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Green Innovation and Competition: R&D Incentives in a Circular Economy

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Abstract: The present paper provides theoretical insights regarding the determinants of firms' incentives to invest in a Circular Economy. The analysis relies on a Cournot model disaggregating the disposal cost in the production function. In a non-simultaneous sequential game, two risk-neutral firms are endowed with a green innovation project that, if successful, would reduce the overall production costs and implement a Circular Economy. Firms are plagued by asymmetric information about the exact value of the other firm's innovation. In this setting, the R&D investment in a Circular Economy, by affecting the distribution of production and disposal costs, influences the production decisions of both the innovating and the rival firms. The sign of the impact depends on the firms' strategy in the product market. Furthermore, the analysis points out that cooperation in R&D of firms competing in the product market reinforces incentives to invest in green innovation. This suggests that governments aimed to advance a Circular Economy should encourage firms' cooperation.

Keywords: circular economy; cournot oligopoly; R&D investment spillovers; green innovation



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1. Introduction

In this contribution, we provide theoretical insights regarding the determinants of firms' incentives to invest in Circular Economy. The Circular Economy (CE) is an extensive rethink of the industrial processes introducing new connections between production, consumption, and resources (Frosch and Gallopoulos [1]). Conceived during the 1970s and 1980s and promoted during the 1990s, the concept of CE is based on the transition from linear economic models based on *take, make, use and waste* towards circular models that *minimise, recover, recycle, and reuse materials, water, and energy* (Geissdoerfer et al. [2]; OECD [3]; Kirchherr et al. [4]). The transition is pursued throughout two crucial steps. One step involves the decoupling of the economic growth from the extraction and consumption of constrained natural resources, like fossil fuels or hard-to-recycle metals and minerals. The other step reshapes the life cycle of products by keeping resources in the overall productive system as long as possible, with the aim to use the essential inputs, have minimal wastes and to turn waste into wealth. Industrial ecology promotes resources minimisation, encourages the adoption of cleaner technologies, and emphasises the benefits of recycling residual waste materials, which become more than just rubbish (Jacobsen [5]; Andersen [6–8]).

Schumpeter [9,10] asserts that innovation is the main force for economic development and CE represents an important means to reduce environmental impact while supporting sustainable economic growth (Millar et al. [11]). A promising line of research seeks to identify the most efficient use of resources for economic sustainability and growth by companies and firms. However, only a few of theoretical and empirical studies have addressed the issue of incentives to invest in Research and Development for green innovation (green R&D)

of firms competing in the product market. Green innovation refers to all types of innovation that incorporate environmental responsibility (Meidute-Kavaliauskiene et al. [12]).

Cella and Etro [13], study competition between firms involved in R&D activities and analyse the incentive-compatible contracts for managers under hidden productivity. In another theoretical paper the same authors find a positive correlation between number of firms and effort differentials (Cella and Etro [14]). They explain the weak but positive relation between competition and incentive mechanisms highlighted in several empirical studies (Hubbard and Palia [15]; Cuñat and Guadalupe [16]; Bloom and Van Reenen [17]).

Lambertini et al. [18], explore the relationship between competition and innovation aimed at reducing polluting emissions. They find an inverted-U relationship between firm's green innovation and competition (as in Aghion [19]), driven by the presence of R&D spillover in the Cournot oligopolistic market.

Another strand of literature that has flourished in recent years studies how the corporate governance structure affects innovation, emphasising that the internal governance mechanism may be a key factor in business innovation. Tylecote and Visintin [20], show that the corporate governance is one of the main determinants for innovation and technological change. More recent empirical papers, focusing on the relationship between governance mechanisms and managers' innovation decisions, point out a significant impact of both ownership structure and shareholder identity on innovation efforts and outcomes (Tribo et al. [21]; Wu [22]; Latham and Braun [23]; Belloc [24]; Block [25]; Balsmeier et al. [26]; Zhang et al. [27]; Tsao et al. [28]). Garrido-Prada et al. [29], find that the knowledge generated by public environmental and energy R&D positively affects SMEs' implementation of CE activities, but its effect on the level of investment is negative.

To the best of our knowledge, there is no paper investigating the incentives to invest in CE of firms operating in oligopolistic product markets. For example, Cella and Etro [14], consider an economic framework where manager's effort can reduce production costs, and in Lambertini et al. [18], the green innovation concerns the lowering of emissions. However, the main goal of investments in CE is to lessen the environmental footprint of production by retaining resources as long as possible in the productive system.

To make a step in this direction, we study a Cournot duopoly in which each competing firm first does R&D in CE and then chooses the production level. If successful, the R&D activity results in a green innovation, which reduces production costs by making the innovator able to use, in the production process, recycled resources from the competitor's production waste. (It has to be highlighted that in our model each firm decides to use the competitor's waste rather than its waste because of its different technical characteristics. For sake of simplicity we consider that innovation does not allow the firm to recycle or reuse its own waste, but our (qualitative) results would be robust with respect to the introduction of such an assumption.) In addition, the innovation produced by each firm also generates a positive spillover on the rival's disposal costs. (Our analysis relies on a Cournot model disaggregating the disposal cost in the production equation.)

The main novelty of our model concerns the distribution of the overall production costs of each firm which is endogenously influenced by the R&D investment of both competing firms. Moreover, the level of R&D investment positively affects the probability of success and is publicly observed, while the R&D outcome is private information of the innovating firm. As a result, each firm forms its expectations about both its disposal cost and the production costs incurred by its competitor, based on the observable R&D investment. This implies that the investment in green R&D affects the production decisions of both the innovating and the rival firm. The sign of the impact depends on the firms' strategy in the product market. In particular, the impact of the R&D investment on the output of the R&D-taking firm is a positive if the rival's firm is sufficiently aggressive in the product market—i.e., it produces large quantities—and negative otherwise. Conversely, the impact on the output of the rival's firm is negative if it plays very aggressively and positive otherwise. Finally, we show that cooperation in R&D of firms competing in the product market reinforces incentives to invest in green innovation. Hence, in order to incentive the

CE implementation, policy makers can not only increase the public investment in green R&D, as suggested by Garrido-Prada et al. [29], but also encourage firms' cooperation.

The remainder of the paper is organised as follows: Section 2 sets up the model, in Section 3 we illustrate the equilibrium outcome of the product market game. In Section 4, we investigate the R&D stage of the game, under the two alternative assumptions that firms act noncooperatively and cooperatively in the R&D game. Finally, Section 5 concludes. All proofs are in the Appendix A.

2. The Model

Players and Environment: Consider a single period economy where two risk-neutral firms, A and B , face Cournot competition in the product market. The inverse market demands are defined by:

$$\begin{aligned} P^A(q^A, q^B) &= D - q^A - \theta q^B, \text{ for firm } A, \\ P^B(q^A, q^B) &= D - \theta q^A - q^B, \text{ for firm } B \end{aligned}$$

where $P^i(\cdot)$ and q^i , with $i = A, B$, denote the price of the good and the quantity sold by firm i , respectively. As standard, θ denotes the intensity of product differentiation, with $0 \leq \theta \leq 1$, and it is a measure of competitive pressure.

The cost function for firm i , with $i = A, B$, is denoted by $C^i(q^i)$. We suppose that it is additive with respect to two components, one strictly related to the production process, $\beta(q^i)$, assumed linear in q^i , and another related to the disposal process, $\alpha^i(q^i)$, assumed increasing and convex in q^i . Then, $C^i(q^i) = \beta(q^i) + \alpha^i(q^i)$.

Green R&D: Firms are endowed with a green innovation project that, if successful, would reduce the production costs. Hence, before undertaking production, each firm decides the level of investment in green innovation, whose outcome is uncertain.

Green innovation makes the innovator able to use in the production process recycled resources from the competitor's production waste, by reducing its marginal production cost. Moreover, the innovation process of each firm gives rise to a positive technological spillover on the expected profit of its competitor, by reducing the disposal costs.

Innovation can either be successful or unsuccessful with respective probabilities μ_i and $1 - \mu_i$, where μ_i represents the intensity of firm i 's R&D. This implies that a more intensive R&D investment (higher μ_i) is more likely to generate a successful green innovation and thus lower production costs for both firms.

In the case of innovation failure, the standard production cost is $\beta(q^i) = c_0 + c_1 q^i$, with $c_0 > 0$ and $0 < c_1 < 1$, and the disposal cost, is $\alpha^i(q^i) = \alpha_i z(q^i)$, where $z(q^i)$ is the production waste, which we assume increasing in the quantity, and $\alpha_i > 0$ is the marginal disposal cost. Hence, in this case, the production costs are described by the following function:

$$C^i(q^i) = \beta(q^i) + \alpha^i(q^i) = c_0 + c_1 q^i + \alpha_i z(q^i).$$

A successful innovation allows firm i to use in the production process a fraction $\sigma_i \in (0, 1)$ of the production waste of the competitor, $z(q^{-i})$, by reducing its marginal production cost of $\delta(\sigma_i z(q^{-i}))$, where $\delta(\cdot) < 1$ is an increasing positive function and measures the innovation productivity. In the case of successful innovation of firm i , indeed, its standard production cost becomes $\beta(q^i) = c_0 + [c_1 - \delta(\sigma_i z(q^{-i}))]q^i$. Moreover, in the case of successful innovation of firm $-i$, the disposal cost of firm i becomes $\alpha^i(q^i) = \alpha_i(1 - \sigma_{-i})z(q^i)$. Hence, in this case the production cost of firm i is described by the following function:

$$C^i(q^i) = c_0 + [c_1 - \delta(\sigma_i z(q^{-i}))]q^i + \alpha_i(1 - \sigma_{-i})z(q^i).$$

To summarize, the cost function of firm i , with $i = A, B$, becomes:

$$C^i(q^i, q^{-i}, \tilde{\gamma}_i, \tilde{\gamma}_{-i}) = c_0 + [c_1 - \tilde{\gamma}_i \delta(\sigma_i z(q^{-i}))]q^i + \alpha_i(1 - \tilde{\gamma}_{-i}\sigma_{-i})z(q^i).$$

We interpret $\tilde{\gamma}_i$ as being the uncertain outcome of the cost-reducing R&D activity carried out by firm i . Formally, $\tilde{\gamma}_i$ is a random variable belonging to $\{0, 1\}$, where $\tilde{\gamma}_i = 1$ corresponds to successful green innovation and thus to a greater material reuse and recycling and $\tilde{\gamma}_i = 0$ corresponds to unsuccessful green innovation. As above mentioned, the probability of $\tilde{\gamma}_i = 1$ is μ_i . Therefore, the distribution function of $\tilde{\gamma}_i$ is endogenous and depends on the intensity of green innovation investment.

To simplify the analysis, we assume that both $z(\cdot)$ and $\delta(\cdot)$ are linear and denote by $z \in (0, 1)$ the waste per unit of output and by $\delta \in (0, 1)$ the constant marginal productivity of innovation.

In addition, a successful innovation of any firm also brings forth a direct effect on its competitor's profit. Indeed, when firm i recycles the production waste of firm $-i$, its marginal disposal cost reduces of $\sigma_i \alpha_{-i}$. Hence, the parameter σ_i captures positive R&D spillover that the innovation produced by firm i generates on firm $-i$'s disposal costs. (In our model, in order to capture the spillover effects which characterise CE, we assume that each firm prefers to use competitors' waste. The justification is in the parameter σ_i which takes into account the positive spillover effect R&D on the competitor's disposal cost).

It is useful to highlight that while standard models consider $C^i(q^i) = c_0 + c_1 q^i$, in our model we disentangle the production cost by considering apart from the standard cost related to the production cost, also a further component, $\alpha^i z(q^i)$, strictly linked to the disposal process.

We assume that while the extent of R&D activities (μ_i) is publicly observed, their outcome γ_i is not: only the innovator has private information on the exact value of their innovation, whereas the rival firm must base its estimate of the green innovation value on the observable R&D investment μ_i . Moreover, we assume that the R&D expenditure is included in the fixed cost, c_0 and does depend on the level investment.

Green R&D is the main novelty of our model and deserves a digression. Spence [30], first pointed out that in a market where firms compete in R&D, there is a significant disincentive for private investment in product development. This disincentive manifests itself through two distinct channels. First, innovative firms limit their investment in product R&D if they perceive a low probability of make exclusive use of the results of their R&D efforts, i.e., if new technological knowledge spills over to competitors. Second, if firms can use the spilled knowledge, they will do so at the expense of their own R&D. Hence, firms operating in technological and scientific environments with a high level of spillover put less effort into innovation. However, in our CE model, firms do not compete in R&D, i.e., cooperative research efforts bring together competitors, D'Aspermont & Jackemin [31] and Brander & Spencer [32]. This implies that there is no disincentive effect and the investment is higher than under R&D competition. Moreover, we assume that a successful investment corresponds to a higher use of waste materials. The idea of using competitors' waste materials is closely linked to the concept of CE: simply using one's own waste materials increases innovator's efficiency, using competitors' waste materials induces a reduction in disposal costs and increases total welfare.

Timing and equilibrium concept: The timing is as follows: at time $t = 0$, each firm i , with $i = A, B$, decides the investment level in green innovation, μ_i . Both μ_A and μ_B are publicly observed. At time $t = 1$, the R&D outcomes $\tilde{\gamma}_A$ and $\tilde{\gamma}_B$ realize. Firm i privately observes $\tilde{\gamma}_i$, with $i = A, B$. At time $t = 2$, product market competition takes place in a standard fashion.

The equilibrium concept will be Bayes–Nash equilibrium and the choice of R&D intensity will be derived backward.

3. The Equilibrium in the Product Market

In this section, we characterise the equilibrium outcome of the product market game described in the previous section for any pair of R&D investment, μ^A and μ^B . Indeed, in our setting, the observable R&D choice of each firm affects the competing firm's expectation about both the innovator's production strength and their own disposal cost. Thus, at the second stage, the production strategy of each firm depends on the intensity of the R&D investments, μ^A and μ^B .

Formally, at time $t = 0$ firm i , with $i = A, B$, anticipating the impact of R&D on the product market outcome, chooses its level of R&D investment μ_i which maximises its expected profit:

$$\Pi^i = \mu_i \bar{\Pi}^i + (1 - \mu_i) \underline{\Pi}^i,$$

where $\bar{\Pi}^i$ and $\underline{\Pi}^i$ are the firm's profits conditional on $\tilde{\gamma}_i = 1$ and $\tilde{\gamma}_i = 0$, respectively, and μ_i is its R&D investment. At time $t = 1$, the R&D outcomes realise and each firm observes the achievement of its own investment. Finally, at time $t = 2$ firm i , with $i = A, B$, chooses the optimal production level, given the realised $\tilde{\gamma}_i \in \{0, 1\}$.

If $\tilde{\gamma}_i = 1$, the optimisation problem of firm i is to choose \bar{q}^i which maximises the expected profit:

$$\begin{aligned} \bar{\Pi}^i = & \mu_{-i} \{ (D - \bar{q}^i - \theta \bar{q}^{-i}) \bar{q}^i - [c_0 + (c_1 - \delta \sigma_{-i} \alpha_{-i} (z \bar{q}^{-i})) \bar{q}^i + (1 - \sigma_{-i}) \alpha_i (z \bar{q}^i)] \} + \\ & (1 - \mu_{-i}) \{ (D - \bar{q}^i - \theta \underline{q}^{-i}) \bar{q}^i - [c_0 + (c_1 - \delta \sigma_{-i} \alpha_{-i} (z \underline{q}^{-i})) \bar{q}^i + \alpha_i (z \bar{q}^i)] \}. \end{aligned}$$

Since firm i does not observe the outcome of the R&D investment of firm $-i$, its expected profit depends on the R&D investment of the competitor in the product market, μ_{-i} . Let us denote with $E_{-i} \equiv \mu_{-i} \bar{q}^{-i} + (1 - \mu_{-i}) \underline{q}^{-i}$ the expected production of firm $-i$. With a simple algebraic calculus, the expected profit simplifies to:

$$\bar{\Pi}^i = -(\bar{q}^i)^2 - c_0 + \bar{q}^i [d_1^i + d_2^i \mu_{-i} - (\theta - \delta d_2^{-i}) E_{-i}],$$

where $d_1^i \equiv D - c_1 - \alpha_i z$ and $d_2^i \equiv \sigma_{-i} \alpha_i z$.

If $\tilde{\gamma}_i = 0$, the optimisation problem of firm i is to choose \underline{q}^i which maximises the expected profit:

$$\begin{aligned} \underline{\Pi}^i = & \mu_{-i} [(D - \underline{q}^i - \theta \bar{q}^{-i}) \underline{q}^i - (c_0 + c_1 \underline{q}^i + (1 - \sigma_{-i}) \alpha_i (z \underline{q}^i))] + \\ & (1 - \mu_{-i}) [(D - \underline{q}^i - \theta \underline{q}^{-i}) \underline{q}^i - (c_0 + c_1 \underline{q}^i + \alpha_i (z \underline{q}^i))], \end{aligned}$$

which with a simple algebraic calculus simplifies to:

$$\underline{\Pi}^i = -(\underline{q}^i)^2 - c_0 + \underline{q}^i [d_1^i + d_2^i \mu_{-i} - \theta E_{-i}].$$

The first order conditions for firm i 's optimisation problem are:

$$\begin{cases} -2\bar{q}^i + d_1^i + d_2^i \mu_{-i} - (\theta - \delta d_2^{-i}) E_{-i} = 0 \\ -2\underline{q}^i + d_1^i + d_2^i \mu_{-i} - \theta E_{-i} = 0. \end{cases} \tag{1}$$

Assume $\theta > \delta d_2^i$ for any $i = A, B$. The production rules, $\bar{q}^i(\mu_A, \mu_B)$ and $\underline{q}^i(\mu_A, \mu_B)$, which associate to any pair of R&D investments, μ_A and μ_B , the optimal quantities chosen in the Cournot–Nash equilibrium, can be obtained by combining the first order conditions of both firms. Next propositions characterise the optimal expected quantities rule, $E_i(\mu_A, \mu_B)$.

Proposition 1. For any pair of R&D investment, μ_A and μ_B , the optimal expected quantity of firm i , with $i = A, B$, is

$$E_i(\mu_A, \mu_B) = \frac{2(d_1^i + d_2^i \mu_{-i} - \frac{1}{2}(\theta - \delta d_2^{-i} \mu_i)(d_1^{-i} + d_2^{-i} \mu_i))}{4 - (\theta - \delta d_2^{-i} \mu_i)(\theta - \delta d_2^i \mu_{-i})}.$$

Proof in Appendix A.

Corollary 1. The impact of the marginal disposal cost α_i on the optimal expected production level, $E_i(\mu_A, \mu_B)$, is negative for any innovation level, $\mu_i > 0$.

Proof in the Appendix A.

Proposition 1 and Corollary 1 describe the optimal expected production as a function of the R&D expenditures and show that an increase in the disposal cost α_i reduces the optimal quantity produced by firm i both in the case of successful innovation and in the event of innovation failure.

The next proposition describes the effect that the investment in R&D has on the expected production. Relative to this, it is interesting to notice that the investment in the green R&D activity positively affects the expected marginal profit of both the innovating and the competing firm, denoted by i and $-i$, respectively. The former increases because a higher probability of success in the innovation process implies lower expected marginal costs. This results in a greater level of expected production, all other variables being equal. Moreover, the magnitude of this effect depends on $E_{-i}(\mu_A, \mu_B)$. Indeed, the availability of environmentally friendly inputs that, in the event of success, firm i can use in its production process depends on the production waste of firm $-i$, which is positively correlated with the production level. The second increases because the R&D investment of firm i also lowers the rival's cost. Indeed, recycling production waste in the circular economy reduces the expected marginal disposal costs of firm $-i$, which becomes more aggressive in the product market. The R&D spillover effect has a negative impact on the optimal production level of firm i . Indeed, since $\theta > \delta d_2^{-i} \mu_i$ by assumption, the standard negative price effect of a more aggressive strategy of firm $-i$, which depends on the competitive pressure, θ , is larger than the positive green effect, measured by the expected productivity of the green technology, $\delta d_2^{-i} \mu_i$. Hence, the cost reduction direct effect of innovation always goes in the opposite direction of the spillover effect.

Proposition 2. There exist $\psi_i > 0$ and $\psi_{-i} > 0$, with $\psi_i < \psi_{-i}$, such that (i) $\frac{dE_i(\mu_A, \mu_B)}{d\mu_i} < 0$ if and only if $D - c_1 < \psi_i$, and (ii) $\frac{dE_{-i}(\mu_A, \mu_B)}{d\mu_i} < 0$ if and only if $D - c_1 > \psi_{-i}$.

Proof in Appendix A.

The first point of Proposition 2 states that a higher expenditure in green innovation gives the R&D-taking firm, i , disincentives to produce if the expected production level of the rival's firm, $-i$, is small enough, that is, if $D - c_1$ is below a threshold level ψ_i . The second point states that it gives the rival's firm disincentives to produce if its production level is large enough, that is, if $D - c_1$ is above a threshold level ψ_{-i} greater than ψ_i .

To gain intuition about this result, consider the Cournot expected reaction functions. The expected reaction functions can be easily obtained by combining the first order conditions (1):

$$\begin{cases} E_A = \frac{d_1^A + d_2^A \mu_B - (\theta - \mu_A \delta \sigma_A \alpha_B) E_B}{2} \\ E_B = \frac{d_1^B + d_2^B \mu_A - (\theta - \mu_B \delta \sigma_B \alpha_A) E_A}{2} \end{cases} \quad (2)$$

A greater investment in the green R&D activity of firm A leads both firms to be more aggressive in the products market. Indeed, if μ_A increases, the innovator's expected reaction function gets steeper in the $E_B - E_A$ plane, due to the lower expected marginal

costs, and the rival’s expected reaction function moves parallel upwards, due to the lower expected disposal costs. Keeping the rival’s strategy constant, firm A ’s higher investment in R&D would result in an increase of $E_A(\mu_A, \mu_B)$ and a simultaneous reduction of $E_B(\mu_A, \mu_B)$. However, the shift in firm B ’s reaction function has a negative impact on $E_A(\mu_A, \mu_B)$ and a positive impact on $E_B(\mu_A, \mu_B)$. The final effect on the innovator’s expected production is negative if $E_B(\mu_A, \mu_B)$ is small enough, that is, $D - c_1$ is lower than the threshold ψ_A , whilst the final effect on the rival’s expected production is negative if $E_B(\mu_A, \mu_B)$ is sufficiently large, that is, $D - c_1$ is higher than the threshold ψ_B . Hence, for low values of $D - c_1$, a greater R&D investment of firm A leads to a decrease in $E_A(\mu_A, \mu_B)$ and an increase in $E_B(\mu_A, \mu_B)$, for intermediate values of $D - c_1$, it implies an increase in both $E_A(\mu_A, \mu_B)$ and $E_B(\mu_A, \mu_B)$, and for high values of $D - c_1$, it determines an increase in $E_A(\mu_A, \mu_B)$ and a decrease in $E_B(\mu_A, \mu_B)$.

The rationale for this result is correlated to the CE concept: the reduction of the innovator’s expected marginal costs is linked to the use of recycled raw materials obtained from the rival’s production waste. The larger the production level of firm B , the greater the fraction of production waste that firm A can recycle and use in the production process. This implies that if $E_B(\mu_A, \mu_B)$ is low ($D - c_1 < \psi_A$), the reduction in the production costs is tiny and the positive direct R&D effect on $E_A(\mu_A, \mu_B)$ is small. In this case, the negative effect connected to the more aggressive strategy chosen by the rival prevails, and then $E_A(\mu_A, \mu_B)$ decreases and $E_B(\mu_A, \mu_B)$ increases. The opposite occurs if $E_B(\mu_A, \mu_B)$ is high ($D - c_1 > \psi_B$). For intermediate values of $E_B(\mu_A, \mu_B)$ ($\psi_A \leq D - c_1 \leq \psi_B$), the reduction in production costs is significant enough to cause an increase in $E_A(\mu_A, \mu_B)$. However, this increase is not such as to induce the rival firm to reduce its production.

To simplify the analysis, we assume that firms are symmetric and thus $\alpha \equiv \alpha_i$ and $\sigma \equiv \sigma_i$ for any $i = A, B$, $d_1 \equiv D - c_1 - \alpha$ and $d_2 \equiv \sigma\alpha$. Under this assumption, the Cournot–Nash equilibrium of the market game is:

$$\begin{cases} \bar{q}^i(\mu_A, \mu_B) = q^i(\mu_i, \mu_{-i}) + \frac{\delta d_2}{2} E_{-i}(\mu_A, \mu_B) \\ \underline{q}^i(\mu_A, \mu_B) = \frac{d_1 + d_2 \mu_{-i} - \theta E_{-i}(\mu_A, \mu_B)}{2} \end{cases}$$

with $E_{-i}(\mu_A, \mu_B) = \frac{2(d_1 + d_2 \mu_i) - (\theta - d_2 \delta \mu_{-i})(d_1 + d_2 \mu_{-i})}{(4 - \theta^2 + \delta d_2(\theta(\mu_i + \mu_{-i}) - \delta d_2 \mu_i \mu_{-i}))}$ and $i \in \{A, B\}$.

In the next section, we shall analyse two different R&D games. In the first game firms act noncooperatively in choosing their R&D green investment. In the second one, cooperation takes place at the R&D stage, although firms remain rivals in the marketplace.

4. The Optimal R&D Strategy

4.1. The Noncooperative Game

In this section, we study the R&D stage of the game, under the assumption that firms act noncooperatively. To this aim we assume that at time $t = 0$ firm i , with $i = A, B$, anticipating the impact of R&D on the product market outcome, chooses the level of R&D investment, μ_i , which maximises its expected profit for any level of investment, μ_{-i} , chosen by its competitor:

$$\max_{\mu_i \in [0, 1]} \Pi^i(\mu_A, \mu_B) \equiv \mu_i \bar{\Pi}^i(\mu_A, \mu_B) + (1 - \mu_i) \underline{\Pi}^i(\mu_A, \mu_B),$$

where

$$\begin{cases} \bar{\Pi}^i(\mu_A, \mu_B) \equiv \bar{\Pi}^i(\bar{q}^i(\mu_A, \mu_B), E_{-i}(\mu_A, \mu_B)) \\ \underline{\Pi}^i(\mu_A, \mu_B) \equiv \underline{\Pi}^i(\underline{q}^i(\mu_A, \mu_B), E_{-i}(\mu_A, \mu_B)) \end{cases}$$

are firm i ’s profits conditional on $\tilde{\gamma}_i = 1$ and $\tilde{\gamma}_i = 0$, respectively.

From the envelope theorem, the R&D marginal value is:

$$\frac{d\Pi^i(\mu_A, \mu_B)}{d\mu_i} = \bar{\Pi}^i(\mu_A, \mu_B) - \underline{\Pi}^i(\mu_A, \mu_B) + \left(\mu_i \frac{d\bar{\Pi}^i(\mu_A, \mu_B)}{dE_{-i}(\mu_A, \mu_B)} + (1 - \mu_i) \frac{d\underline{\Pi}^i(\mu_A, \mu_B)}{dE_{-i}(\mu_A, \mu_B)} \right) \frac{dE_{-i}(\mu_A, \mu_B)}{d\mu_i} \tag{3}$$

From the first order conditions (1), $\bar{\Pi}^i(\mu_A, \mu_B) = (\bar{q}^i(\mu_A, \mu_B))^2$ and $\underline{\Pi}^i(\mu_A, \mu_B) = (\underline{q}^i(\mu_A, \mu_B))^2$. Moreover, $\frac{d\bar{\Pi}^i(\mu_A, \mu_B)}{dE_{-i}(\mu_A, \mu_B)} = -(\theta - \delta d_2)\bar{q}^i(\mu_A, \mu_B)$ and $\frac{d\underline{\Pi}^i(\mu_A, \mu_B)}{dE_{-i}(\mu_A, \mu_B)} = -\theta\underline{q}^i(\mu_A, \mu_B)$. By substituting in Equation (3) and rearranging terms, we get

$$\frac{d\Pi^i(\mu_A, \mu_B)}{d\mu_i} = \underbrace{(\bar{q}^i(\mu_A, \mu_B))^2 - (\underline{q}^i(\mu_A, \mu_B))^2}_{\text{Direct effect (+)}} + \left[\underbrace{-\theta E_i(\mu_A, \mu_B) \frac{d(E_{-i}(\mu_A, \mu_B))}{d\mu_i}}_{\text{Strategic effect (\pm)}} + \underbrace{\mu_i \bar{q}^i(\mu_A, \mu_B) \delta d_2 \frac{d(E_{-i}(\mu_A, \mu_B))}{d\mu_i}}_{\text{Green effect (\pm)}} \right]$$

The direct effect of a higher R&D investment on the firm’s expected profit is always positive since it increases the likelihood of a successful innovation and it is the more significant the greater the difference between the quantity produced in each state. The indirect effect goes through the impact that the probability of success in the green innovation, μ_i , has on the expected output of the competitor, i.e., $\frac{dE_{-i}(\mu_A, \mu_B)}{d\mu_i}$, and can be decomposed in strategic and green effect. The strategic effect is negative if the expected production of firm $-i$ increases in the R&D investment of firm i , and positive otherwise. Indeed, if the green innovation of firm i has a positive impact on the expected productivity of its competitor, then a higher R&D investment, μ_i , induces firm $-i$ to behave more aggressively in the product market. This drives product prices up and weakens the incentives for firm i to make large R&D investments since it reduces the marginal benefit of innovation. On the other hand, the green effect goes in the opposite direction: it is positive if the competitor’s expected production increases in μ_i , and negative otherwise. Indeed, higher expected production of firm $-i$ implies a more significant reduction in the expected marginal production costs of firm i . Finally, the strategic effect always prevails on the green one since $\theta > \delta d_2$ by assumption and $E_i(\mu_A, \mu_B) > \mu_i \bar{q}^i(\mu_A, \mu_B)$ by definition of expected production.

In the symmetric equilibrium, $\mu_A = \mu_B = \mu$ and the optimal quantities for any μ are

$$\bar{q}^A(\mu, \mu) = \bar{q}^B(\mu, \mu) = \bar{q}(\mu) \equiv \frac{(d_1 + d_2\mu)(2 + \delta d_2(1 - \mu))}{2(2 - \delta d_2\mu + \theta)}$$

$$\underline{q}^A(\mu, \mu) = \underline{q}^B(\mu, \mu) = \underline{q}(\mu) \equiv \frac{(d_1 + d_2\mu)(2 - \delta d_2\mu)}{2(2 - \delta d_2\mu + \theta)}$$

Moreover, $E(\mu) = \frac{d_1 + d_2\mu}{2 - \delta d_2\mu + \theta}$ and $\frac{d(E_{-i}(\mu_A, \mu_B))}{d\mu_i}$ evaluated at $\mu_A = \mu_B = \mu$ is positive if $D - c_1 < \psi_{-i}^S$, with $\psi_{-i}^S \equiv \frac{4}{\theta - \alpha d_2 \mu \sigma} + \frac{\alpha \delta (1 - \mu \sigma) + 2}{\delta}$. In this case, the incentives to innovate can be rewritten as:

$$\frac{d\Pi^i}{d\mu_i}(\mu, \mu) = (\bar{q}(\mu))^2 - (\underline{q}(\mu))^2 - (\theta E(\mu) - \mu \bar{q}(\mu) \delta d_2) \frac{dE_{-i}}{d\mu_i}(\mu, \mu).$$

The incentives to innovate for each firm depend on the positive direct impact of R&D on the innovator’s expected profit and on the indirect effect, given by the algebraic sum of the strategic and the green effect, whose sign is influenced by the impact of R&D on the rival’s expected production. In particular, since the strategic effect in the product market is

always stronger than the green effect in the circular economy, in the symmetric equilibrium the final indirect effect is positive if $D - c_1 > \psi_{-i}^S$ and negative otherwise.

4.2. The Cooperative Game

In this section, we introduce cooperation in the R&D game, the second stage remains noncooperative. At the first stage the firms maximise the joint profits, as a function of μ_A and μ_B :

$$\max_{(\mu_A, \mu_B) \in [0, 1]^2} \hat{\Pi}(\mu_A, \mu_B) \equiv \Pi^A(\mu_A, \mu_B) + \Pi^B(\mu_A, \mu_B).$$

From the envelope theorem, the marginal value of the R&D investment in firm i , is:

$$\begin{aligned} \frac{d\hat{\Pi}(\mu_A, \mu_B)}{d\mu_i} &= \sum_{j=\{A,B\}} \frac{d\Pi^j(\mu_A, \mu_B)}{d\mu_i} = \\ &= \underbrace{(\bar{q}^i(\mu_A, \mu_B))^2 - (\underline{q}^i(\mu_i, \mu_{-i}))^2}_{\text{Direct effect (+)}} + \\ &\quad - \underbrace{\theta \left[E_A(\mu_A, \mu_B) \frac{d(E_B(\mu_A, \mu_B))}{d\mu_i} + E_B(\mu_A, \mu_B) \frac{d(E_A(\mu_A, \mu_B))}{d\mu_i} \right]}_{\text{Strategic effect (\pm)}} + \\ &\quad + \underbrace{\delta\sigma\alpha \left[\mu_A \bar{q}^A(\mu_A, \mu_B) \frac{d(E_B(\mu_A, \mu_B))}{d\mu_i} + \mu_B \bar{q}^B(\mu_A, \mu_B) \frac{d(E_A(\mu_A, \mu_B))}{d\mu_i} \right]}_{\text{Green effect (\pm)}}. \end{aligned}$$

According to Proposition 2, $\frac{d(E_A(\mu_A, \mu_B))}{d\mu_i}$ and $\frac{d(E_B(\mu_A, \mu_B))}{d\mu_i}$ are both positive when $\psi_i \leq D - c_1 \leq \psi_{-i}$ and have discordant sign otherwise. Considering the symmetric equilibrium, $\mu_A = \mu_B = \mu$ and the marginal value of the R&D investment can be rewritten as:

$$\frac{d\hat{\Pi}}{d\mu_i}(\mu, \mu) = (\bar{q}(\mu))^2 - (\underline{q}(\mu))^2 - (\theta E(\mu) - \delta\sigma\alpha\mu\bar{q}(\mu)) \frac{d(E_B + E_A)}{d\mu_i}(\mu, \mu), \quad (4)$$

where $\frac{d(E_i(\mu_A, \mu_B))}{d\mu_i}$ evaluated at $\mu_A = \mu_B = \mu$ is positive if $D - c_1 > \psi_i^S$, with $\psi_i^S \equiv \psi_{-i}^S - \frac{(2 - (\theta - \alpha\delta\mu\sigma))(2 + (\theta - \alpha\delta\mu\sigma))^2}{2\delta(\theta - \alpha\delta\mu\sigma)}$. Moreover, since under the symmetric assumption $\frac{d(E_B + E_A)}{d\mu_i}$ is always strictly positive, then the final indirect effect of innovation on the firm's expected profit is negative for all possible levels of $D - c_1$. This implies that in the cooperative setting the incentives to innovate are greater than in the noncooperative framework if $\frac{d(E_A(\mu_A, \mu_B))}{d\mu_i}$ and $\frac{d(E_B(\mu_A, \mu_B))}{d\mu_i}$ evaluated at $\mu_A = \mu_B = \mu$ have discordant sign and $\frac{d(E_i(\mu_A, \mu_B))}{d\mu_i} < 0$. As a result, the cooperative symmetric equilibrium involves higher investment in green R&D whenever $D - c_1$ is lower than ψ_i^S and lower investment otherwise, as summarized in the next proposition.

Proposition 3. *In the symmetric equilibrium, the optimal R&D investment is higher in the cooperative game than in the noncooperative game if and only if $D - c_1 < \psi_i^S$.*

Proposition 3 points out that the green incentives are higher when firms cooperate on R&D investments only if $D - c_1$ is low enough. Since the threshold ψ_i^S is higher the positive effect of each firm's innovation on the disposal costs of the rival firm is greater. For large spillover in the costs the amount of R&D is higher in the cooperative than in the noncooperative equilibrium. This result is due to the fact that firms cooperating can capture more of the surplus created by their joint research activities and this induces higher green investments. Hence, a cooperative behaviour in a CE can play a positive role in

markets where firms are characterised by R&D activities generating important spillover effects throughout both production and disposal costs.

5. Conclusions

The CE embodies policies and strategies for more efficient consumption of energy, materials and water, limiting waste flowing into the environment. Firms in the CE aim to synergically achieve common economic and environmental benefits by using resources effectively and efficiently. A greater CE can improve the productivity, reduce waste and improve efficiency in the production of goods, and diversify and expand the resource base of the economy. This paper fits in this literature by studying, in a product market competition framework, a firm's decision to engage in R&D activities. In a non-simultaneous sequential play, we consider two risk-neutral firms, plagued by asymmetric information, endowed with a green innovation project that, if successful, would reduce the production costs. Hence, before undertaking production, each firm must decide on the level of investment in green innovation, the outcome of which is uncertain. The key assumption of the analysis is that the competitors are unable to observe the outcome of the R&D process, whilst the intensity of R&D activity affects the rivals perception of the firm's strength. We formally analyse a two-stage game in a market in which, in a first stage, the observable R&D choice of each firm affects the competing firm's expectation about both the innovator's production strength and their own disposal cost. In a second stage, the production strategy of each firm depends on the intensity of the R&D investments. The main contributions to the existing literature can be synthesised as follows. Firstly, we find that the impact of the marginal disposal cost on the optimal expected production level is negative for any innovation level. In other terms, we show that an increase in the disposal cost reduces the optimal quantity produced by the innovator both in the case of successful innovation and in the event of innovation failure. The second result concerns the effect that the investment in green R&D has on the expected production. Relative to this, it is interesting to notice that the investment in the green R&D activity positively affects the expected marginal profit of both the innovating and the competing firm. The latest results concern the optimal R&D strategy to adopt in the case of noncooperative and cooperative game. In the first case, we find that the incentives to innovate for each firm depend on the positive direct impact of R&D on the innovator's expected profit and on the indirect effect, given by the algebraic sum of the strategic and the green effect, whose sign is influenced by the impact of R&D on the rival's expected production. Specifically, we show that in the CE the strategic effect in the product market is always stronger than the green effect. When we introduce cooperation in the R&D game, the second stage remaining noncooperative, we find that for large spillovers in the costs the amount of R&D is higher in the cooperative equilibrium than in the non-cooperative one. This effect may be due to the fact that when firms cooperate they catch more of the surplus generated by their joint research activities and this induces higher green investments. Hence, a cooperative behaviour in a CE can play a positive role in markets where firms are characterised by R&D activities generating important spillovers effects throughout both production and disposal costs. Therefore, strong efforts in the CE are economically feasible if competitors pool and create resources and demand through R&D necessary for product innovation. In these cases, competition will not be restricted, as the CE should not lead to the elimination of competition in terms of product or process differentiation, technological innovation or market entry. Further developments will address the assessment of how incentives to innovate change as the number of firms and spillovers changes.

Many papers in the literature focus on first-mover advantages. First-mover advantages are defined in terms of the ability of pioneer firms to earn positive economic returns. In a multi-stage model, many first-mover advantages arise endogenously. In the first stage a certain asymmetry is generated, which allows one firm to have an advantage over the other players. A firm may possess some unique resources or technological leadership. The firm can therefore exploit this advantage, which may last over several periods. In particular,

the first-mover may gain an advantage through sustainable leadership in technology. The leader may have advantages derived from the “learning” or “experience” curve, where costs decrease with cumulative production, or be successful in patent or R&D competitions, where advances in product or process technology are a function of the R&D expenditures themselves. A future development of this research will, therefore, be to consider a multi-period model and analyse the consequences of a first-mover advantage on the optimal level of innovation. In a model with uncertainty about R&D investment, where competitors cannot observe the outcome of the R&D process, the first-mover advantage will be attenuated. It will be very interesting to analyse how cooperation may be an incentive not to exploit a first-mover position due to the positive spillover effects of R&D activities on both production and disposal costs.

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Appendix A. Proof of the Results

Proof of Proposition 1. Assume that the stability condition (SC):

$$\Psi_D \equiv \frac{\partial^2 E(\Pi^A)}{\partial E_A^2} \frac{\partial^2 E(\Pi^B)}{\partial E_B^2} - \frac{\partial^2 E(\Pi^A)}{\partial E_A \partial E_B} \frac{\partial^2 E(\Pi^B)}{\partial E_A \partial E_B} > 0$$

is satisfied. Solving (2) we get:

$$E_i(\mu_A, \mu_B) = \frac{2(d_1^i + d_2^i \mu_{-i} - \frac{1}{2}(\theta - \delta d_2^{-i} \mu_i)(d_1^{-i} + d_2^{-i} \mu_i))}{4 - (\theta - \delta d_2^{-i} \mu_i)(\theta - \delta d_2^i \mu_{-i})} \quad (A1)$$

□

Proof of Corollary 1. Define $f_N(\alpha_i) \equiv d_1^i + d_2^i \mu_{-i} - \frac{1}{2}(\theta - \delta d_2^{-i} \mu_i)(d_1^{-i} + d_2^{-i} \mu_i)$ and $f_D(\alpha_i) \equiv \frac{\Psi_D}{2}$. Substituting in (A1) we obtain:

$$E_i(\mu_A, \mu_B) = \frac{f_N(\alpha_i)}{f_D(\alpha_i)},$$

with $f_N(\alpha_i) > 0$ since $\bar{\Pi}^i > \underline{\Pi}^i > 0$ and $f_D(\alpha_i) > 0$ by the stability condition (SC).

Notice that $\frac{\partial E_i(\mu_A, \mu_B)}{\partial \alpha_i} \propto \frac{\partial f_N(\alpha_i)}{\partial \alpha_i} f_D(\alpha_i) - \frac{\partial f_D(\alpha_i)}{\partial \alpha_i} f_N(\alpha_i)$. Since

$$\begin{aligned} \frac{\partial f_N(\alpha_i)}{\partial \alpha_i} &= -\frac{1}{2}(1 - \sigma_{-i} \mu_{-i}) < 0 \\ \frac{\partial f_D(\alpha_i)}{\partial \alpha_i} &= \frac{1}{2} \delta (\theta - \delta \sigma_i \mu_i \alpha_{-i}) \sigma_{-i} \mu_{-i} > 0 \iff \theta > \delta \sigma_i \mu_i \alpha_{-i} \end{aligned}$$

then, $\frac{\partial E_i(\mu_A, \mu_B)}{\partial \alpha_i} < 0$ if $\theta \geq \delta \sigma_i \mu_i \alpha_{-i}$ and it has an ambiguous sign otherwise. □

Proof of Proposition 2. To simplify notation, define $k_i = (\theta - \mu_i \delta d_2^{-i})$ and $a_i = d_1^{-i} + d_2^{-i} \mu_i$, with $i = \{A, B\}$. Substituting in (2) we get:

$$\begin{cases} -2E_A + a_B - k_A E_B = 0 \\ -2E_B + a_A - k_B E_A = 0. \end{cases} \quad (\text{A2})$$

Assume that the stability condition (SC) is satisfied. Differentiating with respect to μ_i , with $i \in \{A, B\}$, we get

$$\begin{pmatrix} -2 & -k_i \\ -k_{-i} & -2 \end{pmatrix} \begin{pmatrix} \frac{\partial E_i}{\partial \mu_i} \\ \frac{\partial E_{-i}}{\partial \mu_i} \end{pmatrix} = - \begin{pmatrix} E_{-i} \delta d_2^{-i} \\ d_2^{-i} \end{pmatrix}$$

which implies

$$\frac{\partial E_i}{\partial \mu_i} = \frac{d_2^{-i}}{\Psi_D} (2\delta E_{-i} - k_i)$$

and

$$\frac{\partial E_{-i}}{\partial \mu_i} = \frac{d_2^{-i}}{\Psi_D} (2 - \delta k_{-i} E_{-i})$$

Since $\frac{d_2^{-i}}{\Psi_D} > 0$, $\frac{\partial E_i}{\partial \mu_i} \propto (2\delta E_{-i} - k_i)$ and $\frac{\partial E_{-i}}{\partial \mu_i} \propto (2 - \delta k_{-i} E_{-i})$. Since $k_i > 0$ for any $i = \{A, B\}$ by assumption, $\frac{\partial E_i}{\partial \mu_i} < 0$ if and only if $E_{-i} < \frac{k_i}{2\delta}$, and $\frac{\partial E_{-i}}{\partial \mu_i} < 0$ if and only if $E_{-i} > \frac{2}{\delta k_{-i}}$.

Substituting $E_{-i} = \frac{2(a_{-i} - \frac{1}{2} a_i k_{-i})}{4 - k_{-i} k_i}$ and $a_i = D - c_1 - \alpha_{-i} + \sigma_i \alpha_{-i} \mu_i$, simplification and terms collection yield:

$$E_{-i} < \frac{k_i}{2\delta} \iff 2\delta(2(D - c_1 - \alpha_i + \sigma_{-i} \alpha_i \mu_{-i}) - (D - c_1 - \alpha_{-i} + \sigma_i \alpha_{-i} \mu_i) k_{-i}) - k_i(4 - k_{-i} k_i) < 0,$$

which is true if and only if $D - c_1 < \psi_i$, with $\psi_i \equiv \frac{k_i(4 - k_i k_{-i}) + 2\delta(2\alpha_i(1 - \sigma_{-i} \mu_{-i}) - \alpha_{-i}(1 - \sigma_i \mu_i) k_{-i})}{2\delta(2 - k_{-i})}$. Similarly,

$$E_{-i} > \frac{2}{\delta k_{-i}}$$

$$\iff$$

$$2(4 - k_{-i} k_i) - \delta(2(D - c_1 - \alpha_i + \sigma_{-i} \alpha_i \mu_{-i}) - (D - c_1 - \alpha_{-i} + \sigma_i \alpha_{-i} \mu_i) k_{-i}) k_{-i} < 0,$$

which is true if and only if $D - c_1 > \psi_{-i}$, with $\psi_{-i} \equiv \psi_i + \frac{(4 - k_i k_{-i})^2}{2\delta(2 - k_{-i}) k_{-i}}$. \square

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