A Theoretical Model of 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 to one producer of producing a new technology may depend on how many other producers are deploying similar technologies. Specifically, production costs decrease as several producers source similar inputs from shared suppliers, generating economies of scope. To illustrate the mechanism, we develop a stylized model of two producers with a shared supplier. We introduce the possibility that producers innovate in incompatible ways requiring very different inputs from the supplier. This triggers a loss in economies of scope and reduces 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 to show that our model is of particular relevance to the car manufacturing industry and, we highlight how our results help unify findings from several case studies.

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

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1 Introduction and Background

Various positive externalities impede the process of technological change at both the innovation and diffusion stages (Jaffe et al. 2003; Jaffe et al. 2005). These externalities usually justify using 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 (Rockett 2010; Stephan 2010). Attention has also focused on issues faced by adopters such as dynamic increasing returns in learning-by-using and user network effects (Farrell et al. 2007; Liebowitz et al. 1994)[1].

Beyond issues of adoption by end-users is the growing recognition that manufacturing is a critical locus in 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 innovation (Bonvillian 2013). Learning and adjustments seem particularly important as products most often constitute complex combinations of components supplied by different firms (Fuchs 2014). Manufacturing is a time where all suppliers and producers make essential investments towards developing 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 et al. (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

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

therefore innovation (Blanchard et al. 1997; Chen et al. 2011; Gilson et al. 2009). 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, aggregate output and trade in particular, is gradually being recognized, and researchers are increasingly describing them theoretically and empirically (Acemoglu et al. 2012; Atalay et al. 2011; Carvalho 2014; Oberfield 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).

This paper investigates how supply-chain network characteristics impact firms' ambition to innovate. We develop a theoretical model to illustrate and examine a new type of positive externality where the cost of producing a new technology to one producer may depend on how many other producers are deploying similar technologies. We call such externalities *supplier network externalities*, and they can be thought of as a distant cousin to the typical user network externalities discussed in the technology adoption literature. For example, David (1985) discusses the factors that led QWERTY to become "locked in" as the dominant keyboard arrangement.

David (ibid.) argues that three factors played a key role: 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 decrease as it gained acceptance relative to other systems. Eventually this led to the quasi-universal adoption of the keyboard. Importantly, network effects create multiple equilibria: users' expectations are

[2]More complex than just a linear node between a 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".

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 these reasons, the QWERTY example has sometimes been regarded as the 'founding myth' of the path dependence literature (Ruttan 1997).

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 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: 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 its 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, producers would display excess inertia by waiting too long before switching. Absent 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 this may be the case for 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 to decarbonize the economy qualify as *radical*, particularly in the car manufacturing sector. Second, we argue our model is particularly relevant for this sector 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 producers (denoted by subscript 1 and 2, respectively) and one shared supplier (denoted by subscript S). Each 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 a model, good 1 and good 2 are competing products which have 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 products 1 and 2 result from collaborations between producers and their supplier, improving the quality a_j can be done by either of the firms on its own or jointly with complementary investments. We build on the observation that some innovations require

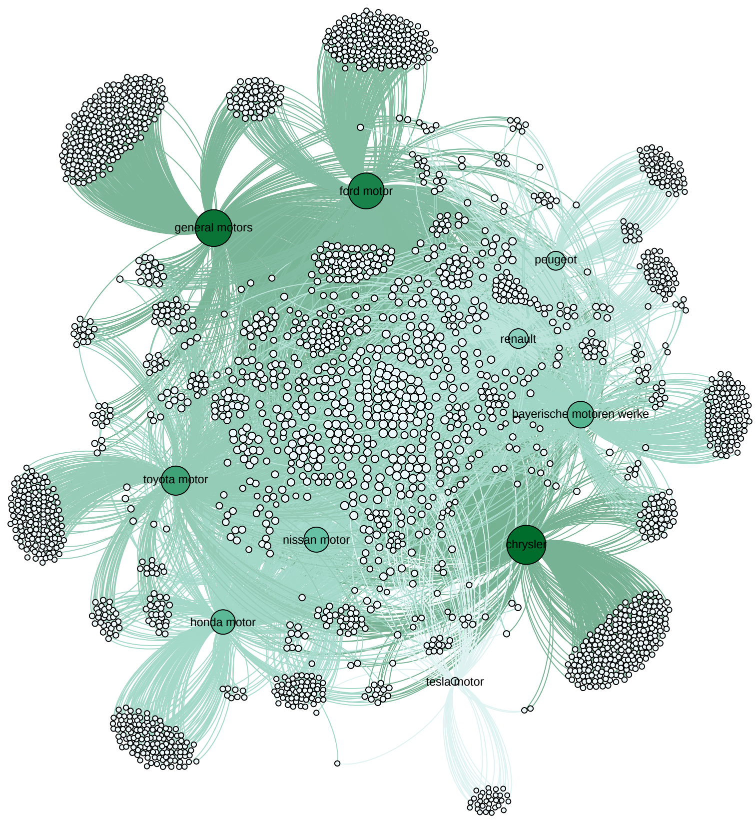


Figure 1: Supplier Network for Ten Car Manufacturers

Note: Each green bond denotes a buyer-supplier relationship. Nodes in the center are shared among two or more producers. The color gradient indicates nodes' number of links and the size of the nodes indicates their eigenvector centrality: we see that a large number of suppliers in the center are highly central.

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 et al. 2010) produced by different firms. Following this example, we think of radical innovations as product changes that require investments from multiple firms because the skills, knowledge, and/or inputs needed to deploy the innovation are not present within the firm[4].

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. 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, also increases.

As we said, what makes an innovation radical is that it requires common effort. We formalize that by assuming that the innovations of each player in the supply-chain are perfect complements: only the lowest degree of "radicalness" wished by a producer j and its supplier can be implemented. We denote $\hat{z}_j$ the resulting degree of "radicalness" in the supply chain of producer j. For example, for producer 1:

$$\hat{z}_1 = \min\{z_1, z_S\} \tag{2}$$

[4]In that sense, a technology might be radical only in relation to a particular organization (Soskice 1997; Teece 1986) and the knowledge and skills for the technology exist in another firm or research laboratory.

The model focuses on the case of symmetric producers, and, as a result, $\hat{z}_1$ and $\hat{z}_2$ will be the same.

We assume that innovations with more ambitious common effort bear the promise of higher quality a_j and, ceteris paribus, higher profits. 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 paying for the actual investments. We take these as a fixed cost whose magnitude increases with the degree of effort. We denote R_j and R_S the fixed costs for producer j and the supplier.

$$\begin{cases} R_j \hat{z}_j & \text{is the fixed cost for producer } j \\ R_S(\hat{z}_1 + \hat{z}_2) & \text{is the fixed cost for the supplier} \end{cases} \tag{4}$$

The variable cost for 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 producers might radically innovate 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 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. Indeed, one reason for which a supplier is often shared amongst multiple competing producers is that the supplier enjoys economies of scale and scope. To capture the effect, we assume the cost function 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 $\rho > 0$ is a parameter governing the extent to which the inputs produced by the supplier are substitutable in the cost function[5]. Remember that q_1 is a function of $p_1, p_2, \hat{z}_1$ and $\hat{z}_2$.

$$C_S(q_1, q_2|\rho, k) = \left(q_1^\rho + q_2^\rho\right)^{\frac{k}{\rho}} \quad \text{where } \rho = \begin{cases} 1 \text{ with probability } 1-\theta \text{ (Coordination)} \\ 1-\sigma\hat{z}_j \text{ with probability } \theta \text{ (Miscoordination)} \end{cases} \tag{5}$$

The move of nature regarding the coordination of the producers impacts ρ such that, under coordination, inputs are purely substitutable ($\rho = 1$). Under miscoordination, inputs are less and less substitutable in the cost functions as $\hat{z}_j$ increases. Since we are in a case of symmetric producers, here $\hat{z}_j = \hat{z}_1 = \hat{z}_2$. Consequently, the supplier loses economies of scope[6].

We assume incomplete contracts between suppliers and producers. Hence, the producers and supplier choose their level of innovative investment independently. We further assume that firms share revenues ex-post and that they split revenues equally. Since we have only one supplier shared between two producers, in our model, the share received by the producer j, s_j, equals 0.5.

The sequence of the game is as follows: 1) All players choose radicalness z, which determines the quality $a_j = \beta * min\{z_j, z_S\}$ for each final product; 2) a move of nature determines

[5] $\rho > 1$ corresponds to economies of scope from producing multiple products, $\rho = 1$ corresponds to purely substitutable products, and $\rho < 1$ corresponds to diseconomies of scope from producing multiple products.

[6] In a scenario with asymetric producers, we could reformulate the cost function under misccordination with $\rho = 1 - \sigma max(\hat{z}_1, \hat{z}_2)$.

whether the producers coordinate or miscoordinate on the direction of innovation, which then affects 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.

Since we define $\hat{z}_j$ as the smallest level of radicalness chosen by either a producer or its supplier, we can solve separately for the optimal $\hat{z}_j^*$ for producers, on one hand, and for the optimal $\hat{z}_S^*$ for the supplier, on the other. To solve for the optimal $\hat{z}_j^*$, we first consider the game between the two competing producers, assuming that the supplier always innovates at the same level as each of the producers. In that game, the supplier makes no decision and has no influence on the variable z. It almost akin to assuming there is no supplier, except that revenues are still split. To solve for the optimal $\hat{z}_S^*$, we consider a game where the supplier alone chooses the z_j. Now it almost akin to assuming there are producers, except that revenues are still split. To derive the Nash Equilibria of the innovation game with the three players choosing their respective levels of radicalness, we combine results regarding optimal $\hat{z}_j^*$ and $\hat{z}_S^*$.

3 Results

3.1 Best Responses in the Two-Producer Game

Here, we consider the game between the two competing producers, assuming that the supplier always 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[7] 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 $z_1 = 0$. In Panel 2b, the blue 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, above this point, the best response is $z_1 = 0$. 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. The best responses of each actor are shown in bold lines (for producer 1, it is the bold blue line). Depending on the parameters, the two curves may or may not cross. Figure 3 illustrates several possible cases. Assuming that they cross, it is useful for what follows to denote $\zeta^{\mathbf{L}}$ and $\zeta^{\mathbf{U}}$ the locus of these intersections.

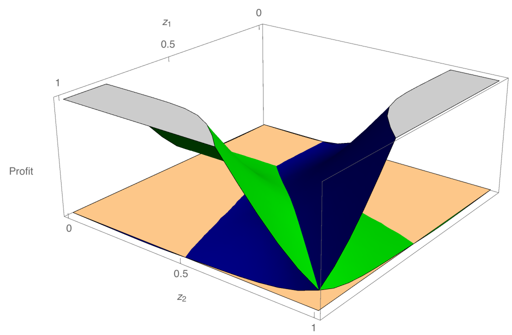
3.2 Nash Equilibria in the Two-Producer Game

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

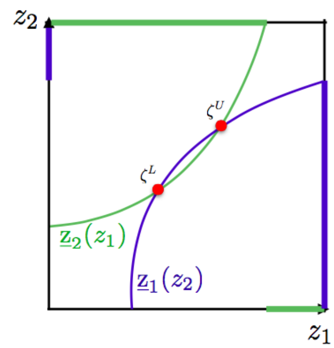
Remark 2. *Assuming that* $\exists\ \underline{z}_j(0) \in [0, 1]$ *for* $j \in (1, 2)$*, we can distinguish two possible cases:*

- *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.*

[7] 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 are 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.

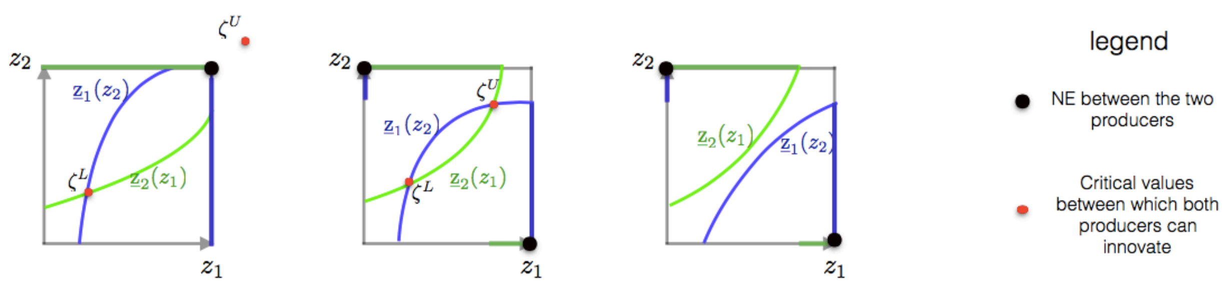


Figure 3: Diagrams showing different cases of Figure 2a. The bold and opaque colored lines represent the best response functions of both producers. The large black dots represent the resulting Nash Equilibrium.

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 can not be positive in any 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 producer innovates maximally and the other innovates only marginally ($z = 0$).

3.3 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[8]. We also focus on 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.

Remark 3. *In the symmetric case, the Nash Equilibria (z_1, z_2, z_S) of the 3-player innovation game are:*

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

where z_S^{max} is the radicalness level that maximizes the expected profits of the supplier assuming

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

she could dictate the level of innovation for other players ($E[\Pi_S(z_S, z_S, z_S)]$), and $\bar{z}_S$ is the threshold value above which expected profits of the supplier are negative.

Because innovation choices are perfect complements, $(0, 0, 0)$ is always a possible equilibrium, even if innovation is profitable. Therefore, the innovation game is a coordination game. We will come back to this in future work as we introduce more shared suppliers and analyze risk-dominant play. In what follows, we focus on explaining the equilibria with positive levels of innovation.

To understand Remark 3, consider Figure 4, which illustrates how the choice of the supplier interacts with that of the producers. 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 $\hat{z}_1 = min\{z_1, z_S\}$, the optimal investment level for producer j is now $z_j = z_S$, as long as $z_S \geq \zeta^L$, and 0 otherwise.

Hence, 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 us focus our attention on the 45 degree line in Figure 4. This line now represents the supplier's choice set, $z_S \in [0, 1]$. Along this line, we plotted $E[\Pi_S]$, the supplier's expected 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 leads to the $(z_S^{max}, z_S^{max}, z_S^{max})$ NE. If $z_S^{max} < \zeta^{\mathcal{L}}$, but $\bar{z}_S$ is still greater than ζ^L, then the supplier can choose $z_S = \zeta^L$. Finally, if $\bar{z}_S < \zeta^L$, then the only NE is $(0, 0, 0)$.

To summarize, 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 producer, 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.

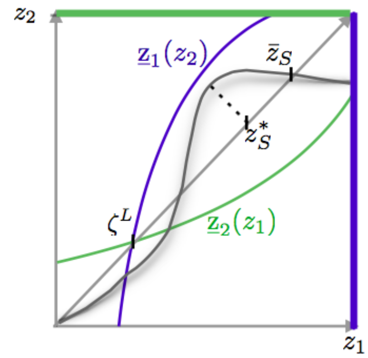


Figure 4: Diagram overlaying the supplier's profit function on the (z_1, z_2) plane. The order of the three points ζ^L, z_S^{max} and $\bar{z}_S$ determines the Nash Equilibrium of the three-player game described in Remark 3

3.4 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, the NE level of innovation decreases. We saw in Remark 3 that at equilibrium, all players choose the same level of radicalness, which is "set" by the shared supplier. To simplify, denote this equilibrium level of radicalness z_S^*.

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; this coefficient governs 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

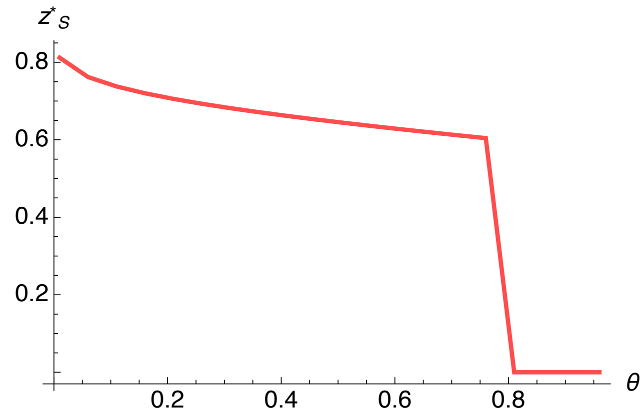


Figure 5: Change in z_S^* as a function of θ, in the 3-player case. The parameters describing the cost function of the supplier are $k = 1$, $\sigma = .9$

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 miscoordination 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.

3.5 Inducing innovation

In many cases, policy-makers wish to induce innovation, i.e. increase a specific quality a of a product, to meet a societal goal such as mitigating climate change. In the case of climate change mitigation, a would be the cleanliness of the product (its low level of carbon emissions). Several parameters in our model affect whether investing in this innovation will be profitable for the decisive player (here the shared supplier), which can be shaped by policy. First, there are parameters that govern the demand for the product: M the size of the market, and β, the marginal value of quality a to the customer's utility. M can be changed by procurement policies, while β can be changed by a carbon tax (which will increase the attractiveness of low-carbon products). Second, there are the parameters affecting the cost, and in particular, the marginal upfront investment cost R_S which can be shaped by subsidies. How does the risk of miscoordination affect the ability to induce innovation via these various policies?

Let $\bar{R}_S$ be the maximum upfront innovation investment cost at which the supplier wishes to innovate, (i.e. such that $E[\Pi^S](z_S^*, \bar{R}_S) = 0$). Similarly, let $\underline{\mathrm{M}}$ be the minimum market size for which the supplier wishes to innovate (analogously, the market size such that expected profit is exactly 0) and $\underline{\beta}$ the minimum marginal utility of quality for the consumer for innovating in quality to be profitable. In other words, these are the threshold values for key parameters that affect the parameter space under which innovation is attractive to the supplier.

Result 3. *In the 3-player game, we find that:*

- $\frac{d\bar{R}_S}{d\theta} < 0$
- $\frac{d\underline{M}}{d\theta} > 0$
- $\frac{d\underline{\beta}}{d\theta} > 0$

These three comparative statics results tell us that an increased risk of miscoordinating technological directions reduces the parameter space under which innovation is attractive to the supplier: all other things equal, if the miscoordination probability increases, the upfront cost cannot be as high, the market must be larger, and the marginal utility to the customer of quality improvements must be higher. In turn, if subsidies are used to induce innovation by reducing the upfront costs borne by the firm, these subsidies will need to be higher, while procurement policies to increase the market size would need to be more vigorous. Similarly, if the marginal utility to customers of products being green is raised by a carbon tax, then this tax needs to be higher.

These three results arise from the same straightforward logic having to do with their effect on the profit function: θ, R_S, β and M all affect the maximized objective function, so a movement in θ changes the threshold value of the other three parameters at which the objective function is positive. However, these three parameters – and the associated policy instruments that can shape them – have different effects on z_S^*, the chosen level of ambition in equilibrium. Hence, although in our model they can all induce a shift from no innovation to some innovation, they are not equally effective in encouraging a higher level of radicalness:

Remark 4. *In the 3-player game, we find that:*

- $\frac{dz_S^*}{dR_S} = 0$
- $\frac{dz_S^*}{dM} > 0$
- $\frac{dz_S^*}{d\beta} < 0$

Remark 4 indicates first that changing the upfront cost has no effect on ambition since it simply shifts the profit function. Second, increasing the market size also raises ambition. Third, raising β has the effect of *lowering* ambition. Hence, although β needs to exceed some minimum level, raising it further can be counter-productive. We interpret this as a note of caution regarding the reliance on carbon taxes to induce innovation, at least within the limited scope conditions of this model. This result stems from two properties of the model: 1) customers compare the products to the utility obtained from some outside option, so as β increases, a lower quality is needed to compete successfully with that outside option; 2) the supplier chooses the level of ambition unilaterally, so beyond the level of quality that successfully draws customers away from the outside option, the supplier has no more competitive incentive to further increase quality.

Although quite minimal, our model illuminates a few interesting tensions that arise when there exist technologically critical suppliers that are shared between competing producers:

1. Although there is competition between producers in price or quantity of the final good, the presence of a shared supplier can create a monopoly-like position upstream in the supply network with regards to innovation choices, and this, in fact, can discourage innovation.

2. If there is a risk that producers will innovate in substantively different ways (miscoordinate their technological direction), shared suppliers will be more reluctant to innovate and they will innovate less ambitiously, for fear of losing their central position in the supply network.

3. This probability of miscoordination between producers reduces the size of the parameter space that supports positive innovation. Consequentially, inducing innovation in the network requires more ambitious policies (such as procurement, subsidies or taxes) when this risk of miscoordination is high.

We see that the network structure underlying production matters for understanding the incentives to engage in radical innovation. Specifically, the model illustrates a case in which attaining higher levels of innovative ambition requires that producers be able to coordinate their technological vision so as to align the suppliers they co-depend on for the success of the innovative projects.

We will now examine the implications of the model for green technological transitions, with a focus on the car manufacturing sector and a discussion of mechanisms to foster coordination between 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 Celsius[9], greenhouse gases emissions need to decrease to zero net emissions by 2100[10] (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 in bringing some technologies from paper to proofs of concept (e.g. nuclear fusion), and more in pushing advanced technologies through the challenges of mass-scale production and diffusion. In that spirit, Pacala et al. (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, by relying on what we already 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 project emissions for passenger transport peaking around 2020, and about 134 million electric vehicles in 2030[11]. Much of this change requires that large networks of firms 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 further our

[9] with more than a 50% chance

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

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

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 for which parts and sub-parts that interact are often produced by different firms (MacDuffie et al. 2010). It is not surprising then that supplier-buyer relationships in this industry have received some high degree of scrutiny. For example, Dyer (1996) attempted to quantitatively study how relationship specialization throughout the supply chain impacts performance measures such as quality or speed of new product development for Japanese and American automakers. For our argument, however, it matters critically that producers *share* suppliers. Since this particular aspect of the industrial organization has not been quantitatively documented, we turn to FactSet Revere[12], a database of supply chain relationships.

Table 1: Summary statistics on the number of suppliers in the car manufacturing sector

	mean	sd	min	max
Total number of suppliers	85.58	81.12	1.86	262.40
Percent shared	80.84	16.14	30.15	100.00
Percent not shared by any other producer	18.81	16.18	0.00	69.62
Percent shared by 2 to 5 producers	32.37	15.24	12.90	79.17
Percent shared by 6 to 9 producers	18.70	7.13	0.00	26.67
Percent shared by at least 10 producers	30.12	16.67	0.00	59.67
Relationship mean duration (in years)	6.00	1.46	1.80	8.02
Relationship max duration (in years)	12.10	4.17	2.00	15.00

Note: The summary statistics are for a sample of 35 car manufacturers using FactSet relationships from 2003 to 2017. Variables are first averaged across years to then generate summary statistics for a cross-section of producers. The "total number of suppliers" for a given producer j is the yearly average of the number of suppliers working with producer j. The variable "relationship mean duration" for a given producer j equals the yearly average of the average duration of all relationships observed in a given year for producer j. Accordingly, the variable "relationship max duration" for a given producer j equals the yearly average of the maximum duration of all relationships observed in a given year for producer j.

We use FactSet Revere relationship database to obtain information on buyer-supplier relationships for car manufacturers. More information on data collection and cleaning is

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

available in Appendix B. Table 1 displays summary statistics for the buyer-supplier relationships. First, we note, in an average year, the average car manufacturer 1) works with about 85 different suppliers and, 2) shares about 80% of those suppliers with its competitors. This indicates that 1) the industry is heavily relying on outsourcing for manufacturing intermediate parts, and that 2) shared suppliers are the norm rather than the exception. We should highlight that, on average, about 30% of a car manufacturer's suppliers are shared by 10 or more of its competitors. Hence, it appears that some suppliers could be labeled as "mega-suppliers", i.e. supplying most of final producers in the sector. The columns "min" and "max" in Table 1, however, are a testimony to significant variation across manufacturers with respect to their supply-chain organization. Figure 6 illustrate this point by showing that, although a group of ten or so manufacturers seem to share many suppliers, others in the industry are less connected.

Table 1 also provides summary statistics regarding the duration of the relationships between producers and suppliers. The relationships with suppliers have been going on for about six years on average (in the average year and for the average producer). The maximal duration observed for a relationship, however, is as high as about 12 years. This indicates that buyer-supplier relationships in this industry seem rather stable on the long-term, which would consistent with more asset-specific product development.

This structure, in fact, reflects the wave of outsourcing and "de-verticalization" that transformed the industry since the mid-80's (Sturgeon et al. 2008). Driven by a need to reduce cost in a globalized market, as well as a conviction that they should emulate the modular structure of the computer industry, producers increasingly outsourced the manufacturing of parts. They spun-off some of the subsidiaries producing intermediate parts, and some suppliers merged giving rise to the "mega-supplier" supplying complex modules to multiple producers (Jacobides et al. 2016). For example, in the 1990s, Nissan announced it would source components from one of Toyota's supplier, Denso (going against a long-standing norm

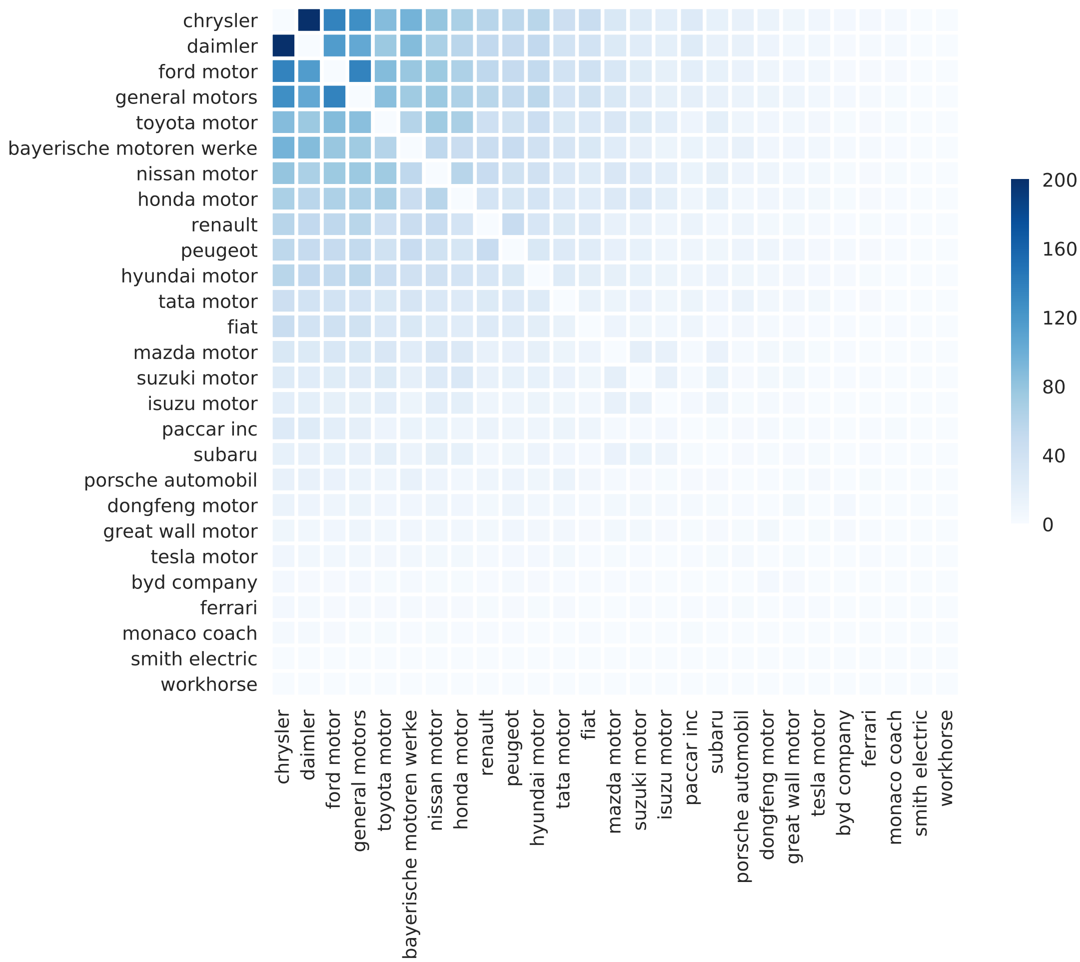


Figure 6: Number of Shared Suppliers

Note: Producers with no declared suppliers were dropped.

that suppliers should not be shared between two rival supply chains or *keiretsu*). Denso had lower cost thanks to Toyota's large market share which provided greater economies of scale.

If, as we argue in this paper, shared suppliers are obstacles to innovation, why do car manufacturers rely so much on them? It is important to highlight here that the outsourcing wave took place jointly with a move towards greater standardization of intermediate inputs. Ahmadjian et al. (2001) describes this phenomenon for the Japanese automotive industry in the 1990s. A simple answer to our question is that shared suppliers are very efficient when intermediate inputs have become standardized and innovation is minimal.

Alternatively, Jacobides et al. (2016) use case studies and historical research to argue that the outsourcing wave was partially a strategic mistake in the U.S. and Europe. Manufacturers saw the idea of outsourcing whole modules to capable suppliers as a new strategic imperative but overlooked contractual risks. Specifically, they put themselves at risk of surrendering power to mega-suppliers becoming strategic bottlenecks. Soon, the limits of the paradigm became apparent, and manufacturers became wary of shared suppliers. The following quote, from a Fiat executive, highlights that manufacturers believed suppliers lacked incentives to innovate: "It's all a question of money – suppliers can't imagine spending lots of money. The mega-suppliers want only big volume, they want to stick with processes they know. Their short-term incentive is to stay focused on components. [...] They are not likely to offer us their latest technologies if that threatens their existing investments – this can be a barrier to our innovation." (quote from ibid.).

The state of affairs described above can be contrasted with somewhat savvier management of supplier relationships by Japanese auto-makers. As we saw, Nissan broke the long-standing Japanese *keiretsu* norm of not sharing key suppliers by starting to source from Denso, Toyota's main supplier of electronics. However, when it became clear that electronics were becoming a central and complex component of car technologies (requiring strong technological coordination), Toyota invested heavily in its internal capacity to manufacture electronics in order to lessen its reliance on Denso and to better monitor and control its dealings with its supplier, who now has split loyalties (Ahmadjian et al. 2001).

These case studies highlight that shared suppliers pose strategic problems in the process of innovation and, our data shows that these relationships abound. We ask: What are the consequences for the low-carbon transition? With the realization that the traditional combustion-engine-based car is responsible for a significant share of greenhouse gases emissions, the car manufacturing sector is in a period of ferment with many alternative power-train technologies under testing (Sierzchula et al. 2012)[13]. Our model suggests that this multitude of technology directions exacerbates the strategic problems documented above, as the "mega-suppliers" have neither the incentive nor the capacity to make the requisite complementary investments, especially given the risk arising from the uncertainty in technological directions.

Empirically, we see that although most major manufacturers have announced ambitious plans for new clean products, investments in these new models still seems limited and driven by compliance with regulatory mandates. For example, Wells et al. (2012) argue that current electric vehicles tend to be of inferior quality because the architecture of most models has not been sufficiently adapted to the new requirement of batteries. Critically, the industry has not scaled up its production and sales to the level hoped for by the Obama administration when it decided to make sizable investments in the battery supply-chain (Canis 2013). To our knowledge, there currently exists no rigorous case studies examining different firms' decisions to innovate in alternative vehicles and how those decisions are shaped by the scope of the firm, and the contracts and relationships with key partners. Such case studies are needed to understand progress in the low-carbon transition and our model provides some hypotheses to be tested in such case studies.

According to our model, we would expect that the players best positioned to make inno-

[13] Sierzchula et al. (2012) documents eight different competing technologies.

vative and successful investments in alternative vehicles would be either firms with long-term relationships with their main suppliers, capable of co-design via relational contracts, such as Toyota, or vertically integrated firms. Interestingly, Tesla, which arguably is one the most innovative and successful producer of electric vehicles, is a new entrant, free from linkages with the historical network of suppliers. According to Dyer et al. (2015), it is also to a large extent vertically integrated. In their 2015 Forbes' article, Dyer et al. explained that Tesla initially 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 its suppliers 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 announced it would do so with the next model (Model 3), but many hurdles seem to lie ahead (The Economist 2016).

5 Discussion

Our model shows that, under the presence of supplier network externalities, a transition to radical innovations is likely to take place only if producers coordinate in ways that create economies of scope for their suppliers. In the context of user network externality, the role of expectations is often highlighted for coordinating actors (Farrell et al. 2007). Naturally we might wonder: what kind of institutions or policies can effectively affect expectations?

Lately, the fight against climate change has called comparison to JFK's moonshot, stressing the importance of goal-setting and planning (Sachs 2015). The Sustainable Development Goals, voted by all countries represented at the United Nations in 2015, can be thought of as an example of goal-setting, and the Deep Decarbonization pathways, mentioned earlier, as examples of planning efforts. Such initiatives could, to a certain extent, be interpreted as “soft” mechanisms for modifying expectations about green transitions. Similarly, although the Paris Climate Agreement remains a non-binding set of pledges to reduce greenhouse gases emissions, it possibly is useful to foster the convergence of expectations of political and economic actors.

Importantly, the need and challenges of corodinating industrial actors echoe studies of the Defense Advanced Research Projects Agency (DARPA) (Fuchs 2010) and discussions about how to replicate it in the energy sector (Anadon et al. 2014; Bonvillian et al. 2011; Fuchs 2009; VanAtta 2007). 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 of identifying and influencing new technology directions, neither the invisible hand of the market nor picking winners. Although DARPA’s original strategy was focused on researchers, the agency swithced its focus to industry after 2001. According to Fuchs (ibid.), DARPA then supported the coordination of technology development across a vertically fragmented industry in whose direction the military has interest and in which long-term coordination of technology platforms was particularly challenging. DARPA actions mainly consisted in bringing together established vendors with academics and start-ups with the goal to support knowledge-sharing within industry, between competitors.

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 quoted by Fuchs (ibid.) clearly makes reference to the importance of coordinating supply chains, and in particular shared suppliers, in the hope of fostering technological change in the industry.

6 Conclusion

To foster green technological change, the economic literature proposes policies rectifying the market failures well-known to environmental and innovation economics (Hallegatte et al. 2011; Jaffe et al. 2005; Popp 2010; Popp et al. 2010). On one hand, the negative pollution externality imposed by greenhouse gases calls for a carbon price either through a tax or an allowance trading scheme. On the other, as discussed in this paper, various positive externalities also impede the process of technological change. It is, as a result, commonly accepted that a carbon tax alone will not be sufficient (Lehmann 2012; Lehmann et al. 2013). We contribute to this literature by suggesting an additional mechanism, supplier network externality, for producing sub-optimal technological transitions. Under the presence of such externalities, a transition to radical innovations is likely to take place only if producers coordinate in ways that create economies of scope for their suppliers. Finally, we argue that this case is relevant to car manufacturing sector and highlights connections to the literature debating the merits of innovation agencies such as DARPA. In the future, we intend to further investigate the policy implications of our model and extend our theoretical results. Specifically, we plan to generalize the model by allowing for m producers and n shared suppliers. With more than one shared supplier, the problem of coordinating on the equilibrium that features positive levels of innovation becomes salient and interesting for us to analyze. We can use an intuitive generalization of risk dominance (Morris et al. 1995) to analyze how an increase in the number of players interacts with the parameter θ to change the overall likelihood of technological change in the system.

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.

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

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:

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

$\square$

Proof of Remark 1

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

$$\Pi_j^*(z_j, z_{-j}) = \Big(s_j p_j^*(z_j, z_{-j}) - c_j\Big) q_j^*(z_j, z_{-j}) - R_j z_j \tag{A.2}$$

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:

$$\Pi_j^*(z_j, z_{-j}) = M\Big(s_j p_j^*(z_j, z_{-j}) - c_j - \mu s_j\Big) - R_j z_j$$

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):

$$\frac{d\Pi_j^*(z_j, z_{-j})}{dz_j} = M s_j \frac{dp_j}{dz_j} - R_j = \beta s_j q_j - R_j. \tag{A.3}$$

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[14]. If $\beta s_j M < R_j$, then $\frac{d\Pi_j^*(z_j,z_{-j})}{dz_j}$ 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 $R_j < \beta s_j q_j^0$, $\frac{d\Pi_j^*(z_j,z_{-j})}{dz_j}$ is always positive and highest profits are reached for $z_j = 1$. In the last case, when $\beta s_j q_j^0 < R_j < \beta s_j M$, there exists a value $\tilde{z}_j(z_{-j}) > 0$ above which $\frac{d\Pi_j^*(z_j,z_{-j})}{dz_j}$ 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 $\Pi_j^*(z_j, z_{-j}) < \Pi_j^*(0, z_{-j})$ 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 $(1,1)$.

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 $(1,0)$. □

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

Proof of Remark 3

Proof. Suppose the supplier could choose for both producers, i.e. $z_1 = z_2 = z_S$. Both producers produce the same quantity (q_j) at the same price (p_j) determined by level of innovation z_S.

$$E[\Pi_S] = 2s_j p_j q_j - \theta C_S(.|\rho = 1 - \sigma z_S) - (1-\theta)C_S(.|\rho = 1) - 2R_S z_S \tag{A.4}$$

In what follows, we use the notation C^m for $C_S(.|\rho = 1 - \sigma z_S)$, and C^c for $C_S(.|\rho = 1)$ (m for miscoordination and c for coordination). The derivative of $\Pi_S(z_S)$ with respect to z_S is:

$$\frac{dE[\Pi_S]}{dz_S} = 2(\frac{dp^*}{dz_S}q(z_S) + p^*(z_S)\frac{dq^*}{dz_S}) - 2R_s - \theta\frac{dC^c}{dq}\frac{dq^*}{dz_S} - (1-\theta)(\frac{\partial C^m}{\partial q}\frac{dq^*}{dz_S} + \frac{\partial C^m}{\partial \rho}\frac{d\rho}{dz_S}) \tag{A.5}$$

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 $p^*(z_S)$ and $q^*(z_S)$ reach a plateau for some value of z_S . The derivative in equation A.5 becomes $-2R_S + (1-\theta)\sigma\partial C^m/\partial\rho$, which is negative. Thus, if the cost and demand parameters are such that there is a value of z_S at which profits are maximized and positive, then there is a larger value of z_S at which point profits fall under $\Pi_S(0)$. Denote it $\bar{z}_S$. Additionally, since at $z_S = 0$, profits originally fall with increasing z_S, there is also a value $\underline{z}_S$ under which profits are less than $\Pi_S(0)$.

Hence either $E[\Pi_S(z_S)] < \Pi_S(0)$ for all $z_S \in]0,1]$ or there exists $\underline{z}_S$ and $\bar{z}_S$ such that $0 < \underline{z}_S < z_S^* < \bar{z}_S$. Given this, the possible NE follow from Remark 2. Indeed, if $z_S^* \geq \underline{z}_j(z_S^*)$, then producers will be willing to invest z_S^* as well. If on the other hand $z_S^* < \underline{z}_j(z_S^*)$, then the supplier will choose z_S^c such that $z_S^c = \underline{z}_j(z_S^c)$. z_S^c is the minimum level that ensures that producers will innovate too (each choosing z_S^c by Remark 2). At z_S^c, the supplier does not make optimal profits but, if $z_S^c < \bar{z}_S$, it still makes higher profits than if $z_S = 0$. Finally, if instead $\bar{z}_S < z_S^c$, or if we are in the case in which $E[\Pi_S(z_S)] < \Pi_S(0)$ for all $z_S \in]0,1]$, then there will be no innovative investments, i.e. $z_S = 0$. $\square$

Proof of Result 1

Proof. We first show that the maximizer z_S^* that arises in the equilibrium (z_S^*, z_S^*, z_S^*) decreases with θ. Then we will show that as θ increases, the equilibrium can shift to $(0,0,0)$. By the envelope theorem, $\frac{dz_S^*}{d\theta} = \frac{\partial^2 E[\Pi_S]/\partial\theta\partial z_S}{-\partial^2 E[\Pi]^S/\partial z_S \partial z_S}$, where the derivatives are estimated at z_S^*. Since at z_S^* 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_S (Remark 3) so denote them $q^*(z_S)$ and $p^*(z_S)$. Also denote $C^c(z_S)$ the cost under successful coordination and $C^m(z_S)$ the cost under unsuccessful coordination.

$$\begin{aligned}
\frac{\partial E[\Pi_S]}{\partial z_S} &= \frac{\partial p^*}{\partial z_S} q(z_S) + p^* \frac{dq^*}{dz_S} - R_s - (1-\theta)\frac{\partial C^c}{\partial q}\frac{dq^*}{dz_S} - \theta\left(\frac{\partial C^m}{\partial q}\frac{dq^*}{dz_S} + \frac{\partial C^m}{\partial \rho}\frac{d\rho}{dz_S}\right) \\
\Rightarrow \frac{\partial^2 E[\Pi_S]}{\partial\theta\partial z_S} &= -\underbrace{\frac{dq^*}{dz_S}}_{\geq 0}\underbrace{\left(\frac{\partial C^m}{\partial q} - \frac{\partial C^c}{\partial q}\right)}_{>0} - \underbrace{\frac{\partial C^m}{\partial \rho}}_{<0}\underbrace{\frac{\partial \rho}{\partial z_S}}_{<0} < 0 \qquad \text{(A.6)}
\end{aligned}$$

The sign of each term is evident given previous results, except for $\frac{\partial C^m}{\partial q} - \frac{\partial C^c}{\partial q}$, which is positive because $\frac{\partial C^m}{\partial q} - \frac{\partial C^c}{\partial q} = (2^{k/(1-\sigma z_S^*)} - 2^k)kq^{k-1} > 0$.

Within the region in which the (z_S^*, z_S^*, z_S^*) solution holds ($z_S^* \geq \underline{z}_j$ and $E\Pi(z_S^*) > \Pi(0)$), we therefore have that z_S^* decreases with θ. But θ also changes the size of that region. First, since z_S^* 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, $\frac{dE\Pi(z_S^*,\theta)}{d\theta} = \frac{\partial E\Pi(z_S^*(\theta),\theta)}{\partial\theta}$. This is $-C^c(z_S^*) + C^m(z_S^*) > 0$ 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. □

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.6:

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

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 $\frac{d^2 z_S^*}{dkd\theta}<0$. □

Proof of Result 3

Proof. Consider a generic function $f(x,y)$. Define $\underline{x}(y)$ such that $f(\underline{x},y)=0$. Then:

- the combination of $f_y(x) > 0$ and $f_x(y) > 0$ in the vicinity of $\underline{x}(y)$, form a sufficient condition for $\frac{d\underline{X}}{dy} < 0$
- the combination of $f_y(x) < 0$ and $f_x(y) < 0$ in the vicinity of $\underline{x}(y)$, form a sufficient condition for $\frac{d\underline{X}}{dy} < 0$
- the combination of $f_y(x) < 0$ and $f_x(y) > 0$ in the vicinity of $\underline{x}(y)$, form a sufficient condition for $\frac{d\underline{X}}{dy} > 0$
- the combination of $f_y(x) > 0$ and $f_x(y) < 0$ in the vicinity of $\underline{x}(y)$, form a sufficient condition for $\frac{d\underline{X}}{dy} > 0$

Hence, to establish the result, it suffices to establish the monotonicity and sign of the derivatives of the supplier's value function $E[\Pi^{S*}](\theta, M, \beta, R_S)$ with respect to those four paramters. For this, we use the envelope theorem:

$$\begin{aligned} \frac{dE[\Pi^{S*}]}{d\theta} &= \frac{\partial E[\Pi_S](z_S^*)}{\partial \theta} \\ &= -C^m + C^c < 0 \end{aligned} \tag{A.7}$$

$$\begin{aligned} \frac{dE[\Pi^{S*}]}{dR_S} &= \frac{\partial E[\Pi_S](z_S^*)}{\partial R_S} \\ &= -1 < 0 \end{aligned} \tag{A.8}$$

The combination of Eq. A.7 and A.8 establishes the first part of the result.

$$\begin{aligned} \frac{dE[\Pi^{S*}]}{dM} &= \frac{\partial E[\Pi_S](z_S^*)}{\partial M} \\ &= sp^* \frac{\partial q}{\partial M} - \frac{\partial q}{\partial M}\frac{\partial E[C]}{\partial q} \end{aligned} \tag{A.9}$$

Denote M^c the value of M at which this derivative is equal to 0. We show that at M^c,

$E[\Pi^{S*}]$ reaches a minimum and is negative, such that $E[\Pi^{S*}]$ is monotonically increasing as M increases beyond M^c.

At M^c, $sp^* = \frac{\partial E[C]}{\partial q}$. Plugging that into the expression for $E[\Pi^{S*}]$, we get:

$$E[\Pi^{S*}] = \frac{\partial E[C]}{\partial q} q^* - E[C](q^*) - R_S z_S^* \approx -R_S z_S^* < 0 \tag{A.10}$$

Hence, Equation A.9 reaches a minimum at a value M^c above which it increases monotonically. Hence in the vicinity of $\underline{\mathrm{M}}$, the derivative is positive. Combining this fact with Equation A.7 establishes the second part of the result.

Very similarly, we have:

$$\begin{aligned} \frac{dE[\Pi^{S*}]}{d\beta} &= \frac{\partial E[\Pi_S](z_S^*)}{\partial \beta} \\ &= sp^* \frac{\partial q}{\partial \beta} - \frac{\partial q}{\partial \beta} \frac{\partial E[C]}{\partial q} \end{aligned} \tag{A.11}$$

This derivative is equal to 0 at two points: when $sp^* = \frac{\partial E[C]}{\partial q}$ (happening at β^{c_1} and when $\frac{\partial q}{\partial \beta} = 0$ (happening at point β^{c_2}. Beyond β^{c_2}, the demand function q saturates, having included the whole market. At this point, both the demand and profits reach a maximum, and $\frac{\partial q}{\partial \beta} = 0$ and $\frac{dE[\Pi^{S*}]}{d\beta}$. In contrast, at β^{c_1}, the profit function reaches a minimum. By the same reasoning as in Equation A.10, the profit function is negative at that point. Suppose $E[\Pi^{S*}]$ is positive for β^{c_2} (whether this is true or not depends on parameters governing the relative importance of costs and revenues, such as c_s, M, u_0 etc...). Then by the intermediate value theorem, $\exists \underline{\beta}$ such that $\beta^{c_1} < \beta < \beta^{c_2}$, at which $E[\Pi^{S*}] = 0$ and at that point $\frac{dE[\Pi^{S*}]}{d\beta} > 0$. The combination of that statement and Equation A.7 establishes the third part of the result. □

Proof of Remark 4

$$\frac{\partial E[\Pi_S]}{\partial z_j} = 2sM\frac{\partial p^*}{\partial z_j}P(z) + 2sMp^*(z)\frac{dP(z)}{dz} - \theta(M\frac{\partial C^m}{\partial MP}\frac{dP(z)}{dz} + \frac{\partial C^m}{\partial \rho}\frac{d\rho}{dz}) - (1-\theta)(M\frac{\partial C^c}{\partial MP}\frac{dP(z)}{dz}) - R$$

$$\Rightarrow = 2sM\beta P^2(z) + 2sMp^*(z)\beta P(z)(1-P(z))^2 - R_s - \tag{A.12}$$

$$k\beta(1-P(z))^2\left(\theta C^m(MP(z)) + (1-\theta)C^c(MP(z)) + \theta\frac{\partial C^m}{\partial \rho}\frac{d\rho}{dz_j}\right) \tag{A.13}$$

$$\frac{\partial^2 E[\Pi_S]}{\partial M \partial z} = 2s\beta P^2(z) + 2sMp^*(z)\beta P(z)(1-P(z))^2 - \tag{A.14}$$

$$\frac{k^2}{M}\beta(1-P(z))^2\left(\theta C^m(MP(z)) + (1-\theta)C^c(MP(z))\right) \tag{A.15}$$

Since $(\theta C^m(MP(z)) + (1-\theta)C^c(MP(z))) \leq 2sp^*(z)MP(z)$ when producing is profitable (cost must be smaller than revenue), we have:

$$\frac{\partial^2 E[\Pi_S]}{\partial M \partial z} \geq 2s\beta P^2(z) + 2sMp^*(z)\beta P(z)(1-P(z))^2 - 2k^2\beta(1-P(z))^2 sp^*(z)P(z) \tag{A.16}$$

$$\Rightarrow \geq 2s\beta P^2(z) + 2sp^*(z)\beta P(z)(1-P(z))^2(1-k^2) \geq 0 \tag{A.17}$$

This is positive because $P(z)$ being a probability is $\in [0,1]$ and k is also $\in [0,1]$ (parameter governing economies of scale, we assume there are no diseconomies of scale here). This establishes the result with respect to changes in M.

B Data Description

We use the FactSet Relationship database to obtain information about suppliers, customers and competitors. FactSet contains the most comprehensive relationship database currently available. It covers relationships for a large number of public and private firms between 2003 and 2017. The database includes information publicly reported by firms[15], and complements this information using firms' SEC filings, press releases, public announcements, investor presentations, and firms' websites. Importantly, the database analysts update relationships on an annual basis. The unit of observation in the FactSet Relationship database is a relationship between two firms. The relationship can be labeled as 'supplier', 'customer', or 'competitor'[16]. The database also indicates the beginning and end dates for each relationship. Firms are identified by a FactSet id, and firms' name are also available.

We choose to focus on the car manufacturing sector. To this end, we first collected names of firms listed under the NAICS code 33611, that is "automobile and light duty motor vehicle manufacturing". We obtain a list of 48 companies (examples include Ford, Toyota, Tesla...). We then use FactSet Revere to obtain information about those firms' relationships. Unfortunately firm FactSet ids do match standardized ids, such as ISINs, we identify firms by matching on names. Furthermore, we only keep in our sample firms that are labeled as being competing against each other. Hence, we obtain a list of 27 companies, and use the FactSet Relationship database to obtain data on supplier relationships between 2003 and 2017. We construct a panel dataset where the observations are at the producer-year level. For example, we observe the number of suppliers each producer work with in a given year, as well as the duration of such relationships.

[15] In particular, Regulation SFAS No. 131 requires firms to report customers representing more than 10 percent of the firm's sales.

[16] Other types of relationship, such as partnerships, are also indicated.