A Theoretical Model of Radical Technological Change in Industrial Networks and Implications for a Green Technological Transition

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Abstract

The literature on technological change has studied several types of positive externalities leading to sub-optimal levels of development and adoption of technologies. In this paper, we suggest another type of positive externality: supplier network externality. In this case, the cost of producing a new technology to one final producer may depend on how many other final producers are deploying similar technologies. Specifically, production costs decrease as several final producers source similar inputs from shared suppliers, generating economies of scope. To illustrate the mechanism, we develop a stylized model of two final producers with a shared supplier. We introduce the possibility that final producers innovate in incompatible ways requiring very different inputs from the supplier. This triggers a loss in economies of scope and redLately, the fight against climate change has called comparison to JFK's moonshot, highlighting the usefulness of goal-setting and planning (Sachs, 2015). uces the equilibrium level of innovation. We argue that the model has implications for a green technological transition. In this case, lock-in situations can lead to market failures since green innovations are socially desirable. We use supply-chain relationship data toshow that our model is of particular relevance to the car manufacturing industry. Additionaly, we highlight how our results help unify several findings from several case studies.

JEL: Q55, Q58, L14, L52, O31, O33

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Contents

1 Introduction and Background

There exists various positive externalities impeding the process of technological change at both the innovation and diffusion stages (Jaffe et al., 2005, 2003). Those externalities usually justify the use of technology-push policies even though the precise type of policy is often debated (Steinmueller, 2010). The market failure most commonly discussed in technology policy relates to the public good aspect of knowledge, and the early literature on this topic has demonstrated the need for subsidizing basic research efforts (Stephan, 2010; Rockett, 2010) Attention has also focused on issues faced by adopters such as dynamic increasing returns in learning-by-using and user network effects (Liebowitz and Margolis, 1994; Farrell and Klemperer, 2007)[1].

In a seminal paper, David (1985) discusses the factors that led QWERTY to become "locked in" as the dominant keyboard arrangement: compatibility issues between a given keyboard and the typist's training, economies of scale, and quasi-irreversibility of investment. Those factors induced QWERTY's user costs to tend to decrease as it gained in acceptance relative to other systems, leading to the quasi-universal adoption of only one keyboard. Network effects create multiple equilibria: users' expectations are often crucial in determining which network succeeds, and early preferences and information are likely to play an excessive role in determining long-term outcomes. For this reason, the QWERTY example has sometimes regarded as the 'founding myth' of the path dependence literature (Ruttan, 1997).

Beyond issues of adoption by end-users, there is the growing recognition that manufacturing is a critical locus of the innovation process. Proofs of concept are not sufficient to guarantee success in manufacturing; product development through pilot and large-scale testings provide opportunities for valuable learning and adjustment that are critical to the in-

[1] Notable papers in this literature include (Farrell and Saloner, 1985, 1986; Katz and Shapiro, 1985, 1986, 1994; Besen and Farrell, 1994; David, 1997).

novation process (Bonvillian, 2013). Learning and adjustments seem even more so important as products most often constitute complex combinations of components supplied by different firms (Fuchs, 2014). This is a time where all suppliers and producers make essential investments towards the development of a new product. However, the most commonly discussed positive externality faced by producers, learning-by-doing, is a type of dynamic increasing returns that is internal to the firm (Thompson, 2010); it remains blind to relationships between final producers and suppliers.

The importance of relationships between a final producer and its suppliers for innovation is widely acknowledged. Jorde and Teece (1990), for example, argue that low levels of cooperation between firms result in low levels of innovation. Additionally, a large part of contract theory studies how the ability to contract between suppliers and buyers affects investment, and therefore innovation (Blanchard and Kremer, 1997; Gilson et al., 2009; Chen and Sappington, 2011). But this literature has focused on producer-supplier relationships within a linear vertical supply chain. It has yet to investigate the role that more complex industrial networks[2] can play in fostering or hindering technological change.

The importance of such networks for various economic phenomena, for aggregate output and trade, in particular, is gradually being recognized; and efforts to describe them theoretically and empirically are increasing (Oberfield, 2012; Atalay et al., 2011; Carvalho, 2014; Acemoglu et al., 2012). A 2008 Senate hearing testimony illustrates the critical role of shared suppliers: Ford's CEO advocated for the bailout of General Motors and Chrysler, Ford's principal competitors to protect their shared suppliers[3] (Carvalho, 2014).

In this paper, we investigate how supply-chain network charateristics impact firms' ambition to innovate. We develop a theoretical model to illustrate a new type of positive

[2]More complex than just a linear node between a final producer and a supplier; for example when two competitors share suppliers

[3]Mulally (2008): 'In addition, the collapse of one of our competitors would have a severe impact on Ford and our transformation plan because the domestic auto industry is highly interdependent. It would also have devastating ripple effects across the entire U.S. economy'.

externality where the cost of producing a new technology to one final producer may depend on how many other final producers are deploying similar technologies. We call such externalities *supplier network externalities*.

We build our model on two main assumptions. First, we assume economies of scope in the supplier's technology. Consequently, the cost of producing intermediate inputs decreases with the number of final producers sourcing similar inputs. Second, we assume that economies of scope may be lost when innovations require complementary investments from producers and suppliers. This is because producers might innovate in ways that are incompatible for the supplier. In what follows, we define *radical innovations* as innovations requiring investments from producers *and* suppliers (complementary investments).

The supplier network externality, hence, produces a positive externality leading to increasing returns in the numbers of producers deploying radical innovations. That is to say, producer 1 has more returns from deploying radical innovations if producer 2 does as well and they can coordinate. In other words, unless all incumbent buyers switch to similar competing technologies and therefore buy the same new intermediate input, the supplier will lose part or all of her economies of scope. Our model, therefore, shows that shared suppliers can be reluctant to engage in radical innovations. But coordinating producers' innovation strategies would encourage shared suppliers to innovate.

A further implication of network externalities is that lock-in situations may arise, especially if barriers to moving to alternative competing technologies are high. In that case, then, producers would display excess inertia by waiting too long before switching. Absent of coordination, such lock-in situations would lead to market failures when it is socially desirable to adopt a technological path different from the one that has been chosen by the market.

We argue that this may be the case in the context of green innovations, where the primary policy instrument to encourage innovation has been market instruments, which are not designed to solve coordination problems. First, we argue that many of the technologies needed

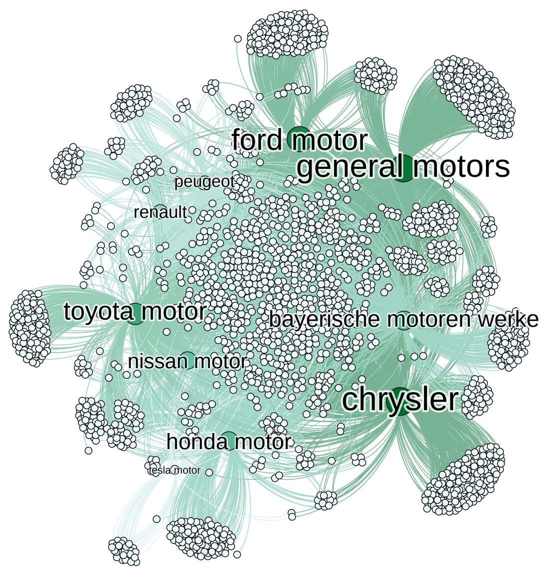


Figure 1: Supplier Network for Ten Car Manufacturers

Note: Each green bond denotes a buyer-supplier relationship. Nodes in the center are shared among two or more prodocers.

to decarbonize the economy qualify as *radical*, and particularly in the car manufacturing sector. Second, we argue that our model is particularly relevant for this industry by showing that automakers often share suppliers. To do this, we use a database of buyer-supplier relationships, FactSet. Figure 1 illustrates the centrality of many suppliers. Finally, we show how our result helps unify several findings from case studies on the automotive industry.

The following section describes our theoretical framework, and Section 3 summarizes the main results. In Section 4, we discuss implications for a green technological transition.

2 Theoretical Framework

We model a network of two final producers (denoted by subscript 1 and 2, respectively) and one shared supplier (denoted by subscript S). Each final producer manufactures a good using inputs from the supplier. The demand function for the goods is derived from a model of discrete-choice demand that appropriately describes industries such as car manufacturing where typically products are differentiated, and consumers choose only one of the competing products (Anderson et al., 1992). In such model, good 1 and good 2 are competing products which differ in their quality a_1 and a_2. Aggregate demand for product 1 with quality a_1 is shown in Equation 1. U_0 is the utility derived from the outside option; M is the number of consumers (the size of the market); μ is the scale parameter of the i.i.d. type 1 extreme values distribution of $\{\epsilon_{kj}\}$ where ϵ_{kj} represents the idiosyncratic preference of consumer k for good j.

$$q_1(p_1, p_2, a_1, a_2) = \frac{e^{\frac{a_1 - p_1}{\mu}}}{e^{U_0} + e^{\frac{a_1 - p_1}{\mu}} + e^{\frac{a_2 - p_2}{\mu}}}.M \tag{1}$$

Since product 1 and 2 result from collaborations between a final producer and its supplier, improving the quality a_j can be done by either of the firms on their own or co-jointly with complementary investments. We build on the observation that some innovations require little change to the components of the previous product. For example, commercializing a fuel-efficient car requires changes within the engine, but all other components roughly remain the same. Producing a fuel-cell electric car, however, requires changes to many components (Zapata and Nieuwenhuis, 2010) produced by different firms. Following this example, we think of radical innovations as innovations that require investments from multiple firms because the skills, knowledge, and/or inputs that are necessary to deploy the innovation are not present within the firm[4].

[4]In that sense, a technology might be radical only in relation to a particular organization (Soskice, 1997;

In the model, firms choose the degree of radicalness for a new product. We can also think of radicalness as the degree of "common effort" required to develop the new product (common within the supply chain). The more common effort required, the more radical the technology. Formally, we denote z_j the degree of "radicalness" that firm j chooses for a particular innovation, where $z \in [0;1]$. If z_j equals zero, firm j chooses not to develop innovations requiring investments from other firms in the supply chain. The firm makes unilateral investments to innovate on the final product "on its own", and we can think of the innovation as being *marginal*.

In contrast, when $z_j > 0$, the innovation can be thought of as *radical* in the sense that it requires investments from multiple actors of the supply chain. As z_j increases, the ambition regarding how radical the innovation is, increases. All firms, including the supplier, independently choose z_j. However, only the lowest degree of "radicalness" wished by all actors can be implemented. We denote $\hat{z}_j$ the resulting degree of "radicalness" in the supply chain of producer j; Equation 2 displays its formal expression.

$$\hat{z}_j = \min\{z_j, z_S\} \tag{2}$$

We assume that innovations with more ambitious common effort bear the promise of higher quality a_j and ceteris paribus, higher profits. Formally, as shown in Equation 3, a_j linearly increases with $\hat{z}_j$ according to a positive constant β. We impose that $\beta > 0$ to capture the idea that more ambitious innovations, while requiring more concerted efforts, also yield higher quality.

$$a_j(\hat{z}_j) = \beta \hat{z}_j, \tag{3}$$

Deploying an innovation also requires to pay for the actual investments: we take these as

Teece, 1986) and the knowledge and skills for the technology exist in another firm or research laboratory.

a fixed cost whose magnitude increases with the degree of "common effort". We denote R_i and R_j the fixed costs for, respectively, supplier i and final producer j.

$$\begin{cases} R_j = R_P \hat{z}_j \\ R_i = R_S \hat{z}_j \end{cases} \tag{4}$$

The variable cost for final producers is a function of the quantity demanded and is denoted $C_j(q_j)$, where q_j is a function of $p_1, p_2, \hat{z}_1$ and $\hat{z}_2$. We impose $\frac{\partial^2 C_j}{\partial q_j^2} \leq 0$ (e.g., $C_j = c * q_j$ where c is a positive constant).

We introduce the possibility that final producers might do radical innovations in ways that are very different from each other and which impose on the supplier the need for producing very different inputs. We can think of this in terms of *multiple technological directions.* For example, if producer 1 chooses to invest in plug-in electric cars, while producer 2 in hybrid vehicles or hydrogen cars. For the supplier, such directions are not compatible and will require different inputs.

Whether or not final producers innovate in the same direction is a move of nature; we denote θ the probability that they do not. This is what we call *miscoordination.* The realization of θ will impact the cost function of the supplier, C_S. To capture the effect, we assume it is a CES function. The formal expression is shown in Equation 5: k $\in [0; 1]$ is a parameter governing the returns to scale; and $\rho \in [0; 1]$ is a parameter governing the extent to which the inputs produced by the supplier are substitutable in the cost function. Remember that q_1 is a function of $p_1, p_2, \hat{z}_1$ and $\hat{z}_2$.

$$C_S(q_1, q_2) = \left(q_1^\rho + q_2^\rho\right)^{\frac{k}{\rho}}, \tag{5}$$

The move of nature regarding the coordination of the producers impacts ρ such that under miscoordination, inputs are less and less substitutable in the cost functions as $\hat{z}_j$ increases.

Consequently, the supplier loses economies of scope. Under coordination, inputs are purely substitutable ($\rho = 1$). Hence, we have the following cost functions.

$$C_S(q_1, q_2) = \begin{cases} C_S^M(q_1, q_2) = \left(q_1^\rho + q_2^\rho\right)^{\frac{k}{\rho}} \text{ and } \rho = 1 - \sigma \hat{z}_j \text{ , with probability } \theta \text{ (Miscoordination)} \\ C_S^C(q_1, q_2) = (q_1 + q_2)^k \text{ , with probability } 1 - \theta \text{ (Coordination)} \end{cases} \tag{6}$$

We assume incomplete contracts between suppliers and producers. Hence, each player chooses their level of innovative investment independently, sharing revenues ex-post. We assume firms split revenues equally and we call s_j the share received by the final producer j. In our model $s_j = 0.5$ since we have only one supplier shared between two producers.

The sequence of the game is as follows. 1) All players choose the radicalness z, which determines the quality $a_j = \beta * min\{z_j, z_S\}$ for each final product. 2) A move of nature determines the marginal costs of production of the shared suppliers. 3) Producers choose the price of their products. 4) Revenues are divided between producers and suppliers according to the shares s_j.

3 Results

3.1 Nash Equilibria of the Innovation Game

In this section, we characterize the Nash equilibrium of the innovation game. We find that, if any level of radical innovation is profitable for one of the producers, given the radicalness of the other producer's innovation, then this producer innovates at the maximal level of radicalness. However, the supplier's choice constrains the producers and eventually determines the Nash equilibrium in this 3-player system.

3.1.1 Best Responses in the Two-Producer Game

We first consider the innovation game between the two competing producers, assuming that there is no supplier (or equivalently that the supplier innovates at the same level as each of the producers). Remark 1 below establishes the best response of producer 1 to the innovation level of producer 2, and vice versa. Π_j denotes the profit of firm j.

Remark 1. *We can distinguish two cases:*

- *Either* $\Pi_1(z_1, z_2) < \Pi_1(0, z_2),\ \forall\ z_1, z_2$.
  In this case the best response is $z_1^{BR}(z_2) = 0$.

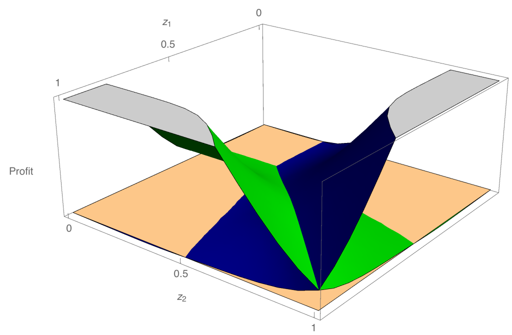
- *Or* $\exists\ \underline{z}_1$ *s.t.* $\Pi_1(z_1, z_2) \geq \Pi_1(0, z_2)$ *and* $\frac{\Pi_1(z_1,z_2)}{dz_1} > 0,\ \forall\ z_1 \geq \underline{z}_1, \forall z_2$.
  In this case, the best response is $z_1^{BR}(z_2) = 1$.

Figure 2 illustrates Remark 1. Panel 2a shows how the profit surfaces $\Pi_1(z_1, z_2)$ and $\Pi_2(z_1, z_2)$ vary with z_1 and z_2. For example, $\Pi_1(z_1, z_2)$ initially decreases[5] and then increases with z_1, becoming positive above some threshold value that depends on z_2. Panel 2b plots these threshold functions $\underline{z}_1(z_2)$ and $\underline{z}_2(z_1)$ in the (z_1, z_2) plane to identify regions where each producer can profit from doing radical innovation. For example, the blue curve $\underline{z}_1(z_2)$ delimits the area where profits for producer 1 are higher than the profits accrued if $z_1 = 0$. We note that the curve crosses the y-axis below the top right corner: for any z_2 beyond that point, there exists no z_1 such that producer 1 profits can have profits higher than with $z_1 = 0$. Hence the best response is $z_1 = 0$. We thickened the top part of the left y-axis in blue to symbolize this. On the other hand, to the right of the blue curve, we know that Π_1 increases with z_1 and therefore the best response level of innovation is 1. Depending on the parameters, the two curves may or may not cross. Figure 3 illustrates several possible cases. Assuming they cross, it is useful for what follows to denote $\zeta^{\mathbf{L}}$ and $\zeta^{\mathbf{U}}$ the locus of these intersections.

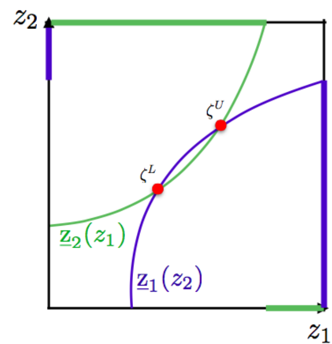
3.1.2 Nash Equilibria in the Two-Producer Game

The possible Nash equilibria of the 2-producer game follow from Remark 1 and are illustrated on 3.

[5]This is difficult to see on the graph, but the surfaces first go down below the pink horizontal plane.



(a) Example of profit surfaces as a function of the radicalness of innovations. The surface on the left-hand side corresponds to Π_1. The surface on the right-hand side corresponds to Π_2. $\Pi_1(z_1, z_2)$ initially decreases with z_1 and then increases with z_1, becoming positive above some threshold value that depends on z_2.



(b) The functions $\underline{z}_1(z_2)$ and $\underline{z}_2(z_1)$ above describe the threshold values above which profits is larger than when choosing $z = 0$. The thick lines represents the best response values for each player.

Figure 2: The profit functions and best response functions.

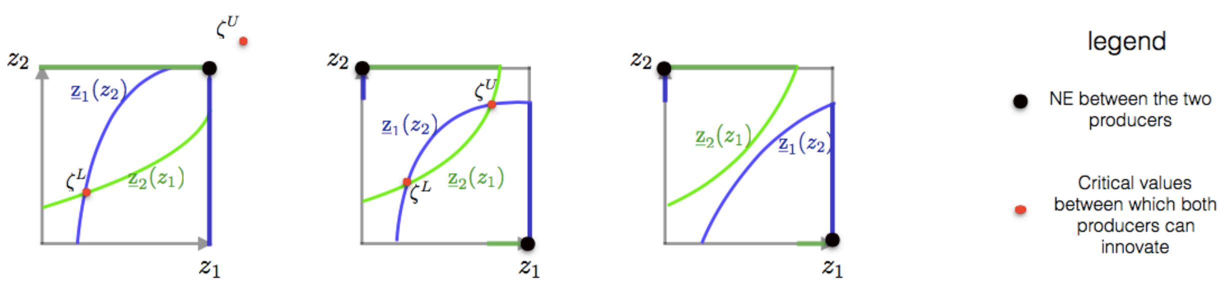


Figure 3: Diagrams showing different cases of Figure 2a. The bold and opaque colored lines represent the best response functions of both producers. The large black dots represents the resulting Nash Equilibrium.

Remark 2. *Assuming that* $\exists\ \underline{z}_j(0) \in [0,1]$ *for* $j \in (1,2)$*, we can distinguish two possible cases:*

- *there is a unique NE equal to* $(1,1)$ *iff* $\zeta^{\mathbf{U}} \geq (1,1)$
- *there are two NE equal to* $(0,1)$ *and* $(1,0)$ *if* $\zeta^U < (1,1)$ *or if* ζ^U *does not exist.*

The assumption that $\exists\ \underline{z}_j(0) \in [0,1]$ for $j \in (1,2)$ simply rules out scenarios in which the profit surfaces are positive in no part of the (z_1, z_2) in Figure 2. In other words, we consider cases where, at the very least, producer 1 would profit from innovating when producer 2 choose not to innovate. Remark 2 says that the NE is unique and equal to $(1,1)$ if and only if both producers find it profitable to innovate at the maximal level $z = 1$ simultaneously. Otherwise, we have an anti-coordination game, in which one of the producers innovates maximally, and the other producer innovates only marginally ($z = 0$).

3.1.3 Nash Equilibrium in the 3-Player Game

We are now ready to bring in the shared supplier. To simplify the analysis, we will focus on the first case above, where the NE of the 2-producer game is unique and equal to $(1,1)$. Note that the first diagram in Figure 3 illustrates this case. This allows us to focus on the case where, in the absence of supplier-buyer relationships, producers would both wish to innovate maximally. This approach presents the advantage of isolating the effects of those structural factors[6]. We also start with the symmetric case, in which producers have the same costs. We denote z_1, z_2 and z_S the levels of radicalness chosen by producer 1, 2 and the supplier, respectively.

[6]The reason it also simplifies the analysis is because, when $\zeta^{\mathbf{L}}$ and $\zeta^{\mathbf{U}}$ exist and lie within $[0,1] \times [0,1]$, then the supplier can pick between different types of equilibria.

Remark 3. *The Nash Equilibrium* (z_1, z_2, z_S) *of the 3-player innovation game is:*

$$\begin{cases} (z_S^{max}, z_S^{max}, z_S^{max}) & \textit{iff } \zeta^L \leq z_S^{max} \\ (\zeta^L, \zeta^L, \zeta^L) & \textit{iff } z_S^{max} < \zeta^L < \bar{z}_S \\ (0,0,0) & \textit{iff } \bar{z}_S < \zeta^L \textit{ or } \Pi_S(z_S^{max}) < \Pi_S(0) \end{cases}$$

where z_S^{max} *is the radicalness level that maximizes the expected profits of the supplier,* $E[\Pi_S(z_S, z_S, z_S)]$*, and* $\bar{z}_S$ *is the threshold value above which expected profits of the supplier are negative. We use the notation* ζ^L *to denote* $\underline{z}_j(\zeta^L)$ *for* $j \in (1,2)$ *where* ζ^L *is the point dividing the region where producers invest in innovation and the region where they don't.*

Figure 4 illustrates Remark 3. As shown before, when producers do not depend on a supplier, they invest $z = 1$. Now, with a shared supplier and the assumption that the effective level of radicalness for producer j is whichever is lowest among the producer's and the supplier's desired levels ($\hat{z}_1 = min\{z_1, z_S\}$), the optimal investment level is z_S^{max}, as long as $z_S^{max} \geq \zeta^L$. The supplier faces an inequality constrained optimization problem: pick z_S such that $z_S \geq \zeta^L$ and such that her own profit is higher than with a marginal innovation level $z_S = 0$. Let's focus our attention to the 45 degree line on Figure 4. This line represents the supplier's choice, z_S. Along this line, we plotted Π_S, the supplier's profit function: it first decreases, then increases, reaching a maximum at z_S^{max}, and finally decreases turning negative at $\bar{z}_S$. If $z_S^{max} \geq \zeta^L$, it is feasible and induces $(z_S^{max}, z_S^{max}, z_S^{max})$ as NE. If $z_S^{max} < \zeta^{\mathcal{L}}$, but $\bar{z}_S$ is still greater than ζ^L, then the supplier chooses $z_S = \zeta^L$. Finally, if $\bar{z}_S < \zeta^L$, then the NE is $(0, 0, 0)$.

3.2 Effects of Miscoordination

We are now ready to state the main results regarding the effects of miscoordination between producers. We start with the finding that, as the probability of miscoordination θ increases,

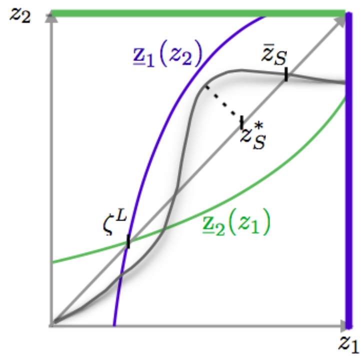


Figure 4: Diagram overlaying the supplier's profit function on the (z_1, z_2) plane. The order of the three points ζ^L, z_S^{max} and $\bar{z}_S$ determines the Nash Equilibrium of the three-player game described in Remark 3

the NE level of innovation decreases.

Result 1. *In the symmetric case, as the probability of miscoordination, θ, increases, z_S^* decreases and, by Remark 2, so do the equilibrium innovation levels of both supply chains.*

When θ increases, the probability that both producers innovate in different directions increases. When this happens, suppliers must produce different types of inputs for each of the producers and they become more vulnerable to losing economies of scope. Since higher radicalness leads to greater specificity in the inputs and thereby larger losses on economies of scope, suppliers decrease their ambition of radicalness. In the model, we capture the sensitivity of the production process to this miscoordination by σ; the coefficient governs by how much radicalness affects the elasticity of substitution between the components supplied to both value chains in the case of miscoordination. Figure 5 illustrates these dynamics for specific parameter values. We note that, first, z_S^* decreases slowly; then comes a value of θ above which the supplier prefer zero degree of radicalness.

In what follows, we show that Result 1 is sensitive to the importance of economies of scale in the supplier's production process.

Result 2. *As the supplier's economies of scale increase, the negative impact of miscoordi-*

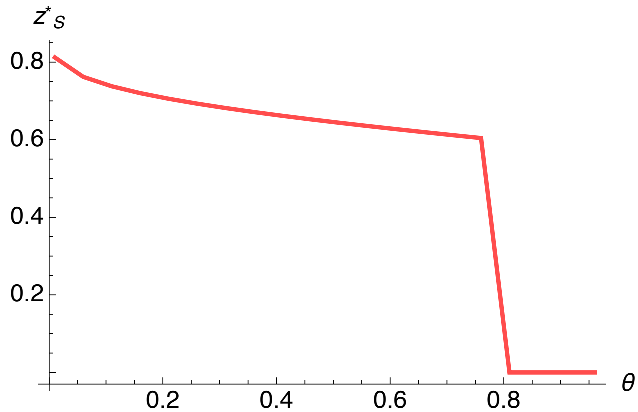


Figure 5: Change in z_S^* as a function of θ, in the 3-player case. The parameters describing the cost function of the supplier are $k = 1$, $\sigma = .9$

nation on radicalness decreases. Formally: $\frac{d^2 z_S^*}{d\theta\ dk} < 0$.

The reason for this result is that large economies of scale reduce the importance of production costs in the supplier's calculus. Also, because more radical innovation leads to higher demand and, therefore, greater production and greater economies of scale which can compensate the loss in economies of scope, or even diseconomies of scope.

Hence, we have explored how the probability that competing producers miscoordinate in the direction of innovation can reduce the overall radicalness of innovation in the industry. In particular, we have shown that the choice of shared suppliers determines the equilibrium level of innovation (in the setting where all actors make simultaneous decisions). If suppliers enjoy economies of scope, and if those can be lost under radical innovation when producers miscoordinate, then suppliers will choose less ambitious innovations.

In what follows, we discuss implications of the model for green technological transitions with a focus on the car manufacturing sector. In particular, we consider possible mechanisms to foster coordination of industrial actors.

4 Implication for a Green Technological Transition

4.1 Climate Change Mitigation Requires Radical Technologies

The last IPCC report asserted that, if the world wants to limit anthropogenic warming to less than two degrees Celcius[7], greenhouse gases emissions shall decrease to zero net emissions in 2100[8] (IPCC, 2014). Many argue that revolutionary changes in technology are needed to achieve such objectives (Hoffert et al., 2002). For example, Barrett (2009) argues that the needed change looks like a technological "revolution" because it "will require fundamental change, achieved within a relatively short period of time." We agree with the statement, but for different reasons.

We think that the "revolution" consists less so in bringing some technologies from paper to proofs of concept (e.g. fusion), and more so in pushing advanced technologies through the challenges of mass-scale production and diffusion. In that spirit, Pacala and Socolow (2004) have claimed that much could be achieved with what is already known, at least up the first half of the century. Similarly, the Deep Decarbonization Pathway Project attempts to demonstrate that, with merely relying on what we know, the world can achieve a reduction between 70% and 100% by 2100 (Deep Decarbonization Pathways Project, 2015).

These pathways don't rely on any R&D breakthrough. But they require fast and massive scaling-up of production and diffusion of advanced technologies. For example, they projects emissions for passenger transport peaking around 2020, and about 134 million electric vehicles in 2030[9]. Here, we highlight that much of this change requires large networks of firms to redirect their production towards radically different products. We argue in this paper that coordinating downstream producers is critical for technological transitions to take place. To

[7] with more than a 50% chance

[8] The reports states that emissions shall decrease between 40 to 70% by 2050 relative to 2010 and to zero net emissions by 2100

[9] together with 75 million plug-in hybrid electric vehicles, 31 million hydrogen fuel cell vehicles, 27 million compressed pipeline gas vehicles

further our point, we focus on the car manufacturing sector in the following section.

4.2 The Case of the Automotive Industry

The automobile is a complex product where parts and sub-parts that interact are often produced by different firms (MacDuffie and Fujimoto, 2010). It is not surprising then that supplier networks in this industry have received some high degree of scrutiny. For example, Dyer (1996) attempted to quantitatively study how asset specificity throughout the supply chain impacts performance measures such as quality or speed of new product development for Japanese and American automakers. For our argument, it matters critically that producers share suppliers. Since this particular aspect of supplier networks has not been precisely documented, we turn to FactSet Revere[10], a database of supply chain relationships.

We first collect names of firms listed as "automobile and light duty motor vehicle manufacturing"[11]. We obtain a list of 48 companies (examples include Ford, Toyota, Tesla...). We then use FactSet Revere to obtain information regarding supply chain relationships[12]. [CONTINUE HERE - ADD DATA DESCRIPTION, GRAPHS AND TABLES]

If supply chain networks represent barriers to innovation, as we argue in this paper, one might wonder why in the first place the automotive industry relies on such strong networks. Such question resonates with the rising standardization observed in the Japanese automotive industry and described by Ahmadjian and Lincoln (2001). In the 1990s, Nissan announced it would source components from one of Toyota's supplier. That supplier had lower cost thanks to Toyota's large market share which provided greater economies of scale. The authors highlight that the move towards shared suppliers in the industry was the result of the rose in the standardization of parts which reduced the asset-specificity of the relationship between producers and suppliers.

In a sense, innovation can be thought of as a decrease in standardization, and our model is

[10] `www.factset.com/data/company_data/supply_chain`

[11] This corresponds to NAICS code 33611.

[12] We match observations on firms' name.

therefore consistent with the increased reliance on shared suppliers in 1990s because then was not a time of radical innovation. But with the realization that the traditional combustion-engine-based car is responsible for a significant share of greenhouse gases emissions, there is a need to transition towards different technologies, with lower carbon impact. To date, many manufacturers are attempting this transition. Tesla can be thought of as one of the most successful; interestingly, it is a completely new entrant, free from linkages to a historical network of suppliers, which is consistent with our model.

Finally, given supply chain networks represent barriers to innovation, one might expect vertical integration to partly solve the problem. The inherent tension here relies on the fact that, although vertical integration provides the ultimate way of coordinating the supply chain, it also completely forgoes economies of scope. Yet, an important implication of our model is that firms with greater proportion of their value chain vertically integrated should also be the one doing more radical innovations. It is interesting to note that one of the most innovative actor of the industry, Tesla, also appears to display an extensive level of vertical integration. In a Forbes' article, Dyer et al. (2015) explained that Tesla tried to set up a global supply chain to reduce costs, but having manufacturing so spread out led to 'massive coordination problems'. The authors highlight that, compared to other car makers, Tesla manufactures many more components in-house, and they further argue this was a great advantage for bringing electric cars to the market because the pace of change was too fast for the supply chain to follow. So far, although Tesla successfully brought to market electric vehicles, those have yet to reach the status of mass-production. The firm has annouced it would do so with the next model (Model 3), but many hurdles seem to lie ahead (The Economist, 2016). In future research, we intend to empirically investigate such relationship by combining supply chain relationships and patent data.

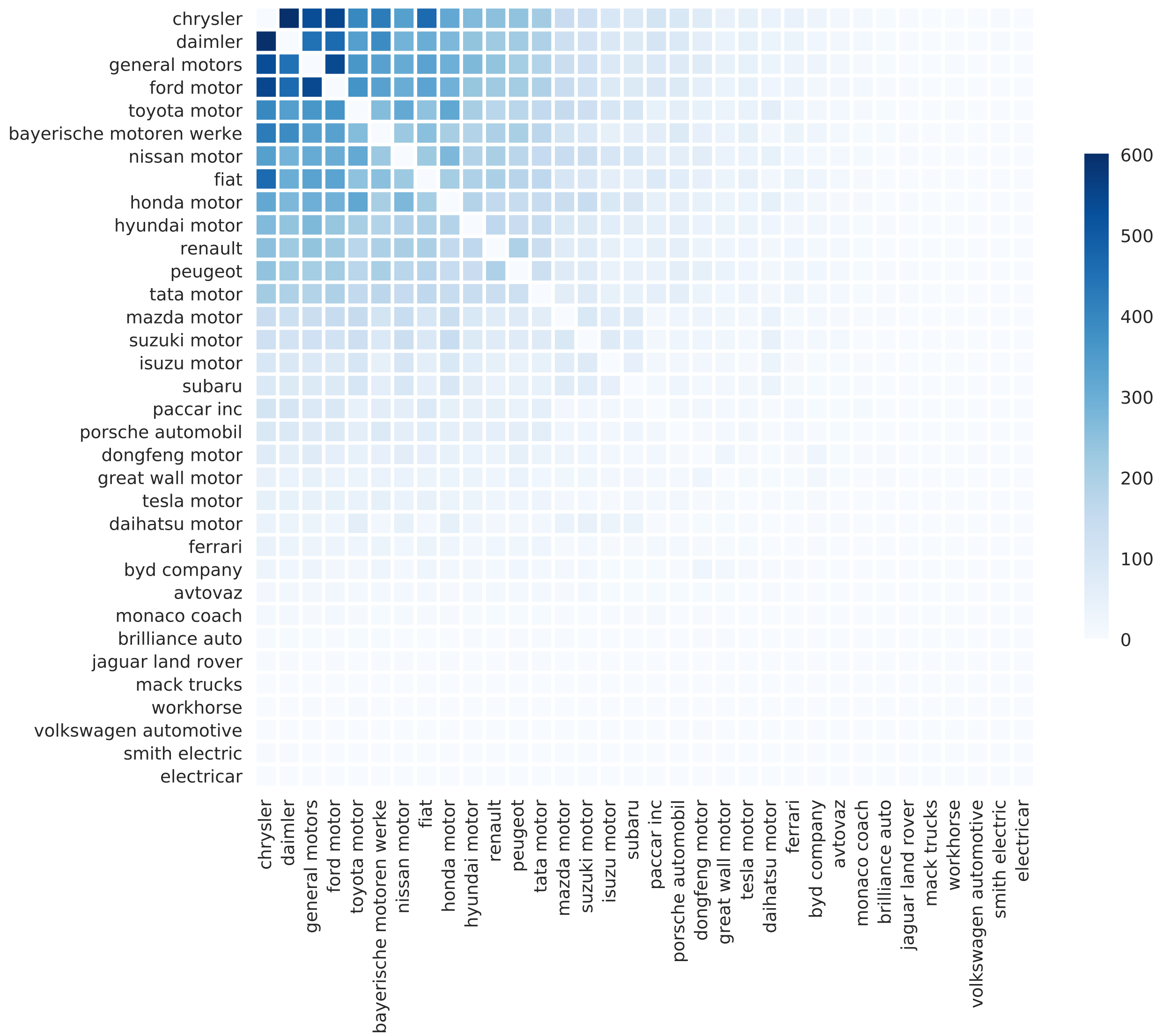


Figure 6: Number of Shared Suppliers

Note: Producers with no declared suppliers were dropped.

Table 1: Summary Statistics on the Number of Suppliers

	mean	sd	min	max
Total number of suppliers	286.17	328.36	1.00	1076.00
Percent not shared by any other producer	15.98	18.89	0.00	100.00
Percent shared by 2 to 5 producers	29.22	16.79	0.00	83.33
Percent shared by 6 to 9 producers	18.95	9.48	0.00	50.00
Percent shared by at least 10 producers	35.85	18.06	0.00	75.00
Number not shared by any other producer	34.00	53.50	0.00	235.00
Number shared by 2 to 5 producers	97.14	144.19	0.00	582.00
Number shared by 6 to 9 producers	59.69	69.97	0.00	243.00
Number shared by at least 10 producers	95.34	89.49	0.00	249.00

Note: The total number of producers in the data is 35. Producers with no declared declared suppliers were dropped.

5 Discussion: Coordinating Industrial Actors

[Very much work in progress still]

To foster green technological change, the economic literature proposes policies rectifying the market failures well-known to environmental and innovation economics (Jaffe et al., 2005; Popp, 2010; Popp et al., 2010). First, the negative pollution externality imposed by greenhouse gases calls for a carbon price either through a tax or an allowance trading scheme; such mechanisms are often referred to as demand-pull policy because internalizing the pollution externality contributes to increasing the demand for non-polluting technologies. As discussed earlier, there are also various positive externalities impeding the process of technological change, and as a result, it is commonly accepted that a carbon tax alone would not be sufficient (Lehmann and Gawel, 2013; Lehmann, 2012). We contribute to this literature by suggesting an additional mechanism, supplier network externality, potentially resulting in sub-optimal technological transitions.

Under the presence of supplier network externalities, a transition to radical innovations is likely to take place only if downstream producers coordinate in ways that create economies of scope for their suppliers. The literature on user network externality has highlighted the important role of expectations (Farrell and Klemperer, 2007) in coordinating actors. A natural question follows: what kind of isntitutional mechanisms can effectively influence expectations, thereby leading in coordinating industrial actors.

Importantly, this echoes studies of DARPA (Fuchs, 2010) and discussions about how to replicate it to the energy sector (Fuchs, 2009; Bonvillian and Van Atta, 2011; VanAtta, 2007; Anadon et al., 2014). Specifically, Fuchs (2010) shows how DARPA facilitates coordination among competitors and describes DARPA's technology policy as "embedded government agents" that re-architect social networks among researchers with the goal to identify and influence new technology directions. Neither the invisible hand of the market nor picking winners.

A quote from an industry participant at a DARPA seminar illuminates the dynamics at stake: "You just can't make anything happen in industry (today) on your own, because it's completely impossible. You have to find a partner, you have to convince your competition this is the right thing to do. You're guiding people [your competitors], ... and they ask, 'Why are you helping me with this?,' and the fact is you give them information so the suppliers are in the right place to help you." Here, the industry actor speaking clearly makes reference to the importance of coordinating supply chains, and in particular, shared suppliers, in the hope to foster technological change in the industry.

6 Conclusion

A Proofs

We first establish two intermediate results, Remark A.1 and A.2 below, which will be useful to establish other results.

Remark A.1. $\forall \hat{z}_j, \quad \frac{dp_j^*(\hat{z}_j)}{d\hat{z}_j}|_{\hat{z}_{-j}} \geq 0$

Proof.

$$\begin{aligned}\frac{d\Pi_{P_j}}{dp_j} = 0 &\Leftrightarrow s_jQ_j + (s_jp_j - c)\frac{\partial Q_j}{\partial p_j} = 0 \\ &\Leftrightarrow s_jQ_j + (s_jp_j - c)\frac{1}{\mu}Q_j(\frac{Q_j}{M} - 1) = 0 \\ &\Leftrightarrow \frac{\mu}{1 - \frac{Q_j}{M}} + \frac{c}{s_j} - p_j = F(p_j, \hat{z}_j, p_{-j}, \hat{z}_{-j}) = 0\end{aligned}$$

In turn, by the implicit function theorem:

$$\begin{aligned}\frac{dp_j^*}{d\hat{z}_j} &= -\frac{\frac{\partial F}{\partial \hat{z}_j}}{\frac{\partial F}{\partial p_j}} = -\frac{\frac{\mu}{M}\frac{1}{(1-\frac{Q_j}{M})^2}\frac{\partial Q_j}{\partial \hat{z}_j}}{-1 + \frac{\mu}{M}\frac{1}{(1-\frac{Q_j}{M})^2}\frac{\partial Q_j}{\partial p_j}} = \frac{\frac{\partial Q_j}{\partial \hat{z}_j}}{\frac{M}{\mu}(1 - \frac{Q_j}{M})^2 - \frac{\partial Q_j}{\partial p_j}} \\ &= \frac{\frac{\beta}{\mu}Q_j(1 - \frac{Q_j}{M})}{\frac{M}{\mu}(1 - \frac{Q_j}{M})^2 + \frac{1}{\mu}Q_j(1 - \frac{Q_j}{M})} = \frac{\beta Q_j}{M - Q_j + Q_j} = \frac{\beta}{M}Q_j > 0 \qquad \text{(A.1)}\end{aligned}$$

□

Remark A.2. $\forall \hat{z}_j, \quad \frac{dQ_j}{d\hat{z}_j}|_{\hat{z}_{-j}} > 0$

Proof. Total derivative of demand:

$$\frac{dQ_j}{d\hat{z}_j} = \frac{\partial Q_j}{\partial \hat{z}_j} + \frac{\partial Q_j}{\partial p_j}\frac{dp_j^*}{d\hat{z}_j} + \sum_{-j}\frac{\partial Q_j}{\partial p_{-j}}\frac{dp_{-j}^*}{d\hat{z}_j}$$

This gives, if $\mu = 1$:

$$\frac{dQ_j}{d\hat{z}_j} = \beta Q_j\Big(1 - \frac{Q_j}{M}\Big) + \frac{1}{\mu} Q_j\Big(\frac{Q_j}{M} - 1\Big)\frac{\beta}{M} Q_j - \sum_{-j} \frac{1}{M\mu} Q_j Q_{-j} \frac{\beta Q_j Q_{-j}}{M^2(1 - \frac{Q_{-j}}{M})}$$

Simplifying:

$$\frac{dQ_j}{d\hat{z}_j} = \beta Q_j(1 - \frac{Q_j}{M})^2 - \sum_{-j} \frac{1}{M^3}(Q_j Q_{-j})^2 \frac{\beta}{(1 - \frac{Q_{-j}}{M})}$$

Since $M - Q_j \geq Q_{-j}$, we have:

$$\begin{aligned} \frac{dQ_j}{d\hat{z}_j} &\geq \beta \frac{Q_j}{M^2} Q_{-j}^2 - \frac{1}{M^2}(Q_j Q_{-j})^2 \frac{\beta}{(M - Q_{-j})} \\ &= \frac{\beta}{M^2} Q_j Q_{-j}^2 (\frac{M - Q_{-j} - Q_j}{M - Q_{-j}}) \geq 0 \end{aligned}$$

□

Proof of Remark 1

Proof. Consider the stage 2 profit function (induced by the equilibrium prices):

$$\Pi^*_{P_j}(z_j, z_{-j}) = \Big(s_j p^*_j(z_j, z_{-j}) - c_j\Big) Q^*_j(z_j, z_{-j}) - R_0 - R_P z_j \tag{A.2}$$

At equilibrium we have: $p^*_j = \frac{c_j}{s_j} + \frac{\mu}{1 - Q^*_j/M} \Leftrightarrow Q^*_j = M\Big(1 - \frac{s_j \mu}{s_j p^*_j - c}\Big)$

Hence, we can rewrite Eq. A.2 as:

$$\Pi^*_{P_j}(z_j, z_{-j}) = M\Big(s_j p^*_j(z_j, z_{-j}) - c_j - \mu s_j\Big) - R_0 - R_P z_j$$

Taking the derivative with respect to z_j and knowing that $\frac{dp_j^*}{d\hat{z}_j} = \frac{\beta}{M} Q_j > 0$ from Eq. A.1 (proof of Remark A.1):

$$\frac{d\Pi^*_{P_j}(z_j, z_{-j})}{dz_j} = M s_j \frac{dp_j}{dz_j} - R_P = \beta s_j Q_j - R_P. \tag{A.3}$$

We know that Q_j monotonically increases with $\hat{z}_j$ (Remark A.2). Q_j therefore takes values between a minimum, call it Q_j^0, when $z_j = 0$, and up to M when z_j goes to infinity[13]. If $\beta s_j M < R_P$, then $\frac{d\Pi^*_{P_j}(z_j,z_{-j})}{dz_j}$ is always negative and the highest possible profits will always be for $z_j = 0$: there is no incentives for more radical innovation. On the contrary, if $R_P < \beta s_j Q_j^0$, $\frac{d\Pi^*_{P_j}(z_j,z_{-j})}{dz_j}$ is always positive and highest profits are reached for $z_j = 1$. In the last case, when $\beta s_j Q_j^0 < R_P < \beta s_j M$, there exists a value $\tilde{z}_j(z_{-j}) > 0$ above which $\frac{d\Pi^*_{P_j}(z_j,z_{-j})}{dz_j}$ is positive, meaning profits increase monotonically. This remark the profit function of each producer increases monotonically with z_j beyond some threshold value $\tilde{z}_j$, and becomes higher than the value at $z_j = 0$ after another threshold $\underline{z}_j$. This threshold value $\underline{z}_j$ does in fact depend on z_{-j} the innovation level of the other player. We can therefore define the function $\underline{z}_1(z_2)$ denoting the minimum level of innovation for firm 1 so that profits become larger than under $z_1 = 0$, given z_2 the value chosen by firm 2. In the same way, we can define $\underline{z}_2(z_1)$. Thus, either $\underline{z}_j(z_{-j}) \in [0, 1]$, or $\Pi^*_{P_j}(z_j, z_{-j}) < \Pi^*_{P_j}(0, z_{-j})$ for $z_j \in [0, 1]$. □

Proof of Remark 2

Proof. By Remark 1, we know that if $\underline{z}_j(z_{-j}) < 1$, then the best response of firm j to the value z_{-j} is the maximum value $z_j = 1$. On the contrary, if $\underline{z}_j(z_{-j}) > 1$, then the best response of firm j to the value z_{-j} is 0.

In the first case above, $\zeta^U > (1, 1)$ implies that $\underline{z}_1(z_2) < 1$ for all z_2, including for $z_2 = 1$, and $\underline{z}_2(z_1) < 1$ including for $z_1 = 1$. Hence, the best response of firm 1 is $z_1 = 1$ and similarly for firm 2, yielding the Nash Equilibrium $(1, 1)$.

[13] There will be a different Q_j^0 for every z_{-j}. The smallest Q_j^0 will be for $z_{-j} = 1$

In the second case above, if $\zeta^U < (1,1)$ or if ζ^U does not exist, this means that $\underline{z}_2(1) > 1$ so the best response of firm 1 to $z_2 = 1$ is $z_1 = 0$. The same is true for firm 2, yielding two equilibria $(0,1)$ and $(1,0)$. $\square$

Proof of Remark 3

Proof. Consider the profit function of the supplier if the supplier could ensure that the producers choose the same level of innovation z_i. Denote it $\Pi_i^S(z_i)$ (is that compatible with other notation choices?). Both producers produce the same quantity at the same price determined by level of innovation z_i. We denote them respectively $Q^*(z_i)$ and $p^*(z_i)$. Also denote $C^c(z_i)$ the cost under successful coordination and $C^m(z_i)$ the cost under unsuccessful coordination. The derivative of $\Pi_i^S(z_i)$ with respect to z_i is:

$$\frac{dE[\Pi_i^S]}{dz_i} = \frac{dp^*}{dz_i}Q(z_i) + p^*\frac{dQ^*}{dz_i} - R_s - \theta\frac{dC^c}{dQ}\frac{dQ^*}{dz_i} - (1-\theta)(\frac{\partial C^m}{\partial Q}\frac{dQ^*}{dz_i} + \frac{\partial C^m}{\partial \rho}\frac{d\rho}{dz_i}) \tag{A.4}$$

Since we have a finite market of size M, there is a point at which the market becomes saturated, i.e. an increase in the level of innovation of the products does not lead to more demand. Hence, in the symmetric case, both $p^*(z_i)$ and $Q^*(z_i)$ reach a plateau for some value of z_i . The derivative in equation A.4 becomes $-R_s + (1-\theta)\sigma\partial C^m/\partial\rho$, which is negative. Thus, if the cost and demand parameters are such that there is a value of z_i at which profits are maximized and positive, then there is a larger value of z_i at which point profits fall under $\Pi_i^S(0)$. Denote it $\bar{z}_i$. Additionally, since at $z_i = 0$, profits originally fall with increasing z_i, there is also a value $\underline{z}_i$ under which profits are less than $\Pi_i^S(0)$.

Hence either there exists $\underline{z}_i$ and $\bar{z}_i$ such that $0 < \underline{z}_i < z_i^* < \bar{z}_i$, or $E[\Pi_i^S(z_i)] < \Pi^S(0)$ for all $z_i \in (0,1]$. Given this, the possible NE follow from 2. Indeed, if $z_i^* \geq \underline{z}_j(z_i^*)$, then producers will be willing to invest z_i^* as well. If on the other hand $z_i^* < \underline{z}_j(z_i^*)$, then the supplier has to instead the first possible value of z_i such that $z_i = \underline{z}_j(z_i)$ (which is the same value for both producers since we are in the symmetric case). Call this value z_i^c. $z_i = z_i^c$ ensures that producers will innovate too (each choosing z_i^c by Remark 2). This is only beneficial to the supplier if $z_i^c < \bar{z}_i$. Finally, if instead $\bar{z}_i < z_i^c$, or if we are in the case in which $E[\Pi_i^S(z_i)] < \Pi^S(0)$ for all $z_i \in (0,1]$, then there will be no innovative investments. □

Proof of Result 1

Proof. We first show that the maximizer z_i^* that arises in the equilibrium (z_i^*, z_i^*, z_i^*) decreases with θ. Then we will show that as θ increases, the equilibrium can shift to $(0,0,0)$.

By the envelope theorem, $\frac{dz_i^*}{d\theta} = \frac{\partial^2 E[\Pi^S]/\partial\theta\partial z_i}{-\partial^2 E[\Pi]^S/\partial z_i \partial z_i}$, where the derivatives are estimated at z_i^*. Since at z_i^* the denominator is positive, the sign is determined by the sign of the cross-derivative.

Since we are in the symmetric case, both producers produce the same quantity at the same price determined by level of innovation z_i (Remark 3) so denote them $Q^*(z_i)$ and $p^*(z_i)$. Also denote $C^c(z_i)$ the cost under successful coordination and $C^m(z_i)$ the cost under unsuccessful coordination.

$$\frac{\partial E[\Pi^S]}{\partial z_i} = \frac{dp^*}{dz_i}Q(z_i) + p^*\frac{dQ^*}{dz_i} - R_s - (1-\theta)\frac{dC^c}{dQ}\frac{dQ^*}{dz_i} - \theta(\frac{\partial C^m}{\partial Q}\frac{dQ^*}{dz_i} + \frac{\partial C^m}{\partial \rho}\frac{d\rho}{dz_i})$$

$$\Rightarrow \frac{\partial^2 E[\Pi^S]}{\partial\theta\partial z_i} = \underbrace{\frac{dQ^*}{dz_i}}_{\geq 0}\underbrace{(\frac{\partial C^m}{\partial Q} - \frac{dC^c}{dQ})}_{>0} + \underbrace{\frac{\partial C^m}{\partial \rho}}_{<0}\underbrace{\frac{\partial \rho}{\partial z_i}}_{<0} > 0 \tag{A.5}$$

The sign of each term is evident except for $\frac{\partial C^m}{\partial Q} - \frac{dC^c}{dQ}$, which is positive because $\frac{\partial C^m}{\partial Q} - \frac{dC^c}{dQ} = (2^{k/(1-\sigma z_i^*)} - 2^k)kQ^{k-1} > 0$.

Within the region in which the (z_i^*, z_i^*, z_i^*) solution holds ($z_i^* \geq \underline{z}_j$ and $E\Pi(z_i^*) > \Pi(0)$), we therefore have that z_i^* increases with θ. But θ also changes the size of that region. First, since z_i^* decreases as the chance of miscoordination increases, it could fall under $\underline{z}_j$ (which does not vary with θ, switching the NE to, at best, $\underline{z}_j, \underline{z}_j, \underline{z}_j$). Second, by the envelope theorem, $\frac{dE\Pi(z_i^*,\theta)}{d\theta} = \frac{\partial E\Pi(z_i^*(\theta),\theta)}{\partial\theta}$. This is $-C^c(z_i^*) + C^m(z_i^*) > 0$ since costs under miscoordination are higher than under coordination. Hence, the profits decrease as the chance of miscoordination increases. In particular, the profits can drop under $\Pi_i(0)$, switching the NE to $(0,0,0)$. These possible discrete changes in the NE lead to the same conclusion that an increase in the chance of miscoordination decreases the equilibrium value of the innovation. $\square$

Proof of Result 2

Proof.

$$\frac{d^2 z_S^*}{dkd\theta} \propto \underbrace{\frac{d}{dk}\Big(\frac{\partial^2 E[\Pi_S]}{\partial\theta\partial z_S}\Big)}_{\mathcal{A}} \underbrace{\Big(-\frac{\partial^2 E[\Pi_S]}{\partial z_S \partial z_S}\Big)}_{>0} + \underbrace{\frac{\partial^2 E[\Pi_S]}{\partial\theta\partial z_S}}_{<0} \underbrace{\frac{d}{dk}\Big(\frac{\partial^2 E[\Pi_S]}{\partial z_S\partial z_S}\Big)}_{\mathcal{B}}$$

Consider the term $\mathcal{A}$ first, for which we use Eq. A.5:

$$\begin{aligned}
\mathcal{A} &= \underbrace{\frac{dQ^*}{dz_S}}_{>0} \underbrace{\frac{d}{dk}\Big(\frac{dC^c}{dQ} - \frac{dC^m}{dQ}\Big)}_{A} - \underbrace{\frac{d\rho}{dz_S}}_{<0} \underbrace{\frac{d}{dk}\Big(\frac{dC^m}{d\rho}\Big)}_{B} \\
\frac{d}{dk}A &= Q^{-1+k}\Big(2^k - 2^{k/(1-z\sigma)} + k\big(2^k + \frac{2^{k/1-z\sigma}}{-1+z\sigma} log(2)\big) + (2^k - 2^{k/(1-z\sigma)}) klog(Q)\Big) < 0 \\
\frac{d}{dk}B &= (-log(2))\frac{2^{k/\rho}Q^k(\rho + klog(2) + klogQ^\rho)}{\rho^3} < 0 \\
\Rightarrow \mathcal{A} &= \underbrace{\frac{dQ^*}{dz_S}}_{>0} \underbrace{\frac{d}{dk}\Big(\frac{dC^c}{dQ} - \frac{dC^m}{dQ}\Big)}_{<0} - \underbrace{\frac{d\rho}{dz_S}}_{<0} \underbrace{\frac{d}{dk}\Big(\frac{dC^m}{d\rho}\Big)}_{<0} < 0
\end{aligned}$$

Then consider the term $\mathcal{B}$:

$$\begin{aligned}
\mathcal{B} = &\frac{d}{dk}\Big(-\frac{dC^c}{dQ}\frac{d^2Q^*}{dz_S^2}\Big) \\
&\underbrace{-\frac{d^2Q^*}{dz_S^2}}_{>0} \underbrace{\Big(\frac{2^{k/\rho}Q^k)(\rho + klog(2) + klog(Q^\rho))}{Q\rho}\Big)}_{>0}
\end{aligned}$$

Combining, we obtain that $\frac{d^2 z_S^*}{dkd\theta} < 0$. $\square$

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