

# Investments under vertical relations and agency conflicts

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## Abstract

We examine the case of an investment project that, i) is characterized by uncertainty and irreversibility, ii) is undertaken in a decentralized setting and iii) its completion is conditional on the provision of an input by an outside supplier with market power.

Our findings suggest that, if compared to a case where the input is insourced, the vertical relation increases the investment cost. Nevertheless, the effect on the timing and the value of the investment is ambiguous since it depends on the information endowment of the involved parties. We discuss three levels of information sharing among the links of the supply chain and we identify the cost, the timing and the value of the option to invest for each one of them.

KEYWORDS: Investment analysis, Real options, Vertical relations, Asymmetric information, Agency conflicts.

JEL CLASSIFICATION: D82, L10.

## 1 Introduction

A standard framework for the analysis of investment opportunities in the literature of corporate finance is the real options approach. The real options approach examines the value and timing of investment projects building on the idea that the option to invest in a project is analogous to an American call option on a real asset. This means that, when evaluating an investment option characterized by uncertainty and irreversibility, the potential investor needs to factor in that, at the time of the investment, s/he forgoes the option to postpone the investment decision for some future time point when the uncertainty will be, naturally, partly resolved.<sup>1</sup>

By construction, the standard real options model does not account for agency conflicts and information asymmetries since the investment is always assumed to be managed by the project originator. However, in many modern corporations, investment decisions are delegated by the owner of the corporation (principal) to a manager (agent) who possesses a relevant skill set or piece of information.<sup>2</sup> Of course the principal benefits from the expertise of the agent but, at the same time, s/he might be exposed to information asymmetries. If the agent has an informational advantage over the principal, then the latter must carefully consider the underlying motives when

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<sup>1</sup>Dixit and Pindyck (1994) and Trigeorgis (1996) provide an excellent overview of the real options approach.

<sup>2</sup>Delegation is a standard practice when managing large enterprises (Amaral et al., 2006). For relevant examples from industries that have to do with textiles, construction, aeronautics, telecommunications, computers, automobiles, electronics and business services, see e.g. Agrell et al. (2004), Lee et al. (2004), Schieg (2008), Tang et al. (2009), Deshpande et al. (2011), Doorey (2011), Kayis et al. (2013), Bolandifar et al. (2016), Agrell and Bogetoft (2017) and Dietrich et al. (2008).

deciding the terms of the delegation. More precisely, the principal needs to develop an appropriate mechanism in order to incentivize the agent to share private information resolving the information asymmetry. The use of such a mechanism is costly for the principal but, without it, s/he is due to face further distortions stemming from the coordination failure.<sup>3</sup>

As we will see in the next section, there is a growing body of papers that incorporate agency conflicts that stem from information asymmetries into the real options model. In spite of the differences in their analyses, what these papers share is the assumption that the investment cost is exogenous. As Billette de Villemeur et al. (2014) point out, this assumption is sensible when an investment is performed largely in-house as, for instance, in a research and development project. Nevertheless, this is not always true. The completion of an investment project might instead depend on the provision of a discrete input produced by an upstream firm.<sup>4</sup> For instance, Billette de Villemeur et al. refer to investments in the vaccine industry where facilities are specifically designed for the production of a novel vaccine. In this case, the needed customized equipment is sourced on an intermediate market from specialized input providers with market power. In the same vein, Pennings (2017) refers to large infrastructure projects as, e.g., a telecommunications network. In that case, an upstream firm (construction company) is responsible for the provision of an indispensable input (network), to a downstream firm (internet provider). In these cases, the investment cost is endogenous since it is specified by the vertical relationship between the external input supplier and the project manager who is making the investment decision on behalf of the project originator.

The key originality of this work is exactly the combination of the decentralized investment setting with the endogenous pricing of a necessary input. Using a stochastic dynamic programming model, we examine an investment project that: i) is characterized by uncertainty and irreversibility, ii) is undertaken in a decentralized setting and iii) depends on the provision of a necessary input by an external supplier with market power. Our results suggest that the effect of the presence of the upstream firm depends on the level of *transparency* in the supply chain, i.e., the extent to which information about the structure of the supply chain as well as the value of the project is readily available to the supply chain partners.<sup>5</sup>

In an opaque supply chain, that is, when contracting and communication are restricted only between adjacent layers of the supply chain, the endogeneity of the investment cost makes the project more expensive, favors its postponement and reduces the value of the opportunity to invest for the principal, the agent and the industry as a whole.<sup>6</sup>

The results differ substantially if we allow for some transparency in the supply chain.<sup>7</sup> We first discuss the case of traceability, that is the ability of all the firms in the supply chain to track a product's flow throughout the production process. Under traceability, the presence of an input

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<sup>3</sup>For an overview of the literature on asymmetric information see e.g. Laffont and Martimort (2002).

<sup>4</sup>See also Hargadon and Sutton (2000) and Linder (2004).

<sup>5</sup>For a discussion on information sharing and supply chain coordination, see Lee and Whang (1998, 1999) and Kouvelis et al. (2006) respectively.

<sup>6</sup>Opaque supply chains are often found in consumer industries such as the garment industry (Boström et al., 2012; Doorey, 2011).

<sup>7</sup>Transparency is usually seen as a mechanism to promote sustainability, improve compliance with labor standards and deter unethical activities at the production site (see Egels-Zanden, 2007; Bartley, 2007 and Zyglidopoulos and Fleming, 2011 respectively). Despite the fact that many companies were initially taking a firm position against it, transparency is perceived today as a new corporate social responsibility strategy signaling that the corporation has "nothing to hide". For instance, Nike, Adidas and H&M have disclosed the names of their first-tier suppliers whereas the All American Clothing Co allows consumers to trace the flow of the final product from the cotton field and onward (see e.g. Egels-Zanden and Hansson, 2016 and the references therein). Actually Bhaduri and Ha-Brookshire (2011), Bradu et al. (2014) and Egels-Zanden and Hansson (2016) show that supply chain transparency influences positively the purchasing intentions of the consumer.

supplier still makes the investment more costly but neutralizes the informational advantage of the agent. This makes the agent worse-off but is beneficial for the project originator, the input supplier and for the industry as a whole.

Last, we discuss a transparent supply chain, that is, a supply chain comprised by firms that share the same information endowment.<sup>8</sup> In this case, the presence of the upstream firm guarantees optimal investment timing and a first-best aggregate value of the opportunity to invest. However, contrary to the first-best case, the value of the opportunity to invest is now shared between the project originator and the input supplier.

The remainder of the paper is organized as follows. In Section 2 we present a short overview of the related literature. In Section 3 we present in detail the model set-up demonstrating the connections with previous work. In Section 4 we analyze the case where a discrete input is a prerequisite for the completion of the project and in Section 5 we discuss our results. Section 6 concludes.

## 2 Overview of the related literature

This work contributes to the research area that integrates the basic theory of irreversible investment under uncertainty as in Dixit and Pindyck (1994) and the literature on asymmetric information as in Laffont and Martimort (2002).

Grenadier and Wang (2005) analyze the timing and efficiency of an investment undertaken in a decentralized setting under the presence of information asymmetries and hidden action between the project originator and the project manager. They show that the principal can induce the agent both to extend effort and to reveal private information by using a bonus-incentive contract. Despite the fact that the use of such an instrument is suboptimal in the sense that the chosen investment timing differs significantly from the timing in the setting with symmetry of information, the principal's losses are reduced since further distortions are avoided.<sup>9</sup> Shibata (2009) extends the analysis presented in Grenadier and Wang (2005) by replacing the bonus-incentive contract with an audit technology. Focusing on the adverse-selection-only case he shows that, by using auditing instead of a bonus-incentive, the timing inefficiency is reduced, the principal's value is larger whereas the agent's value is smaller. Nevertheless, the audit technology does not necessarily lead to an increase in the aggregate value of the opportunity to invest.

Contributing to the same body of work, Shibata (2008) focuses on the impact of uncertainty on the timing and the value of the project whereas Shibata and Nishihara (2010), Grenadier and Malenko (2011), Morellec and Schürhoff (2011), Hori and Osano (2014) and Cardoso and Pereira (2015) among others examine the effect of capital structure and financing of the investment. Cong

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<sup>8</sup>Supply chain transparency is a broader concept than traceability since it has to do with sharing data regarding production statuses and order forecasts among the supply chain partners (see e.g. Gariverni et al., 1999, Lee and Whang, 1999 and Zhou and Benton Jr., 2007). For example, Wal-Mart's Retail Link program provides on-line summary of point-of-sales data to suppliers such as Johnson and Johnson, and Lever Brothers (Gill and Abend, 1997). Similarly, the fish-processing company Oceanpath and the supermarket chain Superquinn in Ireland, shared financial and volume data on purchasing, production, packaging, distribution and sales. The retailer was even aware of the supplier's markup whereas the supplier had access to the retailer's information on downstream demand (see Li et al., 2017).

<sup>9</sup>In Grenadier and Wang (2005) the management effort is assumed to be exogenous. Shibata and Nishihara (2011) approach the same problem using a two-stage optimization problem that allows investment timing and management effort endogenously decided. The numerical examples that they present suggest that the management effort is greater under asymmetric, than under symmetric, information. This in turn implies that there are trade-offs between investment efficiency and management effort under asymmetric information. In the same vein, Hori and Osano (2009) examine the replacement timing of a manager as an incentive mechanism.

(2013) and Bouvard (2014) examine the implications of endogenous learning and experimentation respectively, whereas Mæland (2010) and Koskinen and Mæland (2016) approach the agency conflict assuming that the project manager is the winner of an auction in which a number of potential delegates participate. Last, Broer and Zwart (2013) examine the optimal regulation of an investment undertaken by a monopolist who has private information on the investment cost whereas Arve and Zwart (2014) examine the case where the information asymmetry between the delegator and the delegate has to do with the starting point of the process that is used to capture the fluctuations of the stochastic parameter.

Despite the differences in the adopted framework, what all these papers have in common is the assumption that the investment cost is exogenous. However, as highlighted by Billette de Villemeur et al. (2014), the cost of an investment does not always reflect the project's economic fundamentals. Actually, as the authors show, if the completion of an investment project depends on the provision of an indispensable input from an upstream firm with market power, a vertical distortion arises. The analysis presented in Zormpas (2017) applies the endogenous pricing of the input à la Billette de Villemeur et al. (2014) to a setting that describes an investment project the completion of which depends on the successful interaction between the project originator and a foreign firm. The foreign firm in that framework is an investment partner willing to undertake a share of the sunk investment cost claiming a share of the project in return. Extending Zormpas (2017), we now study the case where the foreign firm is not an investment partner but, instead, an agent delegated by the project originator with the exercise of the investment option.

### 3 The model

#### 3.1 The basic set-up

Firm  $P$  holds the option to undertake an investment project and delegates the investment decision to an agent  $B$ . The value of the project, net of the agent's wage, is represented by  $X_t$  which is assumed to be fluctuating over time according to the following geometric Brownian motion:

$$\frac{dX_t}{X_t} = \mu dt + \sigma dz_t, X_0 = x \quad (1)$$

The parameter  $\mu$  stands for the positive constant drift,  $\sigma$  is the positive constant volatility and  $dz_t$  is the increment of a Wiener process. The structural parameters of process (1) are common knowledge, whereas  $P$  is the only party that can continuously and verifiably observe the realizations of  $X_t$ . In order to facilitate coordination,  $P$  is voluntarily sharing this information with  $B$ .<sup>10</sup>

The completion of the aforementioned investment project is conditional on the provision of a discrete input that is exclusively produced by a firm  $A$ . The production cost of the input is random and its probability distribution is common knowledge. Once  $A$  observes the true magnitude of the production cost, s/he prices the input and then announces the price to the project manager, agent  $B$ .<sup>11</sup>

There is an information asymmetry between  $B$  and  $P$  since the former knows the true magnitude of the input price whereas the latter knows only its distribution. Because of the asymmetry of information and the corresponding incentive misalignment,  $P$  uses a bonus-incentive mechanism in

<sup>10</sup>Information sharing among members of a supply chain is an important mechanism for coordination. See for instance, Lee and Whang (1998), Lee et al. (2004) and Agrell and Bogetoft (2017).

<sup>11</sup>Note that, unless otherwise specified (see subsections 4.2 and 4.3), agent  $B$  is delegated both with the investment decision and with the procurement of the needed input. This is reminiscent of the "delegation to a middleman" case from Mookherjee and Tsumagari (2004) and Mookherjee (2006).

order to make  $B$  reveal private information at the time of the exercise of the investment option in order to prevent further distortions.

All the parties are assumed to be risk neutral with the risk-free interest rate denoted by  $r$ . For convergence we assume  $r > \mu$ .<sup>12</sup>

Before analyzing the agency conflict under the presence of an external input supplier, we briefly review the case with information symmetry and in-house production of the input in subsection 3.2 and the case with information asymmetry and in-house production of the input in subsection 3.3.

### 3.2 Information symmetry and in-house production of the input

In this subsection we assume that  $B$  produces the needed input in-house. Before discussing the delegation of the investment decision from  $P$  to  $B$ , let's recall that, according to the real options literature, when a potential investor contemplates undertaking an investment project characterized by uncertainty and irreversibility, the ability to delay the investment for some future time point is a source of flexibility that profoundly affects the decision to invest (see e.g. McDonald and Siegel, 1986). The investment takes place only as soon as the project's expected payoff exceeds the cost of the investment by a margin equal to the option value of further postponing the completion of the project into the future.<sup>13</sup>

Let  $F(x; I)$  denote the value of the opportunity to invest in a project the value of which fluctuates over time according to process (1), and  $I$  denote the corresponding sunk investment cost. Assuming that the initial state value  $x$  is sufficiently small so that investing at time zero is not preferable,<sup>14</sup> the optimal investment time point  $\tau$  is derived through the solution of the following maximization problem:

$$F(x; I) = \max_{\tau} E_x [e^{-r\tau} (X^* - I)], \quad (2.1)$$

which can be rearranged as<sup>15</sup>

$$F(x; I) = \max_{X^*} (X^* - I) \left( \frac{x}{X^*} \right)^{\beta}, \quad (2.2)$$

where:

-  $\tau = \inf \{t > 0 | X_t = X^*\}$  is the random first time point that  $X_t$  hits the barrier  $X^*$  which is the project value that triggers the investment and,

-  $\beta = \frac{1}{2} - \frac{\mu}{\sigma^2} + \sqrt{\left(\frac{\mu}{\sigma^2} - \frac{1}{2}\right)^2 + \frac{2r}{\sigma^2}} > 1$  is the positive root of the characteristic equation  $\frac{1}{2}\sigma^2\beta(\beta - 1) + \mu\beta - r = 0$ .<sup>16</sup>

Now, applying the real options reasoning to our context, we have the following. The project originator  $P$  contemplates investing in a project like the one described in problem (2.2), and delegates the corresponding investment decision to the project manager  $B$ . The generic term  $I$  corresponds to the in-house production cost of the input which, as outlined in subsection 3.1, is random. By assumption,  $I$  can be "low" ( $I_1$ ) with probability  $q$  or "high" ( $I_2$ ) with probability  $1 - q$  where  $I_2 > I_1 > 0$  and  $\Delta I \equiv I_2 - I_1$ .<sup>17</sup>

<sup>12</sup>See e.g. Dixit and Pindyck (1994, pp. 138).

<sup>13</sup>O'Brien et al. (2003) present strong empirical evidence in favor of this argument. More precisely, they find that entrepreneurs account for the value of the option to delay entering a new market when contemplating such a decision.

<sup>14</sup>If the initial state value  $x$  is sufficiently large so that investing at time zero is preferable, our problem reduces to a standard net present value maximization since the option to invest is exercised as soon as possible.

<sup>15</sup>For the calculation of expected present values, see Dixit and Pindyck (1994, pp. 315-316).

<sup>16</sup>The expressions for  $F(x; I)$  and  $\beta$  are standard in the real options literature (see e.g. Dixit and Pindyck, 1994).

<sup>17</sup>In Section A.2 of Appendix A we extend our analysis considering a continuous  $I$ .

Under symmetry of information, that is when the true magnitude of  $I$  is known both to the principal and to the agent,  $B$  has no informational advantage over  $P$  and, consequently, it is as if we are dealing with a problem without delegation of the investment decision. In this case  $B$  is just an intermediary who is granted access to exactly enough resources to successfully complete the delegated task. Consequently, the ex-ante optimization problem for  $P$  is

$$\max_{X_1^{SI}, X_2^{SI}} q (X_1^{SI} - I_1) \left( \frac{x}{X_1^{SI}} \right)^\beta + (1 - q) (X_2^{SI} - I_2) \left( \frac{x}{X_2^{SI}} \right)^\beta, \quad (3)$$

where  $X_i^{SI}$ ,  $i \in \{1, 2\}$  are the investment thresholds under symmetry of information.<sup>18</sup> From the first-order conditions we have

$$X_i^{SI} = \frac{\beta}{\beta - 1} I_i, i \in \{1, 2\}. \quad (4)$$

Note that, since  $I_2 > I_1$ , we obtain  $X_2^{SI} > X_1^{SI}$ . In words, the completion of a more expensive investment project is, in expected terms, realized later.

Last,  $P$ 's ex-ante value of the opportunity to invest can be written as:

$$f(x; I_1, I_2) = qF(x; I_1) + (1 - q) F(x; I_2) \quad (5.1)$$

$$= q \frac{I_1}{\beta - 1} \left( \frac{x}{X_1^{SI}} \right)^\beta + (1 - q) \frac{I_2}{\beta - 1} \left( \frac{x}{X_2^{SI}} \right)^\beta \quad (5.2)$$

As one can easily see, the quantity  $f(x; I_1, I_2)$  is the ex-ante value of the opportunity to invest, not only for the project originator, but for the whole industry as well.<sup>19</sup>

### 3.3 Information asymmetry and in-house production of the input

As in the previous subsection,  $B$  is qualified to produce the discrete input in-house. What is different from before is that now the true  $I$  is not common knowledge but is instead assumed to be privately observed by the agent  $B$ . This is a reasonable assumption since the individual with the best information on the production cost is usually the producer her/himself (Celik, 2009). Of course, this implies an information asymmetry between  $P$  and  $B$ . As in Grenadier and Wang (2005), Amaral et al. (2006) and Shibata (2009), this information asymmetry results in an agency conflict since the agent has an incentive to report the higher  $I_2$  when  $I_1$  is the true production cost, attempting to appropriate the positive difference  $\Delta I$ .

The principal might not be able to observe the true  $I$  verifying the agent's (dis)honesty, but s/he can induce  $B$  to reveal the true magnitude of the expenditure by giving a bonus-incentive. In order to do so, s/he designs a menu of contracts contingent on the observable  $X_t$ . We assume that  $P$  submits the menu of contracts to her/his delegate at time zero and that the chosen contract commits the actions of the two parties at the time of the investment.<sup>20</sup> Once the menu of contracts is submitted,  $B$  observes the true  $I$  and chooses the corresponding contract. Given that  $I$  can take one of two possible values, "high" or "low", this menu is comprised by two contracts consisting of one money transfer ( $t$ ) and one investment threshold ( $X^{AI}$ ) each.<sup>21</sup> The principal's objective is to

<sup>18</sup>The superscript  $SI$  refers to symmetry of information. In order to be consistent with the assumption according to which investing at time zero is not preferable, we assume  $x < X_i^{SI}$ ,  $i \in \{1, 2\}$ .

<sup>19</sup>Since  $B$  has no informational advantage over  $P$  under information symmetry, her/his option value is equal to zero.

<sup>20</sup>Renegotiation of the contract terms is not allowed. This assumption is justified if the contract is enforceable and if the market of the agent is competitive. For a similar treatment see Grenadier and Wang (2005) and Shibata (2009).

<sup>21</sup>Note that we can also allow for a menu of contracts comprised by one pair of  $t$  and  $X^{AI}$ , i.e. a pooling equilibrium. However, the pooling equilibrium is always dominated by a separating one and this allows us to focus on the latter. See e.g. Shibata (2009).

maximize the ex-ante value of the investment opportunity through the choice of the contract terms  $\{X_i^{AI}, t_i\}$ ,  $i \in \{1, 2\}$ . The problem that  $P$  needs to solve is formulated as:

$$\max_{\{(X_1^{AI}, t_1); (X_2^{AI}, t_2)\}} q (X_1^{AI} - t_1) \left( \frac{x}{X_1^{AI}} \right)^\beta + (1 - q) (X_2^{AI} - t_2) \left( \frac{x}{X_2^{AI}} \right)^\beta \quad (6.1)$$

Subject to:

$$(t_1 - I_1) \left( \frac{x}{X_1^{AI}} \right)^\beta \geq (t_2 - I_1) \left( \frac{x}{X_2^{AI}} \right)^\beta \quad (7.1)$$

$$(t_2 - I_2) \left( \frac{x}{X_2^{AI}} \right)^\beta \geq (t_1 - I_2) \left( \frac{x}{X_1^{AI}} \right)^\beta \quad (8.1)$$

$$t_1 - I_1 \geq 0 \quad (9.1)$$

$$t_2 - I_2 \geq 0 \quad (10.1)$$

$$q (t_1 - I_1) \left( \frac{x}{X_1^{AI}} \right)^\beta + (1 - q) (t_2 - I_2) \left( \frac{x}{X_2^{AI}} \right)^\beta \geq 0 \quad (11.1)$$

As one can see, the objective function in problem (6.1) is symmetric to the objective function in problem (3).<sup>22</sup> The only difference between the two is that the money transfer  $t_i$  replaces the cost expenditure  $I_i$ .

The inequalities (7.1) and (8.1) are the incentive compatibility constraints. They guarantee that if agent  $B$  observes that the true  $I$  is equal to  $I_i$ , s/he will (weakly) prefer contract  $\{X_i^{AI}, t_i\}$  to contract  $\{X_j^{AI}, t_j\}$  where  $i, j \in \{1, 2\}$  and  $i \neq j$ . In other words, constraints (7.1) and (8.1) guarantee that, at the time of the investment, the reported  $I$  is the true one. As one can see, an incentive compatible scheme eliminates potential incentive misalignments since both the principal and the agent are better-off when following the decision rules that are optimal for the system as a whole.<sup>23</sup>

The inequalities (9.1) and (10.1) are the limited liability conditions and they are necessary to provide an incentive for the agent to get involved in the project. Finally, inequality (11.1) is the agent's ex-ante participation constraint which ensures that  $B$ 's total value of accepting to abide by  $P$ 's menu of contracts is non-negative.

The problem (6.1)-(11.1) can be alternatively formulated in the following way:

$$\max_{\{(X_1^{AI}, w_1); (X_2^{AI}, w_2)\}} q (X_1^{AI} - w_1 - I_1) \left( \frac{x}{X_1^{AI}} \right)^\beta + (1 - q) (X_2^{AI} - w_2 - I_2) \left( \frac{x}{X_2^{AI}} \right)^\beta \quad (6.2)$$

Subject to:

$$w_1 \left( \frac{x}{X_1^{AI}} \right)^\beta \geq (w_2 + \Delta I) \left( \frac{x}{X_2^{AI}} \right)^\beta \quad (7.2)$$

$$w_2 \left( \frac{x}{X_2^{AI}} \right)^\beta \geq (w_1 - \Delta I) \left( \frac{x}{X_1^{AI}} \right)^\beta \quad (8.2)$$

$$w_1 \geq 0 \quad (9.2)$$

$$w_2 \geq 0 \quad (10.2)$$

$$q w_1 \left( \frac{x}{X_1^{AI}} \right)^\beta + (1 - q) w_2 \left( \frac{x}{X_2^{AI}} \right)^\beta \geq 0 \quad (11.2)$$

<sup>22</sup>The superscript  $AI$  denotes asymmetry of information. We also assume  $x < X_i^{AI}$ ,  $i \in \{1, 2\}$ .

<sup>23</sup>See e.g. Lee and Whang (1999).

The term  $w_i = t_i - I_i, i \in \{1, 2\}$  stands for the information rent. Formally, the information rent is defined as the difference between the money transfer  $t_k$  and the true expenditure  $I_i$ :  $w_{k,i} \equiv t_k - I_i, i, k \in \{1, 2\}$  where  $k$  is the reported, but not necessarily true ( $i$ ), expenditure.<sup>24</sup> Of course under incentive compatibility the reported and the true expenditures coincide ( $k = i$ ) which gives  $w_{i,i} = t_i - I_i$ . By slightly abusing notation,  $w_{i,i}$  reduces to  $w_i$  which is the term appearing above.

Solving the problem (6)-(11) we obtain the following menu of contracts:<sup>25</sup>

$$\{X_1^{AI}(I_1), w_1(I_1, I_2)\} = \left\{ \frac{\beta}{\beta-1} I_1, \left( \frac{X_1^{AI}(I_1)}{X_2^{AI}(I_1, I_2)} \right)^\beta \Delta I \right\} \quad (12.1)$$

$$\{X_2^{AI}(I_1, I_2), w_2(I_1, I_2)\} = \left\{ \frac{\beta}{\beta-1} I_2 + \frac{\beta}{\beta-1} \frac{q}{1-q} \Delta I, 0 \right\} \quad (12.2)$$

Thanks to the incentive compatibility conditions, contract (12.1) will be chosen by  $B$  when the cost turns out to be equal to  $I_1$ , whereas, contract (12.2) will be chosen when the cost turns out to be equal to  $I_2$ .

Note that, on one hand,  $X_1^{AI}(I_1) = X_1^{SI}(I_1)$ ,  $X_2^{AI}(I_1, I_2) > X_2^{SI}(I_2)$  and that, on the other,  $w_1(I_1, I_2) > 0$ ,  $w_2(I_1, I_2) = 0$ . In words, the agency conflict does not affect the timing of the investment when  $I_1$  is observed, but it does when  $I_2$  is observed causing the (suboptimal) postponement of the investment. However, this does not mean that when  $I_1$  is the true investment cost there is no distortion since a positive information rent is to be paid to  $B$ .

Substituting the components of menu (12) in the value functions of the two parties we obtain

$$\begin{aligned} V_P(x; I_1, I_2) &= q(X_1^{AI}(I_1) - I_1 - w_1(I_1, I_2)) \left( \frac{x}{X_1^{AI}(I_1)} \right)^\beta \\ &\quad + (1-q)(X_2^{AI}(I_1, I_2) - I_2) \left( \frac{x}{X_2^{AI}(I_1, I_2)} \right)^\beta, \end{aligned} \quad (13)$$

$$V_B(x; I_1, I_2) = qw_1(I_1, I_2) \left( \frac{x}{X_1^{AI}(I_1)} \right)^\beta, \quad (14)$$

where  $V_P(x; I_1, I_2)$  and  $V_B(x; I_1, I_2)$  stand for the investment opportunity values of the principal and the agent respectively. The total value of the project  $V(x; I_1, I_2) \equiv V_P(x; I_1, I_2) + V_B(x; I_1, I_2)$ , is then equal to:

$$V(x; I_1, I_2) = q(X_1^{AI}(I_1) - I_1) \left( \frac{x}{X_1^{AI}(I_1)} \right)^\beta + (1-q)(X_2^{AI}(I_1, I_2) - I_2) \left( \frac{x}{X_2^{AI}(I_1, I_2)} \right)^\beta \quad (15)$$

Note that this is symmetric to Eq. (5). The only difference between the two is that, in Eq. (15), the larger  $X_2^{AI}(I_1, I_2)$  replaces the smaller  $X_2^{SI}(I_2)$  resulting in

$$V(x; I_1, I_2) < f(x; I_1, I_2). \quad (16)$$

In words, the agency conflict between the principal and the agent that stems from the corresponding information asymmetry is reflected in a suboptimally lower aggregate value of the opportunity to invest.

<sup>24</sup>See e.g. Laffont and Martimort, 2002.

<sup>25</sup>The solution of the problem is analytically presented in Section A.1 of Appendix A.



## 4 A as the exclusive producer of the input

Up to now, we have discussed the interaction between the principal  $P$  and the agent  $B$  assuming that the latter can produce the needed input in-house. Nevertheless, the project manager might lack the equipment and/or the expertise to manufacture the needed input (Deshpande et al., 2011). Investment projects are often rather complex and relationship-specific inputs tailored to a specific client are common in supply chains (Agrell and Bogetoft, 2017). Keeping this in mind, we assume now that the upstream firm  $A$  is the exclusive producer of the required input.

In subsection 4.1 we examine the case of an opaque supply chain in the sense that every individual in the supply chain is dealing exclusively with her/his immediate neighbor(s).<sup>26</sup> In this case,  $P$  delegates to  $B$  not only the exercise of the investment decision but the procurement of the necessary input as well. At the same time,  $A$  prices the input that s/he sells to  $B$  knowing the fundamental parameters of process (1) but without ever observing the true magnitude of  $X_t$ .

In subsection 4.2 we allow for a framework where all the companies in the supply chain are able to track the product's flow throughout the production process.<sup>27</sup> In this case,  $P$  still delegates the investment decision to  $B$  but can now procure the input directly from  $A$  if this proves to be the better alternative. The upstream firm  $A$  is now informed about the delegation of the project from  $P$  to  $B$  but still prices the input having only partial information about process (1).

Last, in subsection 4.3 we discuss a transparent supply chain where  $P, B$  and  $A$  are informed about the structure of the supply chain and share the same information about  $X_t$ .

### 4.1 Opaque supply chain

In this subsection we discuss an opaque supply chain in the sense that the upstream firm  $A$  deals only with the project manager  $B$  and prices the produced input knowing the structural parameters of process (1) but without ever observing the true magnitude of  $X_t$ .

Algebraically,  $A$ 's problem is given by

$$\max_{p_1, p_2} q(p_1 - I_1) \left( \frac{x}{X_1^M(p_1)} \right)^\beta + (1 - q)(p_2 - I_2) \left( \frac{x}{X_2^M(p_2)} \right)^\beta, \quad (17)$$

where  $p_i$  is the price of the input when the in-house production cost is  $I_i$  and  $X_i^M(p_i)$ ,  $i \in \{1, 2\}$  is the corresponding investment threshold.<sup>28</sup>

$A$  is choosing  $p_i$  anticipating that  $B$  will complete the (supposedly private) investment once the investment threshold  $X_i^M(p_i) = \frac{\beta}{\beta-1}p_i$ ,  $i \in \{1, 2\}$  is reached.<sup>29</sup> Of course the formula for  $X_i^M(p_i)$  is identical to the one for  $X_i^{SI}$  from Eq. (4) if, instead of  $I_i$ , we use  $p_i$ .<sup>30</sup> Given this, we solve the maximization problem (17) and we obtain:

$$p_i = \frac{\beta}{\beta-1}I_i, i \in \{1, 2\} \quad (18)$$

Note that, unsurprisingly,  $p_i > I_i$  which means that the presence of an upstream firm with market power naturally makes the investment more costly.<sup>31</sup>

<sup>26</sup>The plural is for  $B$  who is purchasing the input from  $A$  in order to deliver  $P$ 's project.

<sup>27</sup>In subsection 4.2 below we define this property of the supply chain as *traceability*.

<sup>28</sup>See Billette de Villemeur et al. (2014), pp 112, for a similar treatment.

<sup>29</sup>By assumption,  $x < X_i^M(p_i)$ ,  $i \in \{1, 2\}$ .

<sup>30</sup>Analytically, the term  $X_i^M(p_i) = \frac{\beta}{\beta-1}p_i$ ,  $i \in \{1, 2\}$  is derived solving  $\max_{X_1^M, X_2^M} q(X_1^M - p_1) \left( \frac{x}{X_1^M} \right)^\beta + (1 - q)(X_2^M - p_2) \left( \frac{x}{X_2^M} \right)^\beta$  which of course is reminiscent of the maximization problem (3).

<sup>31</sup>Note also that, thanks to  $I_2 > I_1$ , we obtain  $p_2 > p_1$ .

Now, we can go back to the agency conflict as it was discussed in subsection 3.3 and see how the replacement of  $I_i$  by  $p_i$  affects our results. Replacing also  $\Delta I$  with  $\Delta p \equiv p_2 - p_1$  we obtain:

$$\{X_1^R(p_1), \omega_1(p_1, p_2)\} = \left\{ \frac{\beta}{\beta-1} p_1, \left( \frac{X_1^R(p_1)}{X_2^R(p_1, p_2)} \right)^\beta \Delta p \right\} \quad (19.1)$$

$$\{X_2^R(p_1, p_2), \omega_2(p_1, p_2)\} = \left\{ \frac{\beta}{\beta-1} p_2 + \frac{\beta}{\beta-1} \frac{q}{1-q} \Delta p, 0 \right\} \quad (19.2)$$

The term  $\omega_i$  stands for the information rent that the delegate  $B$  receives through the menu of contracts in (19), whereas the term  $X_i^R$  stands for the (real) investment threshold.<sup>32</sup> Note that  $X_1^R(p_1) = X_1^M(p_1)$  but  $X_2^R(p_1, p_2) > X_2^M(p_2)$ . This implies that  $A$ 's inability to acknowledge that  $s/he$  is selling the input to the agent, and not to the principal, is costly when the true  $I$  is equal to  $I_2$ . In that case, the input supplier expects to cash the lump sum  $p_2$  when  $X_2^M(p_2)$  is reached but will have to wait until  $X_t$  reaches the higher  $X_2^R(p_1, p_2)$  before this actually happens.

The investment opportunity values for the three parties  $P$ ,  $B$  and  $A$  are:

$$\begin{aligned} \Pi_P(x; p_1, p_2) &= q(X_1^R(p_1) - p_1 - \omega_1(p_1, p_2)) \left( \frac{x}{X_1^R(p_1)} \right)^\beta \\ &\quad + (1-q)(X_2^R(p_1, p_2) - p_2) \left( \frac{x}{X_2^R(p_1, p_2)} \right)^\beta \end{aligned} \quad (20)$$

$$\Pi_B(x; p_1, p_2) = q\omega_1(p_1, p_2) \left( \frac{x}{X_1^R(p_1)} \right)^\beta \quad (21)$$

$$\Pi_{AR}(x; p_1, p_2) = q(p_1 - I_1) \left( \frac{x}{X_1^R(p_1)} \right)^\beta + (1-q)(p_2 - I_2) \left( \frac{x}{X_2^R(p_1, p_2)} \right)^\beta \quad (22.1)$$

Note that  $A$  anticipates to receive

$$\Pi_{AM}(x; p_1, p_2) = q(p_1 - I_1) \left( \frac{x}{X_1^M(p_1)} \right)^\beta + (1-q)(p_2 - I_2) \left( \frac{x}{X_2^M(p_2)} \right)^\beta, \quad (22.2)$$

where  $\Pi_{AR}(x; p_1, p_2) < \Pi_{AM}(x; p_1, p_2)$ . As we have already underlined above, the difference between the true  $\Pi_{AR}$  and the expected  $\Pi_{AM}$  has to do with the difference between  $X_2^R(p_1, p_2)$  and  $X_2^M(p_2)$ .

Last, the aggregate value of the investment opportunity is:

$$\Pi(x; p_1, p_2) \equiv \Pi_P(x; p_1, p_2) + \Pi_B(x; p_1, p_2) + \Pi_{AR}(x; p_1, p_2) = \quad (23.1)$$

$$q(X_1^R(p_1) - I_1) \left( \frac{x}{X_1^R(p_1)} \right)^\beta + (1-q)(X_2^R(p_1, p_2) - I_2) \left( \frac{x}{X_2^R(p_1, p_2)} \right)^\beta \quad (23.2)$$

Let's now check how the presence of the upstream firm  $A$  affects the timing and the value of the investment. As we have already seen above, the presence of a supplier with market power makes the investment more costly since  $p_i/I_i = \beta/\beta - 1$ ,  $i \in \{1, 2\}$ . The fact that the investment is more expensive is then reflected in higher investment thresholds and a larger information rent. More precisely, we have:

$$\frac{X_1^R(p_1)}{X_1^{AI}(I_1)} = \frac{X_2^R(p_1, p_2)}{X_2^{AI}(I_1, I_2)} = \frac{\omega_1(p_1, p_2)}{w_1(I_1, I_2)} = \frac{\beta}{\beta-1} > 1 \quad (24)$$

<sup>32</sup>The derivation of menu (19) is totally symmetric to the one of menu (12).

One can also show that

$$\Pi_P(x; p_1, p_2) < V_P(x; I_1, I_2), \quad (25.1)$$

$$\Pi_B(x; p_1, p_2) < V_B(x; I_1, I_2), \quad (25.2)$$

$$\Pi(x; p_1, p_2) < V(x; I_1, I_2). \quad (25.3)$$

In words, the presence of an external input supplier with market power makes both the project originator and the project manager worse-off a result which is eventually mirrored in a lower aggregate investment value.<sup>33</sup>

The following proposition summarizes our findings:

**Proposition 1** *Consider an investment project that i) is characterized by uncertainty and irreversibility, ii) is undertaken in a decentralized setting and iii) is conditional on the provision of a necessary input by an outside supplier with market power. When the supply chain is opaque, the vertical distortion is reflected in, a) higher investment costs and investment triggers and, b) a smaller value of the investment opportunity for the principal, the agent and the supply chain as a whole.*

## 4.2 The case of traceability

A supply chain is characterized by *traceability* when the names of the firms involved in the supply chain are disclosed to the other firms in the supply chain as well as to end-users.<sup>34</sup>

In our setting, traceability implies that:

i)  $A$  knows the structure of the downstream industry, that is, s/he knows that  $P$  is the project originator whereas  $B$  is the project manager and,

ii)  $P$  knows that  $A$  is the supplier of the necessary input.

It is important to stress here that  $A$  is still assumed to be pricing the input taking into consideration the structural parameters of process (1), but without observing the realizations of the stochastic parameter over time. The importance of this point will become clearer in the next subsection where this assumption will be relaxed.

Reapproaching the problem from subsection 4.1, we have the following. The input supplier  $A$ , observing the delegation of the investment decision downstream, anticipates that the agency conflict will result in, not  $\Pi_{AM}(x; p_1, p_2)$  but the smaller,  $\Pi_{AR}(x; p_1, p_2)$ . Of course  $A$  can prevent that from happening by sharing the true price of the input with both  $B$  and  $P$ . This way, the input supplier makes sure that there will be information symmetry downstream and that, consequently, the principal will not have to use a bonus-incentive mechanism in order to guarantee the successful delivery of the project. Actually, by pricing the input according to Eq. (18),  $A$  can secure  $\Pi_{AM}(x; p_1, p_2)$  for her/himself.

As far as the principal and the agent are concerned, the symmetry of information implies a zero investment opportunity value for  $B$  and a positive investment opportunity value for  $P$  that is equal to:

$$\pi_P(x; p_1, p_2) = q(X_1^M(p_1) - p_1) \left( \frac{x}{X_1^M(p_1)} \right)^\beta + (1 - q)(X_2^M(p_2) - p_2) \left( \frac{x}{X_2^M(p_2)} \right)^\beta \quad (26.1)$$

$$= \left( \frac{\beta - 1}{\beta} \right)^{\beta - 1} f(x; I_1, I_2) \quad (26.2)$$

<sup>33</sup>Using standard option valuation arguments, we know that a firm stands to gain more by exercising rather than holding an investment option with a low strike price. In our setting where  $p_i > I_i$ , one expects to find  $X_i^R > X_i^{AI}$ ,  $i \in \{1, 2\}$  and  $V_j > \Pi_j$ ,  $j \in \{P, B\}$  which is exactly what we have in Eq. (24) and Eq. (25).

<sup>34</sup>See e.g. Doorey (2011) and Laudal (2010).

The inequality  $\pi_P(x; p_1, p_2) < f(x; I_1, I_2)$  implies that, even under information symmetry downstream, the investment opportunity value of the principal is suboptimal. Of course this is to be expected since, despite the fact that  $P$  does not need to pay an information rent to  $B$  anymore, s/he still needs to pay a "market rent" to  $A$  who exploits her/his market power as the exclusive producer of the needed input.

The aggregate investment opportunity value in this case is:

$$\begin{aligned} \pi(x; p_1, p_2) &\equiv \pi_P(x; p_1, p_2) + \Pi_{AM}(x; p_1, p_2) & (27.1) \\ &= q(X_1^M(p_1) - I_1) \left( \frac{x}{X_1^M(p_1)} \right)^\beta + (1 - q)(X_2^M(p_2) - I_2) \left( \frac{x}{X_2^M(p_2)} \right)^\beta & (27.2) \end{aligned}$$

As one can see, Eq. (27) is symmetric to Eq. (5). Also, one can easily check that  $\pi(x; p_1, p_2) < f(x; I_1, I_2)$  which means that the market power of the input supplier is reflected in a suboptimal aggregate investment opportunity value, even under information symmetry downstream.

Let's now identify how traceability affects the investment project. First of all, agent  $B$  is clearly worse-off since there is no information asymmetry for her/him to exploit. On the contrary, we see that the input supplier as well as the principal are both better-off since  $\Pi_{AR}(x; p_1, p_2) < \Pi_{AM}(x; p_1, p_2)$  and  $\Pi_P(x; p_1, p_2) < \pi_P(x; p_1, p_2)$ . This of course has to do with the fact that the principal does not need a bonus-incentive mechanism to guarantee that the agent reports the true investment cost. At the same time, also the aggregate value of the investment opportunity is higher since  $\Pi(x; p_1, p_2) < \pi(x; p_1, p_2)$ .

Summing up, traceability in a supply chain might not be beneficial for the project manager but is beneficial for all other parties as well as the supply chain as a whole.

The following proposition summarizes our findings:

**Proposition 2** *Consider again the investment project from Proposition 1. When the supply chain is characterized by traceability, there is no information asymmetry for the agent to exploit. This makes the agent worse-off but is beneficial for the principal, the input supplier and the supply-chain as a whole.*

Finally, one can notice that  $V(x; I_1, I_2)$  from Eq. (15) and  $\pi(x; p_1, p_2)$  from Eq. (27) correspond to the two ends of the same spectrum:  $V(x; I_1, I_2)$  is the aggregate value of an investment project that involves downstream asymmetry of information but a perfectly competitive input market, whereas  $\pi(x; p_1, p_2)$  is the aggregate value of the opportunity to invest in a project that involves downstream symmetry of information but a monopolist input supplier.

### 4.3 Transparent supply chain

In this subsection, we allow for a transparent supply chain in the sense that, apart from traceability, we also assume that  $P$ ,  $B$  and  $A$  all share the same information related to the stochastic parameter. Of course,  $P$  would be willing to share private information about  $X_t$  with  $A$  under the condition that s/he receives a reservation value not smaller than  $\Omega_i \equiv (X_i^M(p_i) - p_i) \left( \frac{x}{X_i^M(p_i)} \right)^\beta$ ,  $i \in \{1, 2\}$ . This way, and by dictating the first-best investment threshold  $X_i^{SI}$ ,  $A$  can appropriate all the benefits above  $P$ 's reservation value.

Keeping all this in mind,  $A$  is choosing the input price solving

$$\max_{\varphi_i} (\varphi_i - I_i) \left( \frac{x}{X_i^{SI}} \right)^\beta \quad (28)$$

subject to

$$(X_i^{SI} - \varphi_i) \left( \frac{x}{X_i^{SI}} \right)^\beta \geq \Omega_i, i \in \{1, 2\}.^{35} \quad (29)$$

The term  $\varphi_i$  stands for the (new) price of the input. Since the objective function in problem (28) is increasing in  $\varphi_i$ , the solution is derived from the constraint (29). A binding constraint (29) implies that,  $\varphi_i$  is such that  $P$  is indifferent between an investment that costs  $\varphi_i$  and takes place when  $X_i^{SI}$  is reached, and an investment that costs  $p_i$  and takes place when the higher  $X_i^M(p_i)$  is reached. Solving we obtain

$$\varphi_i = \frac{\beta}{\beta - 1} I_i \left( 1 - \frac{(\beta - 1)^{\beta-1}}{\beta^\beta} \right).^{36} \quad (30)$$

The input supplier  $A$ , chooses  $\varphi_i (> I_i)$  at  $X_i^{SI}$  submitting a take-it-or-leave-it offer to the project originator  $P$  and to her/his delegate  $B$ .

In this case, the principal's ex-ante value of the investment opportunity is:

$$\Phi_P(x; \varphi_1, \varphi_2) = q (X_1^{SI} - \varphi_1) \left( \frac{x}{X_1^{SI}} \right)^\beta + (1 - q) (X_2^{SI} - \varphi_2) \left( \frac{x}{X_2^{SI}} \right)^\beta \quad (31)$$

The ex-ante value of the investment opportunity for  $A$  is given by:

$$\Phi_A(x; \varphi_1, \varphi_2) = q (\varphi_1 - I_1) \left( \frac{x}{X_1^{SI}} \right)^\beta + (1 - q) (\varphi_2 - I_2) \left( \frac{x}{X_2^{SI}} \right)^\beta \quad (32)$$

Finally, combining the two, the aggregate value is

$$\Phi(x; \varphi_1, \varphi_2) \equiv \Phi_P(x; \varphi_1, \varphi_2) + \Phi_A(x; \varphi_1, \varphi_2) \quad (33.1)$$

$$= q (X_1^{SI} - I_1) \left( \frac{x}{X_1^{SI}} \right)^\beta + (1 - q) (X_2^{SI} - I_2) \left( \frac{x}{X_2^{SI}} \right)^\beta \quad (33.2)$$

$$= f(x; I_1, I_2) \quad (33.3)$$

The equality  $\Phi(x; \varphi_1, \varphi_2) = f(x; I_1, I_2)$  is to be expected since, as we have seen in the beginning of this subsection,  $A$  will attempt to dictate the investment thresholds that maximize the industry value and then appropriate all the benefits above the potential investor's reservation value. In other words, by construction, we have  $\Phi_A(x; \varphi_1, \varphi_2) = f(x; I_1, I_2) - \Phi_P(x; \varphi_1, \varphi_2)$  and consequently  $\Phi_P(x; \varphi_1, \varphi_2) + \Phi_A(x; \varphi_1, \varphi_2) = f(x; I_1, I_2)$ .

Comparing the transparent-supply-chain case with the one under traceability we have  $\pi_P(x; p_1, p_2) = \Phi_P(x; \varphi_1, \varphi_2)$  and  $\Phi_A(x; \varphi_1, \varphi_2) > \Pi_{AM}(x; p_1, p_2)$ .<sup>37</sup> In words, while the project originator and the project manager are indifferent between a supply chain characterized by traceability and a transparent one, both the input supplier and the supply chain as a whole are better-off.

Proposition 3 summarizes our findings:

**Proposition 3** *Consider again the investment project from Proposition 1. When the supply chain is transparent the investment is realized when the first-best investment threshold is reached. The principal and the agent are indifferent between a supply chain that is transparent and one that is characterized by traceability, however, the input supplier and, consequently, the supply chain as a whole, are better-off.*

<sup>35</sup> See Billette de Villemeur et al. (2014), pp 114 for a similar treatment.

<sup>36</sup> Note also that, thanks to  $I_2 > I_1$ , we obtain  $\varphi_2 > \varphi_1$ .

<sup>37</sup> Note that  $\pi_P(x; p_1, p_2) = \Phi_P(x; \varphi_1, \varphi_2)$  holds as soon as constraint (29) is binding.

## 5 Discussion

TABLE 1 below presents how the investment costs, the investment thresholds and the values of the investment opportunity change given the different levels of transparency in the supply chain.

TABLE 1

	Opacity		Traceability		Transparency	First-Best
Cost	$p_i$	=	$p_i$	>	$\varphi_i$	$I_i$
Threshold	$X_i^R$	$\geq$	$X_i^M$	>	$X_i^{SI}$	$X_i^{SI}$
Inv. Value:						
Aggregate	$\Pi$	<	$\pi$	<	$f$	$f$
$B$	$\Pi_B$	>	0	=	0	0
$A$	$\Pi_{AR}$	<	$\Pi_{AM}$	<	$\Phi_A$	0
$P$	$\Pi_P$	<	$\pi_P$	=	$\Phi_P$	$f$

First of all, one can see that irrespective of the level of information sharing in the supply chain, the presence of an upstream input supplier with market power is always making the investment more expensive ( $\varphi_i > I_i, i \in \{1, 2\}$ ). As for the investment triggers, our comparisons suggest that the higher investment costs are not always reflected in higher investment thresholds. Actually, as we saw in subsection 4.3, in a transparent supply chain, the investment takes place as soon as the optimal investment trigger ( $X_i^{SI}, i \in \{1, 2\}$ ) is reached, i.e., there is no inefficient postponement of the investment at all.

The way that the presence of the input supplier affects the aggregate value of the investment opportunity is also ambiguous. According to Eq. (25.3), the presence of an upstream firm with market power in an opaque supply chain will reduce the value of the investment opportunity if compared to the case where the input is insourced ( $\Pi(x; p_1, p_2) < V(x; I_1, I_2)$ ). Nevertheless, the level of transparency makes a difference since, as one can see, the aggregate value of the investment opportunity reaches its first-best when the supply chain is transparent.

As far as the components of the aggregate value of the investment opportunity are concerned, we find that the presence of the upstream firm is affecting differently the principal and the agent. Starting with the latter, the presence of the input supplier is always making the agent worse-off. Even under an opaque supply chain which is the most favorable scenario for the delegate, the higher sunk investment costs imply an investment opportunity with lower value.<sup>38</sup> Of course, both under traceability and under transparency, the agency conflict is automatically resolved and consequently there is no information asymmetry for the agent to exploit. This might be unfavorable for the agent but is clearly favorable for the principal who, nevertheless needs to deal with the monopolist input supplier ( $\pi_P(x; p_1, p_2) = \Phi_P(x; \varphi_1, \varphi_2) < f(x; I_1, I_2)$ ).

Given the results presented above, it is worth stressing the difference between investments undertaken in a transparent supply chain and investments undertaken in a centralized setting. In both settings the aggregate value of the investment opportunity as well as the investment trigger are the same. However, the two frameworks differ significantly since under a transparent supply chain the project originator shares the project with the input supplier. In other words, even under frictionless information sharing, the presence of an agent with market power changes the balance in the supply chain even if this is not translated in distortions in the timing and/or the aggregate value of the investment.

The inequality  $\Pi_{AR}(x; p_1, p_2) < \Pi_{AM}(x; p_1, p_2)$  presents also an interesting result. As we have already discussed in subsection 4.1, in an opaque supply chain the principal uses a menu

<sup>38</sup>Recall that from Eq. (25.2) we have  $\Pi_B(x; p_1, p_2) < V_B(x; I_1, I_2)$ .

of contracts to guarantee that, at the time of the investment, the project manager will truthfully report the magnitude of the sunk investment cost. Furthermore, in line with the relevant literature, we find that the mechanism is costly for the principal ( $\Pi_P(x; p_1, p_2) < \pi_P(x; p_1, p_2)$ ) who has the contractual obligation to, i) pay a positive information rent to the agent if  $p_1$  turns out to be the true input price, or, ii) wait until the inefficiently high investment threshold  $X_2^R(p_1, p_2)$  is reached if  $p_2$  turns out to be the true input price. Apparently however, the distorting effects of the use of the bonus-incentive mechanism are not limited to the principal. The inequality  $\Pi_{AR}(x; p_1, p_2) < \Pi_{AM}(x; p_1, p_2)$  suggests that, even parties that are not involved in the downstream agency conflict are affected by it. In our case for instance, the upstream firm  $A$ , who does not anticipate the investment threshold  $X_2^R(p_1, p_2) (> X_2^M(p_2))$  suffers an ex-ante loss equal to  $\Pi_{AM}(x; p_1, p_2) - \Pi_{AR}(x; p_1, p_2)$ , which is directly reflected in a reduced aggregate value of the opportunity to invest. It is important to stress that this is actually a deadweight loss in the sense that the difference  $\Pi_{AM}(x; p_1, p_2) - \Pi_{AR}(x; p_1, p_2)$  is not funding a bonus-incentive mechanism as for instance is the case with the difference  $\pi_P(x; p_1, p_2) - \Pi_P(x; p_1, p_2)$ . Consequently, when considering the merits of supply chain transparency, one should keep in mind that by making the bonus-incentive mechanism obsolete, supply chain transparency is not only benefiting the principal, but is effectively dealing with the corresponding negative externalities as well.

Finally, given the comparison of the results presented in TABLE 1, we can deduce the following. As already stated above, by definition,  $B$  possesses a relevant expertise. For instance, s/he might be a professional manager with specialized information related to the outsourced input (Mookherjee and Tsumagari, 2004), or s/he might be responsible for the solution of a matching problem if direct communication between the project originator and the input supplier is impossible, or prohibitively expensive (Faure-Grimaud and Martimort, 2001). In cases like these, the level of information sharing among the principal  $P$  and the input supplier  $A$  depends exclusively on the willingness of the intermediary  $B$  to ease communication between the two extreme links of the supply chain. Since according to TABLE 1 the manager has nothing to gain from transparency in the supply chain, one expects to find an agent with these characteristics when studying opaque supply chains.

On the other hand,  $B$  might just be what Hayek (1945) calls the "person on the spot". For instance, McAfee and McMillan (1995) assume that the principal opts for disintegration when the management of the project takes time and the principal's time is limited. Similarly, Van Zandt (1999) argues that the need for delegation might stem from the fixed information processing capacity of the principal. In both cases, the principal is benefiting from disintegration by focusing her/his limited resources on core operations delegating the rest to the agent. Of course, if this is the case, the communication between the input supplier and the principal does not depend on the agent's willingness to behave as an information channel. Consequently, one expects to find agents behaving as "the person on the spot" when studying transparent supply chains.

Last, note that an agent  $B$  who cannot prevent communication between the other two links of the supply chain is a necessary but not sufficient condition for transparency in the supply chain. For instance, in our model we tacitly assume that all the supply chain partners possess the skills to process the shared information costlessly. Nevertheless, this is not necessarily true. In reality, companies might actually need to invest in developing capabilities to utilize the shared information in an effective way. Let's for instance go back to subsection 4.2. There we show that, under traceability, the input supplier  $A$  shares information with  $P$  who is benefited by the updated information endowment gaining the positive difference  $\pi_P(x; p_1, p_2) - \Pi_P(x; p_1, p_2)$ . Now, if  $P$  faces a positive information processing cost larger than this difference, s/he will not make use of the new information endowment and the supply chain will remain opaque in spite of  $A$ 's actions. Equivalently, in subsection 4.3 we show that, under transparency,  $P$  shares information related to process (1) with  $A$  who is benefited by the updated information endowment gaining the positive

difference  $\Phi_A(x; \varphi_1, \varphi_2) - \Pi_{AM}(x; p_1, p_2)$ . However, if  $A$  faces a positive information processing cost larger than this difference, s/he will not make use of the new information endowment in spite of  $P$ 's actions.

## 6 Epilogue

This paper contributes to a growing research area that integrates the theory of irreversible investment under uncertainty and the literature on asymmetric information and agency conflicts. According to this body of papers, when an investment project that is characterized by uncertainty and irreversibility is undertaken in a decentralized setting, the information asymmetry between the project originator and the project manager will lead to an agency conflict. This results in the postponement of the investment and in the reduction of the value of the investment opportunity.

In this paper we examine how the analysis changes if the investment is conditional on the provision of an indispensable input that is outsourced. Using a stochastic dynamic programming model, we identify the cost, the timing and the value of the opportunity to undertake an investment that i) is characterized by uncertainty and irreversibility, ii) is undertaken in a decentralized setting and iii) its completion depends on the provision of a discrete input that is exclusively produced by an upstream firm with market power. Our results suggest that the presence of the external supplier always makes the project more expensive which, other things being equal, implies the suboptimal postponement of the investment as well as a reduced value of the opportunity to invest for the principal, the agent and the industry as a whole. However, the effect of the upstream firm's presence depends heavily on her/his information endowment. Under traceability in the supply chain, i.e., when the structure of the supply chain is common knowledge, the presence of the input supplier restores information symmetry between the principal and the agent. The investment might be more expensive, but the presence of the foreign firm impedes the development of the agency conflict and the associated negative externalities.

Similarly, if the supply chain is transparent, that is, if all the firms in the supply chain can continuously and verifiably observe the realizations of the project's stochastic value over time, then, information symmetry, optimal investment timing and a first-best aggregate value of the opportunity to invest are guaranteed. Nevertheless, a transparent supply chain does not coincide with the first-best case since the aggregate value of the investment opportunity is, under transparency, shared between the principal and the input supplier.

This paper has limitations that can be addressed in future work. Firstly, in our analysis we assumed that traceability and transparency do not require any kind of infrastructure along the supply chain. In reality, information sharing is on its own a demanding and expensive practice. The implementation of a cross-organizational information system is costly, time-consuming and risky. Partners may not agree on the exact specifications of the system or on how to split the relevant investment costs. Secondly, distributional channel phenomena like the bullwhip effect<sup>39</sup> suggest that information sharing is generally subject to a certain level of "noise". This in turn implies that a transparent supply chain is, by construction, unattainable. It could be interesting to reapproach the present analysis taking explicitly into consideration noise in the information channels along the supply chain.

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<sup>39</sup>The bullwhip effect refers to the case where a small shift in the consumer demand causes a distortion between sales and orders which is increasing as we move along the supply chain (Lee et al., 2004).



## A Appendix

### A.1 Information asymmetry and in-house production of the input

Under information asymmetry and in-house production of the discrete input,  $P$  needs to solve the following problem:

$$\max_{\{(X_1^{AI}, w_1); (X_2^{AI}, w_2)\}} \left( \frac{x}{X_1^{AI}} \right)^\beta (X_1^{AI} - w_1 - I_1) + \frac{1-q}{q} \left( \frac{x}{X_2^{AI}} \right)^\beta (X_2^{AI} - w_2 - I_2) \quad (\text{A.1})$$

Subject to:

$$\left( \frac{x}{X_1^{AI}} \right)^\beta w_1 \geq \left( \frac{x}{X_2^{AI}} \right)^\beta (w_2 + \Delta I) \quad (\text{A.2})$$

$$\left( \frac{x}{X_2^{AI}} \right)^\beta w_2 \geq \left( \frac{x}{X_1^{AI}} \right)^\beta (w_1 - \Delta I) \quad (\text{A.3})$$

$$w_1 \geq 0 \quad (\text{A.4})$$

$$w_2 \geq 0 \quad (\text{A.5})$$

$$q \left( \frac{x}{X_1^{AI}} \right)^\beta w_1 + (1-q) \left( \frac{x}{X_2^{AI}} \right)^\beta w_2 \geq 0 \quad (\text{A.6})$$

Working with constraints (A.2) and (A.5) we have:

$$\begin{aligned} \left( \frac{x}{X_1^{AI}} \right)^\beta w_1 &\geq \left( \frac{x}{X_2^{AI}} \right)^\beta (w_2 + \Delta I) \geq \left( \frac{x}{X_2^{AI}} \right)^\beta \Delta I > 0 \\ &\rightarrow \\ w_1 &> 0 \end{aligned}$$

Consequently, constraint (A.4) and constraint (A.6) are slack. This allows us to solve problem (A.1) only subject to constraints (A.2), (A.3) and (A.5). Setting constraint (A.3) aside for now, the Lagrangian is

$$\begin{aligned} L &= \left( \frac{x}{X_1^{AI}} \right)^\beta (X_1^{AI} - w_1 - I_1) + \frac{1-q}{q} \left( \frac{x}{X_2^{AI}} \right)^\beta (X_2^{AI} - w_2 - I_2) \\ &+ \lambda_1 \left[ \left( \frac{x}{X_1^{AI}} \right)^\beta w_1 - \left( \frac{x}{X_2^{AI}} \right)^\beta (w_2 + \Delta I) \right] \\ &+ \lambda_2 w_2, \end{aligned} \quad (\text{A.7})$$

where  $\lambda_1$  is the Lagrangian multiplier that corresponds to constraint (A.2) and  $\lambda_2$  is the Lagrangian multiplier that corresponds to constraint (A.5).

Now, keeping in mind the complementary slackness conditions for the two constraints, we can maximize the Lagrangian with respect to  $X_1^{AI}$ ,  $X_2^{AI}$ ,  $w_1$  and  $w_2$ . The first-order conditions with respect to  $w_1$  and  $w_2$  give  $\lambda_1 = 1$  and  $\lambda_2 = \left( \frac{1-q}{q} + \lambda_1 \right) \left( \frac{x}{X_2^{AI}} \right)^\beta > 0$  respectively. This means that both the incentive compatibility condition (A.2) and the limited liability condition (A.5) are binding, i.e.,

$$w_2 = 0 \quad (\text{A.8})$$

and

$$w_1 = \left( \frac{X_1^{AI}}{X_2^{AI}} \right)^\beta \Delta I. \quad (\text{A.9})$$

Given these, the first-order conditions with respect to the investment thresholds  $X_1^{AI}$  and  $X_2^{AI}$  result in:

$$X_1^{AI}(I_1) = \frac{\beta}{\beta - 1} I_1 \quad (\text{A.10})$$

$$X_2^{AI}(I_1, I_2) = \frac{\beta}{\beta - 1} \left( I_2 + \frac{q}{1 - q} \Delta I \right) \quad (\text{A.11})$$

One can easily show that the derived solutions in Eq. (A.8)-(A.11) satisfy the constraint (A.3) comprising the menu of contracts that  $P$  submits to  $A$ .

## A.2 The investment cost as a continuous variable

In the main body of the paper we use a two-point distribution for the in-house production cost  $I$ . Here we generalize allowing for a continuum of different levels of  $I$  in the interval  $[I_1, I_2]$ . Let  $c(I)$  and  $C(I)$  be the density and the cumulative distribution of  $I$  respectively. The interval  $[I_1, I_2]$  is the support and, consequently,  $C(I_1) = 0$  and  $C(I_2) = 1$ . As in Section 3 and Section 4 of the main body of the paper, we first analyze the case with in-house production of the input and then we consider the case with an external input supplier.

### A.2.1 Information symmetry and in-house production of the input under a continuous distribution of $I$

Following the analysis of subsection 3.2 we know that when the agent has no informational advantage over the principal, it is as if there is no delegation of the investment decision. In this case, the optimization problem that  $P$  needs to solve is given by

$$\max_{X^{CSI}(I)} \left\{ \int_{I_1}^{I_2} (X^{CSI}(I) - I) \left( \frac{x}{X^{CSI}(I)} \right)^\beta dC(I) \right\}. \quad (\text{A.12})$$

Solving pointwise we obtain:

$$X^{CSI}(I) = \frac{\beta}{\beta - 1} I, \text{ for any } I \in [I_1, I_2] \quad (\text{A.13})$$

As expected, Eq. (A.13) is reminiscent of Eq. (4).<sup>40</sup>

### A.2.2 Information asymmetry and in-house production of the input under a continuous distribution of $I$

Following the analysis of subsection 3.3, we now examine the case where the true magnitude of the investment cost is not common knowledge but is instead privately observed by the agent  $B$ . As in subsection 3.3, the principal needs to design a menu of contracts contingent on the observable component  $X_t$ . The only difference with respect to the case that we examine in subsection 3.3

<sup>40</sup>The letter  $C$  in the superscript stands for "continuum" whereas the letters  $SI$  stand for "symmetric information". Also, in line with the assumption according to which investing at time zero is not preferable, we assume  $x < X^{CSI}(I)$ .

is that here the menu is comprised, not by two, but by a continuum of contracts, one for every  $I \in [I_1, I_2]$ . The problem that  $P$  needs to solve is formulated as:

$$\max_{\{X^{CAI(I)}, w^{CAI(I)}\}} \left\{ \int_{I_1}^{I_2} (X^{CAI(I)} - I - w^{CAI(I)}) \left( \frac{x}{X^{CAI(I)}} \right)^\beta dC(I) \right\} \quad (\text{A.14})$$

Subject to:

$$w^{CAI(I)} \left( \frac{x}{X^{CAI(I)}} \right)^\beta \geq (w^{CAI(\tilde{I})} + \tilde{I} - I) \left( \frac{x}{X^{CAI(\tilde{I})}} \right)^\beta \quad (\text{A.15})$$

$$w^{CAI(I)} \geq 0 \quad (\text{A.16})$$

$$\int_{I_1}^{I_2} w^{CAI(I)} \left( \frac{x}{X^{CAI(I)}} \right)^\beta dC(I) \geq 0, \text{ for any } \tilde{I}, I \in [I_1, I_2] \quad (\text{A.17})$$

The objective function in problem (A.14) is the ex-ante value of the opportunity to invest for the principal.<sup>41</sup> The inequalities in (A.15) are the incentive compatibility constraints, the inequalities in (A.16) are the limited liability conditions and inequality (A.17) is the agent's ex-ante participation constraint. The term  $I$  stands for the true, whereas the term  $\tilde{I}$  stands for the reported, level of investment cost.

Following the analysis from Section A.1 of the Appendix and using similar arguments we know that the constraint (A.17) is slack, whereas the constraint (A.16) gives  $w^{CAI(I_2)} = 0$  and  $w^{CAI(I)} > 0$  for every  $I \in [I_1, I_2]$ . The problem that we need to solve is then reduced to:

$$\max_{\{X^{CAI(I)}, w^{CAI(I)}\}} \left\{ \int_{I_1}^{I_2} (X^{CAI(I)} - I - w^{CAI(I)}) \left( \frac{x}{X^{CAI(I)}} \right)^\beta dC(I) \right\} \quad (\text{A.14})$$

Subject to:

$$w^{CAI(I)} \left( \frac{x}{X^{CAI(I)}} \right)^\beta \geq (w^{CAI(\tilde{I})} + \tilde{I} - I) \left( \frac{x}{X^{CAI(\tilde{I})}} \right)^\beta \quad (\text{A.15})$$

$$w^{CAI(I_2)} = 0, \text{ for any } \tilde{I}, I \in [I_1, I_2] \quad (\text{A.18})$$

Let's now focus on the constraints in Ineq. (A.15). It is useful to recall that the information rent is defined as  $w^{CAI}(\tilde{I}, I) = t(\tilde{I}) - I, \forall \tilde{I}, I \in [I_1, I_2]$  where  $I$  is the true investment cost and  $t(\tilde{I})$  is the money transfer from the principal to an agent who reports  $\tilde{I}$ . Now, according to Ineq. (A.15), the quantity  $(t(I) - I) \left( \frac{x}{X^{CAI(I)}} \right)^\beta$  needs to be larger than any quantity  $(t(\tilde{I}) - I) \left( \frac{x}{X^{CAI(\tilde{I})}} \right)^\beta$ ,  $\tilde{I} \neq I$ . Let's now write this using the first and the second order conditions:

**FOC and SOC** Note first that

$$\frac{\partial \left( t(\tilde{I}) - I \right) \left( \frac{x}{X^{CAI(\tilde{I})}} \right)^\beta}{\partial \tilde{I}} = \left( \frac{x}{X^{CAI(\tilde{I})}} \right)^\beta \left( \dot{t}(\tilde{I}) - \beta \left( t(\tilde{I}) - I \right) \frac{\dot{X}^{CAI}(\tilde{I})}{X^{CAI}(\tilde{I})} \right), \quad (\text{A.19})$$

<sup>41</sup>The letter  $C$  in the superscript stands for "continuum" whereas the letters  $AI$  stand for "asymmetric information". Again, in line with the assumption according to which investing at time zero is not preferable, we assume  $x < X^{CAI(I)}$ .

where  $\frac{\partial t(\tilde{I})}{\partial \tilde{I}} \equiv \dot{t}(\tilde{I})$  and  $\frac{\partial X^{CAI}(\tilde{I})}{\partial \tilde{I}} \equiv \dot{X}^{CAI}(\tilde{I})$ . Now, given the first-order derivative from Eq. (A.19), the first-order condition gives:

$$\dot{t}(I) - \beta(t(I) - I) \frac{\dot{X}^{CAI}(I)}{X^{CAI}(I)} = 0 \quad (\text{A.20})$$

where  $\frac{\partial t(\tilde{I})}{\partial \tilde{I}} \Big|_{\tilde{I}=I} = \dot{t}(I)$  and  $\frac{\partial X^{CAI}(\tilde{I})}{\partial \tilde{I}} \Big|_{\tilde{I}=I} = \dot{X}^{CAI}(I)$ . The second-order derivative is:

$$\frac{\partial^2 \left( t(\tilde{I}) - I \right) \left( \frac{x}{X^{CAI}(\tilde{I})} \right)^\beta}{\partial \tilde{I}^2} = \quad (\text{A.21})$$

$$\left( \frac{x}{X^{CAI}(\tilde{I})} \right)^\beta \left[ \begin{aligned} & -\beta \frac{\dot{X}^{CAI}(\tilde{I})}{X^{CAI}(\tilde{I})} \left( \dot{t}(\tilde{I}) - \beta \left( t(\tilde{I}) - I \right) \frac{\dot{X}^{CAI}(\tilde{I})}{X^{CAI}(\tilde{I})} \right) + \\ & \left( \ddot{t}(\tilde{I}) - \beta \left( \dot{t}(\tilde{I}) \frac{\dot{X}^{CAI}(\tilde{I})}{X^{CAI}(\tilde{I})} + \left( t(\tilde{I}) - I \right) \frac{\dot{X}^{CAI}(\tilde{I}) X^{CAI}(\tilde{I}) - \dot{X}^{CAI}(\tilde{I})^2}{X^{CAI}(\tilde{I})^2} \right) \right) \end{aligned} \right]$$

From the second-order condition and keeping in mind Eq. (A.20) we have:

$$\ddot{t}(I) - \beta \left( \dot{t}(I) \frac{\dot{X}^{CAI}(I)}{X^{CAI}(I)} + (t(I) - I) \frac{\ddot{X}^{CAI}(I) X^{CAI}(I) - \dot{X}^{CAI}(I)^2}{X^{CAI}(I)^2} \right) \leq 0 \quad (\text{A.22})$$

Last, from the first-order condition we have:

$$\frac{\partial \left( \dot{t}(I) - \beta(t(I) - I) \frac{\dot{X}^{CAI}(I)}{X^{CAI}(I)} \right)}{\partial I} = 0 \quad (\text{A.23})$$

$$\rightarrow$$

$$\ddot{t}(I) - \beta \dot{t}(I) \frac{\dot{X}^{CAI}(I)}{X^{CAI}(I)} - \beta(t(I) - I) \frac{\ddot{X}^{CAI}(I) X^{CAI}(I) - \dot{X}^{CAI}(I)^2}{X^{CAI}(I)^2} = -\beta \frac{\dot{X}^{CAI}(I)}{X^{CAI}(I)}$$

From Ineq. (A.22) and Eq. (A.23) we obtain:

$$\dot{X}^{CAI}(I) \geq 0 \quad (\text{A.24})$$

This is a standard monotonicity constraint.<sup>42</sup> Last, applying the envelope theorem we obtain:

$$\frac{\partial (t(I) - I) \left( \frac{x}{X^{CAI}(I)} \right)^\beta}{\partial I} = - \left( \frac{x}{X^{CAI}(I)} \right)^\beta \quad (\text{A.25})$$

**Rewriting the problem** Using Ineq. (A.24) and Eq. (A.25) we can rewrite the problem in the following way:

$$\max_{\{X^{CAI}(I), w^{CAI}(I)\}} \left\{ \int_{I_1}^{I_2} (X^{CAI}(I) - I - w^{CAI}(I)) \left( \frac{x}{X^{CAI}(I)} \right)^\beta dC(I) \right\} \quad (\text{A.14})$$

Subject to:

$$\dot{X}^{CAI}(I) \geq 0 \quad (\text{A.24})$$

$$\frac{\partial (t(I) - I) \left( \frac{x}{X^{CAI}(I)} \right)^\beta}{\partial I} = - \left( \frac{x}{X^{CAI}(I)} \right)^\beta \quad (\text{A.25})$$

$$w^{CAI}(I_2) = 0 \quad (\text{A.18})$$

<sup>42</sup>See Chapter 2 from Laffont and Martimort (2002) for more details. One can easily check that the monotonicity holds also when  $I$  is a discrete random variable.

Now, from Eq. (A.25) and Eq. (A.18) we have:

$$(t(I) - I) \left( \frac{x}{X^{CAI}(I)} \right)^\beta = \int_I^{I_2} \left( \frac{x}{X^{CAI}(\nu)} \right)^\beta d\nu \quad (\text{A.26a})$$

$$w^{CAI}(I) \left( \frac{x}{X^{CAI}(I)} \right)^\beta = \int_I^{I_2} \left( \frac{x}{X^{CAI}(\nu)} \right)^\beta d\nu \quad (\text{A.26b})$$

Using Eq. (A.26), the objective function from problem (A.14) becomes:

$$\int_{I_1}^{I_2} \left[ \left( X^{CAI}(I) - I - \frac{C(I)}{c(I)} \right) \left( \frac{x}{X^{CAI}(I)} \right)^\beta \right] dC(I) \quad (\text{A.27})$$

Using this expression we can rewrite the problem as:

$$\max_{X^{CAI}(I)} \left\{ \int_{I_1}^{I_2} \left[ \left( X^{CAI}(I) - I - \frac{C(I)}{c(I)} \right) \left( \frac{x}{X^{CAI}(I)} \right)^\beta \right] dC(I) \right\} \quad (\text{A.28})$$

subject to,

$$\dot{X}^{CAI}(I) \geq 0. \quad (\text{A.24})$$

Momentarily ignoring the monotonicity constraint (A.24), we solve the maximization problem (A.28) pointwise and we obtain

$$X^{CAI}(I) = \frac{\beta}{\beta - 1} \left( I + \frac{C(I)}{c(I)} \right), \text{ for any } I \in [I_1, I_2]. \quad (\text{A.29})$$

From Eq. (A.29) we see that there is no timing distortion when the investment cost  $I$  takes its minimum value (since  $C(I_1) = 0$ ), whereas there is an upward distortion for any  $I \in (I_1, I_2]$ . Of course, the  $X^{CAI}(I_1) = X^{CSI}(I_1)$  and  $X^{CAI}(I) > X^{CSI}(I), \forall I \in (I_1, I_2]$  are symmetric to the  $X^{AI}(I_1) = X^{SI}(I_1)$  and  $X_2^{AI}(I_1, I_2) > X_2^{SI}(I_2)$  that we derived in subsection 3.3 of the main body of the paper.

The last thing that we need to check is under what conditions our solution respects the monotonicity constraint (A.24). From Eq. (A.29) we have

$$\dot{X}^{CAI}(I) = \frac{\beta}{\beta - 1} \left( 1 + \frac{\partial}{\partial I} \left( \frac{C(I)}{c(I)} \right) \right).$$

The monotone hazard rate property  $\frac{\partial}{\partial I} \left( \frac{C(I)}{c(I)} \right) \geq 0$  is a sufficient condition for  $\dot{X}^{CAI}(I) \geq 0$  to hold. This condition is satisfied by most parametric single-peak densities (see Bagnoli and Bergstrom, 2005).

Last, note that from Eq. (A.26) we can also derive the relevant information rent:

$$w^{CAI}(I) = \int_I^{I_2} \left( \frac{X^{CAI}(I)}{X^{CAI}(\nu)} \right)^\beta d\nu, \text{ for any } I \in [I_1, I_2] \quad (\text{A.30})$$

In words, the menu of contracts designed by  $P$  is built in such a way that for any  $I \in [I_1, I_2]$  a positive information rent is to be paid. The information rent is equal to zero only when  $I$  takes its maximum value ( $w^{CAI}(I_2) = 0$ ). As one can notice, this is symmetric to  $w_1 > 0$  and  $w_2 = 0$  from subsection 3.3 of the main body of the paper.

### A.2.3 The presence of an upstream supplier

When an upstream supplier is responsible for the provision of the needed input, we can distinguish between two separate cases:

- If there is no information asymmetry downstream (subsection 4.2 and 4.3 of the main body of the paper), no information rent is paid to the project manager.

More precisely, under traceability (subsection 4.2), the price of the input is derived as the solution of

$$\max_{p_I} \int_{I_1}^{I_2} (p_I - I) \left( \frac{x}{X^{CM}(p_I)} \right)^\beta dC(I), \quad (\text{A.31})$$

where  $X^{CM}(p_I) = \frac{\beta}{\beta-1}p_I$ , for any  $I \in [I_1, I_2]$ . Note that  $X^{CM}(p_I)$  is identical to  $X^{CSI}(I)$  from Eq. (A.13) if instead of  $I$  we use  $p_I$ .<sup>43</sup> Solving, we obtain

$$p_I = \frac{\beta}{\beta-1}I, \text{ for any } I \in [I_1, I_2]. \quad (\text{A.32})$$

In this case, the value of the opportunity to invest for the principal  $P$  is equal to

$$\pi_P(x; p.) = \int_{I_1}^{I_2} (X^{CM}(p_I) - p_I) \left( \frac{x}{X^{CM}(p_I)} \right)^\beta dC(I), \quad (\text{A.33})$$

whereas the value of the opportunity to invest for the upstream firm  $A$  is equal to

$$\Pi_{AM}(x; p.) = \int_{I_1}^{I_2} (p_I - I) \left( \frac{x}{X^{CM}(p_I)} \right)^\beta dC(I).<sup>44</sup> \quad (\text{A.34})$$

Under a transparent supply chain (subsection 4.3), that is when  $A$  observes continuously and verifiably the evolution of the stochastic term, the price of the input is derived as the solution of

$$\max_{\varphi_I} \int_{I_1}^{I_2} (\varphi_I - I) \left( \frac{x}{X^{CSI}(I)} \right)^\beta dC(I), \quad (\text{A.35})$$

subject to,

$$(X^{CSI}(I) - \varphi_I) \left( \frac{x}{X^{CSI}(I)} \right)^\beta \geq \Psi_I, \text{ for any } I \in [I_1, I_2]. \quad (\text{A.36})$$

Similarly to what we have in subsection 4.3 of the main body of the paper, the term  $\varphi_I$  stands for the price of the input and the term  $\Psi_I$  is the chosen reservation value. Using similar argumentation, we choose  $\Psi_I = (X^{CM}(p_I) - p_I) \left( \frac{x}{X^{CM}(p_I)} \right)^\beta$  and solving we obtain:

$$\varphi_I = \frac{\beta}{\beta-1}I \left( 1 - \frac{(\beta-1)^{\beta-1}}{\beta^\beta} \right), \text{ for any } I \in [I_1, I_2]. \quad (\text{A.37})$$

Finally, the values for the two parties are

$$\Phi_P(x; \varphi.) = \int_{I_1}^{I_2} (X^{CAI}(I) - \varphi_I) \left( \frac{x}{X^{CAI}(I)} \right)^\beta dC(I), \quad (\text{A.38})$$

<sup>43</sup>The symmetry between  $X^{CM}(p_I)$  and  $X^{CSI}(I)$  is reminiscent of the symmetry between  $X_i^M(p_i)$  and  $X_i^{SI}$  (see subsection 4.1 of the main body of the paper).

<sup>44</sup>The term  $p.$  stands for the continuum of input prices that corresponds to the continuum of investment costs.

and

$$\Phi_A(x; \varphi.) = \int_{I_1}^{I_2} (\varphi_I - I) \left( \frac{x}{X^{CSI}(I)} \right)^\beta dC(I), \quad (\text{A.39})$$

for the principal and for the agent respectively.<sup>45</sup> Last,

- If the supply chain is opaque (subsection 4.1 of the main body of the paper), we can use Eq. (A.32) as our starting point and reapproach the analysis of subsection A.2.2 deriving an updated menu of a continuum of contracts. Of course, this new menu of contracts will be totally symmetric to the one that we derived in subsection A.2.2 as the menu of contracts in (19) is totally symmetric to the menu of contracts in (12).

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<sup>45</sup>The term  $\varphi.$  stands for the continuum of input prices that corresponds to the continuum of investment costs.

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