should be noted that not only do we assume $r' > 0, C' > 0$, but we also allow the possibility that the marginal cost of capital and inputs are increasing. That is, we assume that $r'' \geq 0, C'' \geq 0$. The notion of an increasing marginal cost of capital is not only related to an imperfect capital market. In our model, capital can broadly include physical capital as well as human capital and managerial capital. A lack of either one of them may justify the assumption of increasing r'. Meanwhile, an innovator who has monopsony power over upstream suppliers would face an increasing marginal cost of inputs. We assume that the capital devoted to feedstock production is k_1 with production function $x_1 = f(k_1)$. It is convenient to use $g(x_1)$, the inverse of production function f, to capture the capital requirement for producing x_1. Finally, the revenue function denoted by $R(x)$.

We characterize the innovator's decision problem by a two-stage optimization procedure: in the first stage, the innovator chooses the optimal make and buy combination given a particular production level; in the second stage, the innovator chooses the optimal production level.

The first stage problem is:

$$(1) \qquad \min_{x_1, x_2 \geq 0} \; r(x_1 + x_2 + g(x_1)) + C(x_2), \;\; s.t. \;\; x_1 + x_2 = x.$$

In the second stage of the problem, the innovator solves:

$$(2) \quad \max_{x} \; R(x) - V(x),$$

where $V(x) = r(x_1^*(x) + x_2^*(x) + g(x_1^*(x))) + C(x_2^*(x))$ is the minimum cost derived from first stage. We begin with the analysis of the first stage. A first question is whether the innovator will choose to only own-produce or to purchase from upstream suppliers, instead of mixing the strategies. The following lemma provides the conditions for which mixing cannot be a preferred solution.

Lemma 1 *(Condition for interior solution) If, for all $x > 0$, $g'(x) < \frac{C'(x)}{r'(x)}$, then the innovator will choose to only own-produce; If, for all $x > 0$, $g'(x) > \frac{C'(x)}{r'(x+g(x))}$, then the innovator will choose to buy from upstream only.*

See appendix A.1 for proof.

Figure 1 gives an illustration for the cases when there could only be corner solutions, i.e., the innovator would choose only to buy or only to own-produce instead of mixing. The dashed curve r_1 corresponds to the case where $g'(x) < \frac{C'(x)}{r'(x)}$, and the curve r_2 corresponds to the case where $g'(x) > \frac{C'(x)}{r'(x)}$. Essentially, the two cases are the times when the innovator either has absolute cost advantage or disadvantage of producing in-house.

[Figure 1 about here.]

Given that an interior solution is possible, the optimality conditions are:

$$(3) \quad r'(x+g(x_1))(1+g') = \lambda; \;\; r'(x+g(x_1)) + C'(x_2) = \lambda,$$

where λ is the Lagrange multiplier for the capacity constraint. Combining the two equations, we have $r'(x+g(x_1))(1+g') = r'(x+g(x_1)) + C'(x_2)$. We can further rewrite it as:

$$(4) \quad g'(x_1) = \frac{C'(x_2)}{r'(x+g(x_1))}.$$

Notice that the first order conditions imply that, at optimal input production point, the marginal input requirement for in house production must equal to the ratio of the marginal cost of upstream purchased inputs to the marginal cost of capital. The intuition for the condition is thus: if $g'(x_1) < \frac{C'(x_2)}{r'(x+g(x_1))}$, then the innovator could reach the same input goal of x by allocating one less unit of input on purchasing from upstream and one more unit of input to own-production. By doing so, the production plan requires $r' + C'$ less of cost of purchasing from upstream and processing the product, and needs $r'(1+g')$ of cost of capital if the innovator produces the one extra unit by itself. Therefore, as long as $g'(x_1) < \frac{C'(x_2)}{r'(x+g(x_1))}$, the original final output production amount is still feasible but using less units of total cost. Meanwhile, if $g'(x_1) > \frac{C'(x_2)}{r'(x+g(x_1))}$, by the same logic, it is efficient to allocate more unit of x to upstream purchase and one less unit of x to self-production. Thus, when the production plan is optimized, we must have $g'(x_1) = \frac{C'(x_2)}{r'(x+g(x_1))}$.

[Figure 2 about here.]

Figure 2 provides an illustration for the input cost minimization problem and output expansion path. In the first quadrant, we plot in-house production against purchase from upstream suppliers. For any level of x, the green dashed lines determine the isoquants: $x_1 + x_2 = x$. The blue curves are isocosts. To plot the isocosts, we first find the total cost if the firm is producing in-house. In the second quadrant, we plot the in-house production total cost curve $r(x+g(x))$ where the x axis is the dollar amount. Using a 45 degree line, we map this dollar amount to the y-axis in the third quadrant. Finally, in the fourth quadrant, we plot the total cost for the innovator if it is solely relying on upstream providers and we can easily see how many units of x can be produced if the same amount of money were not invested in own-production. The following lemma is convenient for determining the shape of the isocost curves.

Lemma 2 *The isocost curves are concave.*

See appendix A.2 for proof.

The concavity of the isocost curves comes from the fact that both r' and c' are increasing. Therefore, on any isocost curve, a combination of in-house production and purchase from upstream suppliers incurs a higher cost.

Once the shape of isocost curves are determined, the tangency between isocost curves and isoquants yields the optimal input mix.[1] The red curve shows the output expansion path.

Proposition 1 *As production of final output increases, the innovator will always buy more inputs upstream unless $r'' = g'' = 0$; the innovator will make more if $\varepsilon_{C'} > \varepsilon_{r'}$, where $\varepsilon_{C'}$ is the elasticity of marginal cost of input from upstream and $\varepsilon_{r'}$ is the elasticity of marginal cost of capital.*

See appendix A.3 for the proof.

Proposition 1 essentially says that as long as the marginal cost of in-house produced input is increasing, either due to increasing marginal cost of capital or decreasing marginal product[2], production expansion always involves higher volumes of purchases from upstream. Moreover, whether the innovator would produce more in-house depends on if there is a relative cost advantage in producing it. The intuition behind proposition 1 is that, when $\varepsilon_{C'} > \varepsilon_{r'}$, the cost of buying the input from upstream is increasing faster than the cost of inputs produced in-house. Then the innovator will have a cost advantage in producing in-house at a higher capacity level (which we call relative cost advantage, to distinguish from absolute advantage. i.e., the innovator could produce the feedstock at lower cost for any capacity level). For an extra unit of output, the extra marginal cost of input from upstream is C'', but the marginal cost from own-production is $r''g'$. Thus, the $\varepsilon_{C'} > \varepsilon_{r'}$ condition indicates that although the innovator does not have an absolute cost advantage, own-production may become more plausible after total output reaches some critical level as C' increases more rapidly than r'. Again, from figure 2, we can see that x_1 might increase as x increases.

Proposition 1 illustrates that contracting with upstream suppliers allows an innovator to overcome capital scarcity. A real world example comes from the broiler industry in the US: Tyson Foods conceived of a new way of processing chicken, to sell parts rather than sell the whole frozen

chicken; they wanted to increase market share and needed to produce a larger volume of chicken parts. They faced a fundamental problem: how many resources to put in building processing facilities and how many resources to put into own-production of feedstock, given that the Bank of America only approved them for a billion dollar loan. Tyson decided to invest most of their money in marketing and processing and buy their chicken from farmers rather than producing the chicken in-house, so that they could capture a large market. In the case of Tyson, our proposition implies that the elasticity of marginal cost of capital is relatively large.

The motivation and arrangements of contracting upstream as reflected in the case of Tyson Foods are common both in the US and in other countries. Suri (2008) showed that in the 1990s the pineapple shippers in Ghana found a cost-saving technology for shipment, to wit, using sea rather than air shipment. That was the main inducement for the shippers to start to contract farmers for the pineapples. Suzuki et al. (2011) found that the pineapple exporters in Ghana not only use upstream suppliers to buy pineapples, the export companies have a partly vertically integrated supply chain, in that they partly grow their own pineapples and partly buy from contracted farmers. Here, the new technology reduces $\varepsilon_{C'}$, thus, we observe the emergence of contracts as the proposition predicts.

Corollary 3 *If the innovator does not have monopsony power over upstream suppliers, then the innovator will own-produce less as production capacity increases. If the innovator faces a constant marginal cost of capital, then the innovator will always make more as production capacity increases.*

See appendix A.4 for the proof.

Standard monopsony model suggests that a firm that possesses monopsony power over input providers will reduce input use to gain monopsony profit from lower input price. In our model, when an innovator has monopsony power over feedstock suppliers, it would acquire less feedstock from upstream suppliers in order to exploit its market power. But, at the same time, the innovator faces the constraint of getting adequate feedstock. Thus, the innovator will rely more on own-production. Therefore, when the monopsony power is eliminated, the optimal business model would involve getting more feedstock from upstream. Moreover, when the marginal cost of capital

is not increasing, the innovator could assign one extra unit of feedstock production to in-house production without incurring higher additional cost. Thus, the innovator would make more in-house $r'' = 0$.

An example of diminishing monopsony power comes from the case of hog production in China [3]. Shuanghui, the biggest hog production company in China, is trying to gain market share in the market for high-end pork products. Although Shuanghui has significant market power over upstream suppliers for conventional hog production, its monopsony power over the high quality variety of hogs is relatively low. Consequently, we observe that Shuanghui, instead of raising the pigs themselves, looks for partners from upstream, which was a factor leading to the acquisition by Shuanghui of Smithfield.

Now, we turn to the second stage of the innovator's problem. Recall that, in the second stage of the problem, the innovator solves:

$$(5) \qquad \max_{x} \; R(x) - V(x),$$

The first order condition yields: $R' - V' = 0$. Using the envelope theorem, we have $V' = \lambda^*$, where λ^* is the shadow price of output x at the optimal production portfolio. We are interested in how a demand shifter would change the equilibrium. Formally, let θ be a demand shifter such that $R = R(x, \theta)$ and $R_\theta > 0$. We have the following proposition to characterize the comparative statics:

Proposition 2 *As demand shifts out, the innovator will buy more feedstock from upstream and will produce more (less) in-house if* $\varepsilon_{C'} - \varepsilon_{r'} > 0 (< 0)$.

See appendix A.5 for the proof.

Figure 3 provides an illustration for proposition 2. As demand shifts from D to D', apparently, the innovator would expand its final output production. Thus, following from proposition 1, we know that the innovator would always buy more. In figure 5, the optimal production expansion $x_1^*(x)$ and $x_2^*(x)$ are illustrated by the blue and red curves respectively. We can see from the figure

that the innovator purchases from upstream more and, in this case, the innovator is making less in-house as $\varepsilon_{C'} < \varepsilon_{r'}$.

[Figure 3 about here.]

Proposition 2 is especially pertinent to the discussion of make and buy decisions when a newly introduced product is increasingly accepted and adopted by consumers. When a new variety of chicken or a new brand of wine is getting approval from consumers, a direct consequence is that the innovator has to increase processing capacity. Therefore, if the marginal cost of capital is increasing, it is intuitive to see that the marginal cost of own-produced feedstock must increase as well. This means $\varepsilon_{C'} < \varepsilon_{r'}$ is more likely to happen and less own-production may occur.

Meanwhile, if the innovator has monopsony power over upstream suppliers, then $\varepsilon_{C'}$ is larger. It should be noted that, in this case, the innovator is a middleman in the market. The concept of middlemen is discussed in Lerner (1934), Just et al. (1979), and Vercammen (2011). A major conclusion of the middleman model is that, when a firm has both monopoly and monopsony power in the market, production is reduced even further and profit margin is higher than in the case where the firm has only one form of market power. In our model, when the innovator has monopsony power over upstream suppliers and the marginal cost of capital is not rising too rapidly, we will observe more own-production as the innovator would reduce purchase from upstream to exercise its monopsony power. Overall, proposition 2 suggests that the innovator may respond to a demand shock by altering its way of acquiring feedstock. In our deterministic setting, the key factors that drive the decision are the firm's capital abundance and whether it has monopsony power over its suppliers. When the innovator faces both of the factors, then the relative magnitude of $\varepsilon_{C'}$ and $\varepsilon_{r'}$ matters.

This proposition may help to explain different supply chain structures over firms in the US broiler industry. Tyson and Perdue use more contracts while Foster Farms emphasizes vertical integration. Tyson uses more contracts in the US but it uses vertical integration (own production of birds in addition to processing) in China. A plausible explanation is that Foster Farms was started

by turkey farmers, while Tyson was started by truckers and Perdue was from the beginning specialized in selling genetic material to other farmers. Therefore, Foster Farms emphasized quality and it appeared it did not want to risk compromising it with subcontracting, so they operate at a relatively small scale in the US but emphasize vertical integration. In the case of Perdue and Tyson, expansion was important, and therefore they moved to contract farming. Here the difference between Tyson and Foster Farms can be mainly explained by $\varepsilon_{r'}$: when a firm emphasizes expansion, the elasticity of marginal cost of capital is higher.

When Tyson introduced the innovation of chicken processing to China, although vertical integration reduced its expansion rate, the benefit from the consumer perception of higher quality offset the cost of limiting the rate of expansion. But to deliver higher quality chicken, $\varepsilon_{C'}$ is higher. Again, our proposition predicts what is happening: Tyson relies more vertical integration in China. In both the cases, introducing a new technology together with the processor's core competence shaped the final structure of governance.

Uncertainty

We now consider an innovator's decision under uncertainty. The uncertainty may come from several sources: the demand side, the processing technology, feedstock production, and contracting. Demand uncertainty is often associated with new product introduction. Processing uncertainty is most pertinent when a new processing technology is invented (new biofuel refining technology for instance). Production uncertainty such as stochastic weather is faced in both own-production and by contracted producers. Contract uncertainties may occur due to asymmetric information. That is, the innovator may not observe the ability of and effort being devoted by the contracted supplier.

Using the notations from above, let θ_1 be a random disturbance term that affects demand. We assume that the revenue function is of the form $\theta_1 R(x)$. To keep the solution tractable, we add the assumption that the function $r(x+g(x))$ is additive separable: i.e.,

$$r(x+g(x_1)) = r(x) + r(g(x_1)). \tag{6}$$

We use $C_1(x_1)$ to denote $r(g(x_1))$, which is the total cost of producing x_1. Then the assumption is essentially saying that the total in-house cost can be written as the sum of the processing cost and the in-house feedstock production cost. Furthermore, we use the random variable θ_2 to denote the random fluctuation of the processing cost and θ_3 the randomness of in-house production costs. Then, the total in-house cost is $\theta_2 r(x) + \theta_3 C_1(x_1)$. Finally, θ_4 is the stochastic variation of the outsourcing feedstock production cost. In sum, the innovator's profit can be written as:

$$(7) \quad \pi = \theta_1 R(x) - \theta_2 r(x) - \theta_3 C_1(x_1) - \theta_4 C_2(x - x_1).$$

For all $i = 1,2,3,4$, θ_i are such that $E\theta_i = 1$, $Var\theta_i = \sigma_i^2$. The correlation coefficient between θ_i and θ_j is ρ_{ij}. To write the summation in a tighter form, we redefine $f^1(x) \equiv R(x)$, $f^2(x) \equiv -r(x)$, $f^3(x_1) \equiv -C_1(x_1)$, $f^4(x,x_1) \equiv -C_2(x - x_1)$. Then, we can rewrite $\pi(x,x_1) = \sum_i \theta_i f_i$ where the expected profit is:

$$(8) \quad E\pi(x,x_1) = \sum_i f^i,$$

and the variance of profit is of the following form:

$$(9) \quad \sigma^2(\pi(x,x_1)) = \sum_{i=1}^{4} \sum_{j=1}^{4} f^i f^j \sigma_i \sigma_j \rho_{ij}.$$

In the general case, the innovator has a risk preference over the random events. We use $U(\pi)$ to denote the innovator's utility of profit with $U'(\pi) > 0, U''(\pi) < 0$. Assuming $U(\pi)$ has CARA with an absolute risk aversion parameter, r, the maximization of expected utility is equivalent to the following problem:

$$(10) \quad \max_{x,x_1} \; E\pi(x,x_1) - \frac{r}{2}\sigma^2(\pi(x,x_1)) \;\; s.t \;\; 0 \le x_1 \le x,$$

where the constraint comes from the fact that both in-house and contract production $x_1, x - x_1$ are nonnegative and cannot exceed the total processing capacity x. It should also be noted that, in the deterministic case, there is a well-established equivalence between the two-stage problem we set up and the simultaneous decision problem where the innovator chooses processing capacity and the feedstock production plan at the same time. However, in the uncertainty case, the equivalence does not apply due to the potential correlation between cost side uncertainty and demand side uncertainty. The Lagrangian for the problem is:

$$(11) \quad \mathscr{L} = E\pi(x, x_1) - \frac{r}{2}\sigma^2(\pi(x, x_1)) + \mu_1 x_1 + \mu_2(x - x_1).$$

Our formulation is closely related to Just and Zilberman (1983), in which the theoretic framework considered decisions under two sources of uncertainty with a capacity constraint. In our model, the capacity is endogenously determined and, as we take a supply chain approach, we also consider possible correlation between the demand side and cost side uncertainty. The Just and Zilberman (1983) model can be viewed as the innovator's first stage problem.

The FOC gives:

$$(12) \quad \sum_i f_x^i = \frac{r}{2}\sum_{i=1}^{4}\sum_{j=1}^{4}(f_x^i f^j + f^i f_x^j)\sigma_i\sigma_j\rho_{ij} - \mu_2,$$

and

$$(13) \quad \sum_i f_{x_1}^i = \frac{r}{2}\sum_{i=1}^{4}\sum_{j=1}^{4}(f_{x_1}^i f^j + f^i f_{x_1}^j)\sigma_i\sigma_j\rho_{ij} - (\mu_1 - \mu_2).$$

In general, this framework still allows the possibility to discuss the discrete choice of whether the innovator should solely rely on vertical integration (adding own-production) or outsourcing to secure its feedstock. $\mu_1 = 0, \mu_2 > 0$ indicates vertical integration. $\mu_1 > 0, \mu_2 = 0$ implies all production comes from upstream. Finally, $\mu_1 = \mu_2 = 0$ indicates diversification. However, the general framework needs further simplification for meaningful discussion. Here, we consider

several special cases of the general model.

Case 1. No correlation among the random variables. ($\rho_{ij} = 0$ for all i, j)

In this case, the general conclusions of Sandmo (1971) apply. Under either demand uncertainty, or processing or production uncertainties, expected feedstock production is less than in the case of certainty. However, whether the decline in feedstock production only happends for own-production or upstream production, or total production decreases, depends on the source of the uncertainty. In particular, if demand or processing technology is uncertain, then both in-house and contracted production will be below the production level when there is no uncertainty present. On the other hand, if the uncertainty comes only from feedstock production, then contracted production will decrease and own-production of feedstock may be above or below certainty case. The intuition behind this scenario is that the firm may choose to diversify its production under certainty. However, when there is uncertainty due to asymmetric information, the consequence is twofold: for one thing, the firm will reduce total production; for another, the firm may choose to use only own-production of feedstock if the uncertainty is too high.

The key notion from case 1 is that, when we apply Sandmo's model to supply chain design, the type and source of uncertainty matters. It is not hard to imagine that, in the winery sector, feedstock production risk due to weather fluctuations is relatively high but the processing technology is more or less established. Meanwhile, in the case of second generation biofuel, the processing technology is uncertain and the contracting cost with farmers is uncertain as well. It should be also noted that a well-designed contract will reduce (or even eliminate) the uncertainty that comes from asymmetric information, which we will discuss in case 2.

Case 2. θ_3 and θ_4 significant, θ_1 and θ_2 negligible.

In this case, θ_3 is production uncertainty. θ_4 includes both production and contract uncertainty. We assume that the uncertainty in feedstock production from upstream, θ_4, is a mean-preserving spread of θ_3: let θ_5 be a random variable, which can be interpreted as the randomness in contracting

itself, with zero mean such that

$$(14) \quad \theta_4 = \theta_3 + z\theta_5,$$

where z is an arbitrary given parameter. We assume that as optimal contract design is being implemented, the influence of θ_5 on total risk from purchasing feedstock from upstream is reduced, that is $z \to 0$. Thus, one must have $\sigma_4^2 \to \sigma_3^2$, $\sigma_{34} \to \sigma_3^2$.

Remark 4 *Optimal contract design will increase total production. As total feedstock production expands, more (less) feedstock will be produced in house if* $\sigma_4^2\sigma^2 34 > (<) 0$.

This result is closely related to Just and Zilberman (1983), wherein, under a capacity constraint on fixed input use, the correlation between different sources of uncertainties matters and may have an impact on the firm's choice. In our model, we extend the model of Just and Zilberman (1983) by allowing for endogenously determined optimal capacity. One way to look at our model is that it is a combination of Just and Zilberman (1983) and Sandmo (1971) where the conclusions of Just and Zilberman (1983) model apply to the portfolio selection of feedstock production sources, which is the first stage of the firm's problem, and the propositions in Sandmo (1971) apply to the firm's second stage problem.

The first part of proposition 3 requires the assumption that better contract design reduces contract uncertainty. This assumption is relatively mild and is well established in contract design literature. For instance, in a signaling game where the principal does not observe the agents' abilities, optimal contract design allows for a separating equilibrium where agents will truthfully report their types. As a consequence, σ_4^2 becomes smaller. However, it does not necessarily mean more feedstock will be produced through contracts as better contract design also increases σ_{34}.

The second part of the proposition shows that risk affects whether an innovator would choose to produce in-house or contract: it affects the share of contracting. At the same time, not only do different types of risks matter as we have shown in case 1, but as insights from Just and Zilberman

(1983) suggest, the correlation between the two disturbances matters. Namely, the sign of $\sigma_4^2 - \sigma_{34}$ governs whether more feedstock will be produced in-house as total production expands.

Case 4. θ_2 and θ_3 are significant, θ_1 and ρ_{34} are negligible.

A motivating example comes from biofuel refining. The refining technology is uncertain. Rubber producers in Africa and Malaysia face decisions on how to allocate resources between facilities vs. farms (Wang et al. 2014). They can produce more rubber if they rely on upstream growers, however then they must face uncertainty about supply reliability, etc. Thus the decision about the magnitude of the purchase from upstream is important. Another case comes from palm oil in Africa: again, to what extent should an investor allocate resources to processing or secure supply sources. Large investments in fruits and vegetable industries, often for export, face similar decisions: how much processing capacity to build and how much to invest in own-production.

Conclusions and Future Directions

In this paper, we investigate an innovator's decision on supply chain design when it has the option of acquiring the feedstock through upstream suppliers and own-production. We first established that as the production of final output increases, the innovator will always buy more inputs upstream. The innovator will make more in-house if the elasticity of the marginal cost of input from upstream is greater than the elasticity of the marginal cost of capital. A direct consequence of this proposition is that if the innovator does not have monopsony power over upstream suppliers, then the innovator will make less as production capacity increases. If the innovator faces a constant marginal cost of capital, then the innovator will always make more as production capacity increases.

Under an uncertainty setting, our model emphasizes that optimal contract design will increase total production. One way to look at our model is that it is a combination of Just and Zilberman (1983) and Sandmo (1971) where the conclusions of Just and Zilberman (1983) model applies to the portfolio selection of feedstock production sources, which is the first stage of the firm's problem, and the propositions in Sandmo (1971) can be applied to the firm's second stage problem. We

show that risk affects whether an innovator would choose to produce in-house or contract, which affects the share of contracting. Not only do different types of risks matter, but the correlation between the two disturbances matters as well. However, the effect of optimal contract design on contract produced feedstock is not determined.

Our results can be empirically tested by and applied to many real world applications. For instance, our model could partly answer why Tyson Foods would use upstream farmers to raise chickens– the core competence of Tyson Foods is in processing and marketing its final product and production of the feedstock requires a huge amount of capital. Thus, it will allocate more capital to building processing facilities and less to raising chickens. Similarly, McDonald's may find it more profitable to franchise its chain stores rather than run stores itself as developing another chain store is costly. Our model could also provide guidance for new industries. For example, a second generation biofuel refinery may face a capital allocation problem regarding investment in refining facility and growing the feedstock. Our model suggests that the refinery firm could produce the feedstock initially while learning the technology of feedstock production by growing. Later on, the refinery could switch to purchase from upstream to lower its cost of production.

There are several future directions that our model can be extended to. The first and most natural extension of our certainty model is to further understand the welfare of contract farmers and policy implications. People who introduce innovation expect to gain. Some of the innovations introduced by agribusiness are embodied in the product or in the processing machinery, while others are disembodied in nature. In the case of disembodied innovation, they may capture benefits by the design of the supply chain. However, unlike patents that come with embodied innovation and expires after a certain duration by regulation, the monopsony power that comes with disembodied innovation does not expire nor is it regulated. Rausser et al. (2015) provide a summary and discussion of the general public's view of current issues related to contract farming practices.

A second direction of our model is a dynamic framework to depict the timing of the building of a supply chain for a representative firm after it generates a disembodied technology innovation that creates value added for processing a raw product. Since the innovation is not patentable, market

concentration for the final product decreases over time. In a dynamic setting, the key trade-off for the innovator is that the marginal cost of resources for securing feedstock is the discounted sum of resources allocated to the building of processing capacity, which has implications for market share of the final product in the long run.

Appendix

A.1 Proof for Lemma 1

Proof. Let $F(x) = C(x) + r(x) - r(x + g(x))$. The $F(x)$ captures whether the innovator has absolute advantage or disadvantage over input production. The first two terms, $C(x) + r(x)$, measure the total cost of production if the innovator relies solely on upstream supplier and the third term, $r(x + g(x))$, is the total cost of the innovator if production is completely in house. Clearly, $F(0) = 0$. Note that

$$(15) \quad F'(x) = C'(x) + r'(x) - r'(x + g(x))(1 + g').$$

If, for all $x > 0$, $g'(x) < \frac{C'(x)}{r'(x)}$, then $F'(x) > 0$, which means that $F(x)$ is monotonically increasing, then making has the absolute cost advantage over buying. The other half of the proof is by symmetry. Figure 1 gives an illustration for the lemma. $g'(x) < \frac{C'(x)}{r'(x)}$, the total cost of capital is r_1. It is easy to see that, for any unit of x, making incurs lower cost. Similarly, r_2 shows the case where purchasing from upstream has absolute advantage. Essentially, the lemma suggests that, in order for mixing make and buy a preferred supply chain than make or buy only, the functions $C(x) + r(x)$ and $r(x + g(x))$ must intersect at some level of x, as r_3 curve depicts. ■

A.2 Proof for Lemma 2

Proof. The isocost curves are implicitly defined by: $G(x_1, x_2) = r(x_1 + x_2 + g(x_1)) + C(x_2) - \bar{c}$, where $\bar{c}$ is some total cost level.

Using implicit function theorem, we notice that:

$$(16) \quad \frac{dx_1}{dx_2} = -\frac{G_{x_2}}{G_{x_1}} = -\frac{C' + r'}{r'(1 + g')} < 0,$$

and

$$(17) \quad \frac{d^2 x_1}{dx_2^2} = -\frac{G_{x_2 x_2} G_{x_1}^2 - 2G_{x_1 x_2} G_{x_2} G_{x_1} + G_{x_1 x_1} G_{x_2}^2}{G_{x_1}^3},$$

where $G_{x_2x_2} = C'' + r''$, $G_{x_1x_1} = r''(1+g')^2 + r'g''$, and $G_{x_1x_2} = r''(1+g')$. After some algebra, we can show that the numerator of $\frac{d^2x_1}{dx_2^2}$ is $C''r'(1+g')^2 + r''C'^2(1+g')^2 + (r'c'g'' + r'^2g'')(c'+r') > 0$. Therefore, we have $\frac{d^2x_1}{dx_2^2} < 0$. ■

A.3 Proof for Proposition 1

Proof. The bordered Hessian for the problem is:

$$(18) \quad |H| = \begin{vmatrix} 0 & 1 & 1 \\ 1 & r''(1+g')^2 + r'g'' & r''(1+g') \\ 1 & r''(1+g') & C'' + r'' \end{vmatrix}$$

It is easy to verify that $|H| = -C'' - r''g'^2 - r'g'' < 0$. Our goal is to find $\frac{dx_1^*}{dx}$ and $\frac{dx_2^*}{dx}$. Total differential w.r.t the equations yielded from first order conditions, we have:

$$(19) \quad H \begin{bmatrix} \frac{d\lambda^*}{dx} \\ \frac{dx_1^*}{dx} \\ \frac{dx_2^*}{dx} \end{bmatrix} = \begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix}$$

Using the Cramer's rule, we can find that:

$$(20) \quad \frac{dx_1^*}{dx} = -\frac{C'' - r''g'}{|H|},$$

Therefore, $\frac{dx_1^*}{dx} > 0$ as long as $C'' - r''g' > 0$. Moreover,

$$(21) \quad \frac{dx_2^*}{dx} = -\frac{r''(g'^2 + g') + r'g''}{|H|} \geq 0.$$

It is easy to see that $\frac{dx_2^*}{dx} = 0$ only if $r'' = g'' = 0$. Notice that

$$(22) \quad C'' - r''g' = \frac{dC'}{dx_2} - g'\frac{dr'}{dx_2} = \frac{dC'}{dx_2}\frac{x_2}{C'} - g'\frac{dr'}{dx_2}\frac{x_2}{C'}$$

Meanwhile, at optimal, we have $C' = r'g'$, thus,

$$(23) \quad C'' - r''g' = \frac{dC'}{dx_2}\frac{x_2}{C'} - \frac{dr'}{dx_2}\frac{x_2}{r'} = \varepsilon_{C'} - \varepsilon_{r'}.$$

Then we have, $\frac{dx_1^*}{dx} > 0$ as long as $\varepsilon_{C'} > \varepsilon_{r'}$. ■

A.4 Proof for Corollary 3

Proof. This follows directly from proposition 1. Notice that, if the innovator does not have monopsony power on upstream, then $C'' = 0$. And $\frac{dx_1^*}{dx} = \frac{-r''g'}{|H|} < 0$. Similarly, if $r'' = 0$, then $\frac{dx_1^*}{dx} = \frac{C''}{|H|} > 0$.

■

A.5 Proof for Proposition 2

Proof. The comparative statics we are looking for are $\frac{dx_1^*}{d\theta}, \frac{dx_2^*}{d\theta}$ respectively. Note that,

$$(24) \quad \frac{dx_1^*}{d\theta} = \frac{dx_1^*}{dx}\frac{dx^*}{d\theta}.$$

$\frac{dx^*}{d\theta} > 0$ as it's the best response to positive demand shifters. Thus, $\frac{dx_1^*}{d\theta}$ is of the same sign as $\frac{dx_1^*}{dx}$.

■

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Figures

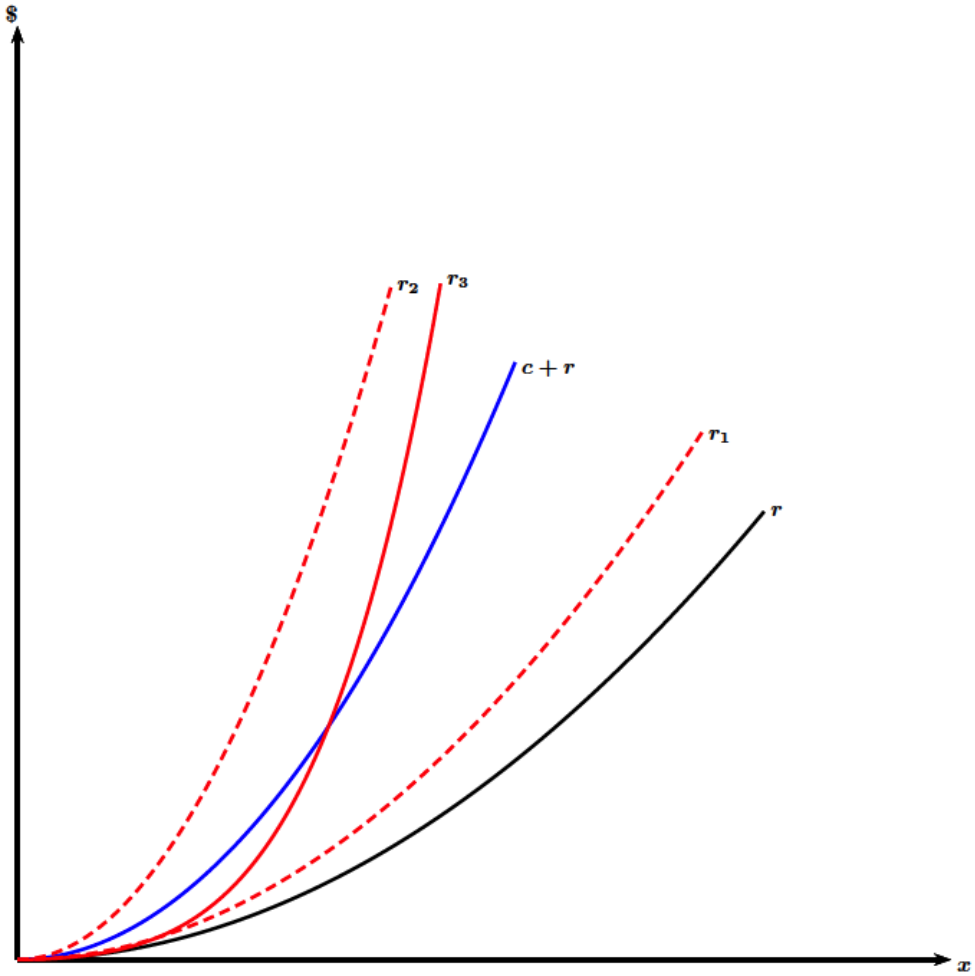

Figure 1. Illustration for buy only and make only

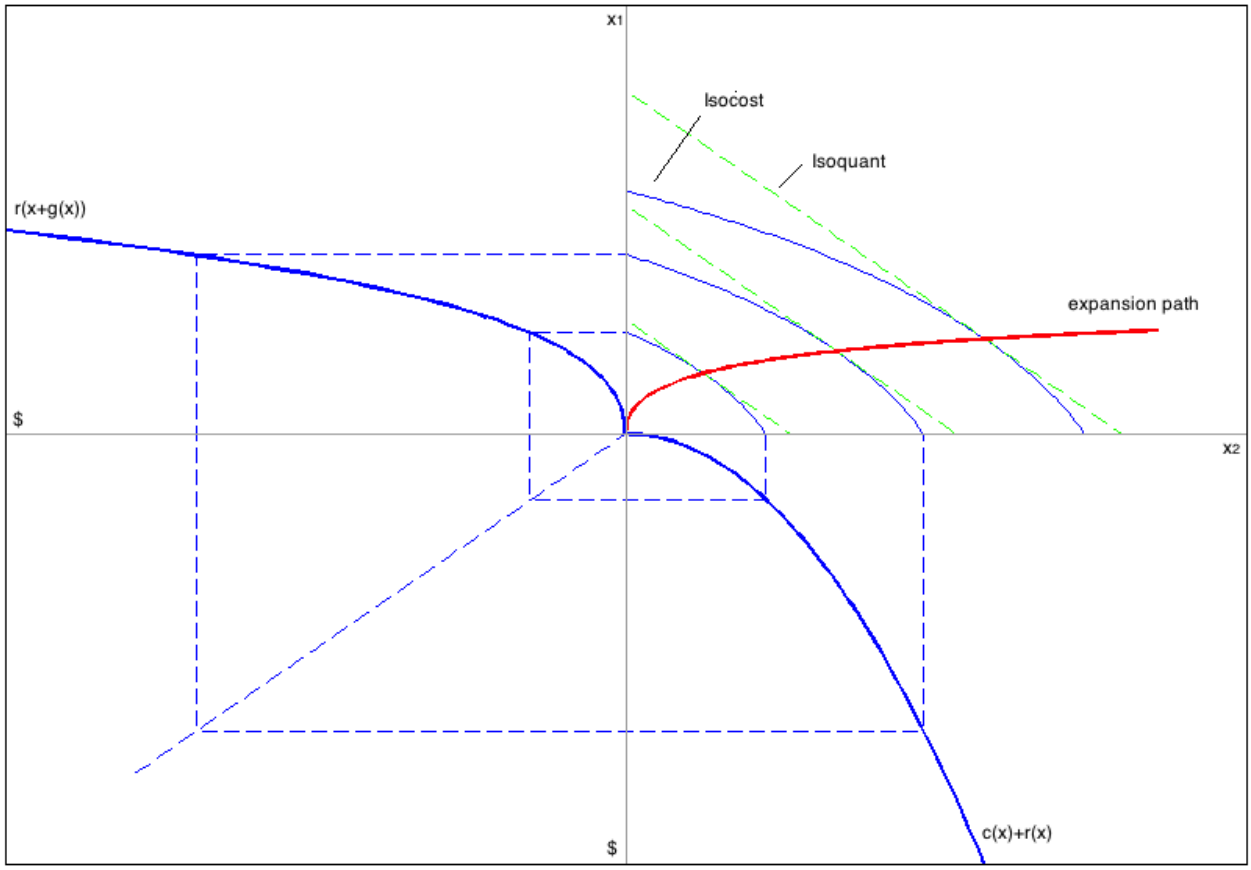

Figure 2. Output expansion path

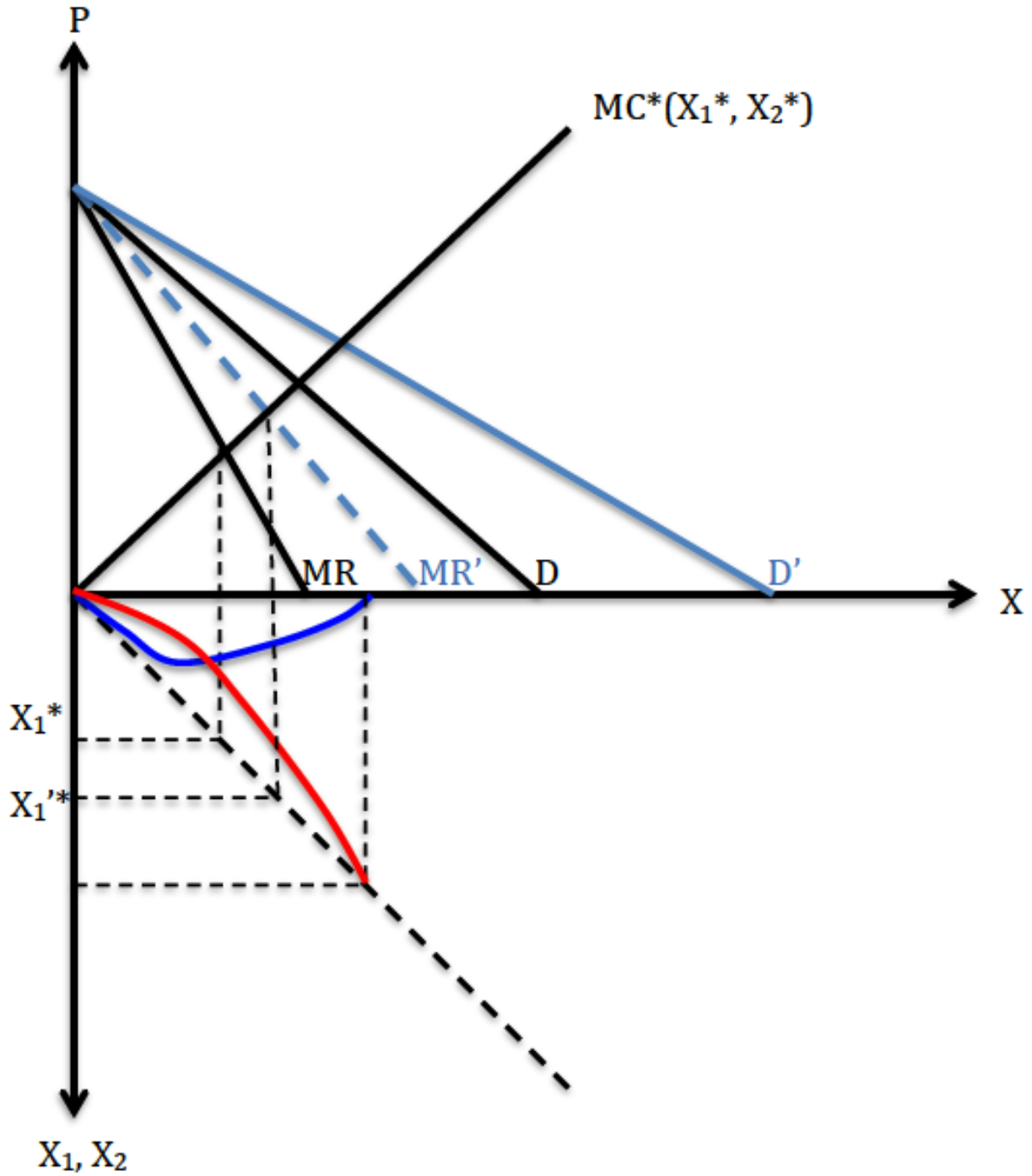

Figure 3. Optimal production plan as demand expands