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Environmental and innovation performance in a dynamic impure public good framework

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Abstract

We model investment decisions regarding innovation and emissions abatement in a dynamic theoretical framework. Considering knowledge stock as an impure public good, we study the reaction function between one representative agent's investments in innovation and the other agents' investments in the public characteristic of the impure public good. We demonstrate that the reaction function has a positive slope under general conditions and that its sensitiveness is affected by assumptions on the elasticity of substitution in the benefit function. The positivity of the reaction function is then empirically tested in an econometric estimation. We exploit an original sector-based database by gathering innovation efforts as well as polluting emissions and economic dimensions over the time span 1996-2005 for 15 European countries and 23 manufacturing sectors. Empirical results show that sector-based innovation investment is positively driven by the public characteristics provided by other sectors. Different reactivity strength for different polluting emissions also allows us to disclose the role of complementarity in agents' decisions.

Keywords: impure public goods, environmental externalities, innovation spillovers.

J.E.L.: D21; H41; O33; Q53; Q55.

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1. Introduction

The current policy agenda of advanced economies, particularly within the European Union (EU), has devoted increasing attention to the relationships between environmental performance and innovation patterns. Doubts over cost effectiveness and political feasibility of regulatory measures for environmental protection give rise to further investigation on which kind of policy measures are more suitable for win-win solutions and innovation is playing a leading role (OECD, 2011a,b). In a certain sense, environmental regulation and innovation patterns are increasingly jointly investigated in order to understand how to ensure the conditions for fostering economic development while protecting the environment (Jaffe *et al.*, 2003; OECD, 2010; van den Bergh *et al.*, 2007).

One specific point in this debate relates to the potential influence of innovation efforts on environmental performance in a sense that technological advancements may produce positive externalities by making less polluting technologies available as a side effect of the general innovative process. In order to deal with this issue, we investigate the reasons behind an agent's innovation decision in a context of impure (or mixed) public good provision (Cornes and Sandler, 1984, 1986).

We propose a theoretical model in which we examine how private agents behave in a dynamic setting when innovation efforts produce a fully appropriable private characteristic and a public characteristic in a typical impure public good framework. We then specifically apply this model to environmental issues in this way: the private characteristic of innovation could be generally given by higher resource productivity (given by higher labour productivity, or higher energy efficiency, for instance), whereas the public characteristic could be represented by a general higher availability of accumulated knowledge (in a typical knowledge spillover framework) or a more specific effect in terms of lower negative environmental externalities (given by a reduction in emissions intensity, for instance).

Our impure public good can be defined as the total amount of cumulated research and development (R&D) efforts, namely an impure public capital good. When the environmental specification is given to the two characteristics of the mixed public good, we can interpret them as typically technical complements (i.e., with a reduction in energy intensity, we also obtain an emissions abatement per unit of output). The investment decisions are then analysed in a dynamic framework; as a main testable implication, we focus on the reaction function between one agent's investment in the mixed good (R&D) and the other agents' investment in the public characteristic.

We show that the degree of complementarity between the private characteristic and the public characteristic of R&D affects the sign of the reaction function. We find that under general conditions, the reaction curve has positive slope in a dynamic setting and the assumptions on the elasticity of substitution in the benefit function affect its sensitiveness. To some extent, the investment decisions of each agent contribute to forming a public good whose benefits spill over to all other agents.

The theoretical findings are then tested by an econometric estimation of the reaction function for a panel of European countries over the period 1995-2006. Since dynamics play a crucial role in the theoretical model, our representative agent is shaped as a sector unit rather than a firm-based statistical unit in order to obtain a long enough time series for a panel of countries. The only available and complete dataset in this sense is the National Accounting Matrix including Environmental Accounts (NAMEA) available from EUROSTAT which provides a large set of EU countries sector-based data on polluting emissions as well as on economic information (Costantini *et al.*, 2011). The NAMEA sector disaggregation is also suitable for a complete and coherent combination with data on innovation efforts, thus giving us an original and unique dataset gathering information on the dynamics of innovation jointly with the evolution of pollution patterns.

The empirical test on the positive slope of the reaction function when the public characteristic is shaped as knowledge spillovers reveals that internal R&D investment choices are strongly influenced by the global R&D stock accumulated both by the other sectors at country level and by the same sector in other countries.

When we refer to the public characteristic of our mixed good in the more specific environmental case, our empirical analysis tests the positivity of the reaction function for two different polluting emissions, carbon dioxide (CO_2) and non-methane volatile organic compounds (NMVOC). The diffusion patterns of these pollutants are different enough to define CO_2 as global pollution, whereas NMVOC are defined as more localised environmental damage. They also differ from a production function point of view since CO_2 is related to energy consumption at general level, whereas NMVOC is closely related to more specific usage of fossil fuels as in road transport or chemical use. Finally, although CO_2 is strictly related to climate change with a damage function diffused over a longer time horizon (and only with an indirect impact on health), NMVOC emissions directly influence health over a shorter horizon. These differences allow us to provide some interesting insights not only into the positivity of the reaction function but also into potential relationships between the degree of complementarity between private and public components and the nature of the environmental externality under scrutiny.

The rest of the paper is structured as follows. Section 2 presents a short literature review. Section 3 describes the theoretical model and main testable implications. Section 4 presents the empirical strategy whereas Section 5 provides the main empirical results. Section 6 concludes the paper.

2. Relevant Literature

An impure public good, or mixed public good, can be broadly defined as a marketed good that jointly provides private and public characteristics, or a good that jointly offers private and public benefits (Cornes and Sandler, 1984, 1986). The early adoption of an impure public good approach to better understand activity like philanthropy in Cornes and Sandler (1984) was further developed by Andreoni (1989, 1990) in his well-known specification of warm-glow giving.[2] The existence of these two characteristics of an impure public good finds theoretical basis where the exclusion principle can be applied only to a portion of the benefits gained by the consumption of that good (Musgrave, 1959).

Cornes and Sandler (1994) analyzed how different degrees of substitutability or complementarity of the private and public characteristics of the impure public good lead to divergent comparative static results. The comparative static allows to investigate how changes in the relative magnitude of parameters quantifying the private and the public characteristics of the impure public good may influence the reaction function. Changes in such parameters lead to different results, according to the fact that the two characteristics are substitutes or complements in the agents' utlity function. A relevant policy implication arises from this result: if a policy action may influence the relative magnitude of the two characteristics, it is possible to induce different provision levels of the impure public good through the distribution of private and public components in the utility function.

The concept and theoretical models of mixed public good have been applied extensively to environmental issues. Environmental protection activities may generate ancillary (or secondary) benefits which in some cases may be substantial (Ekins, 1996; Rübbelke, 2002).

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[2] In the conduction of empirical works Vicary (1997) stressed the relevance of the joint production model of Cornes and Sandler with respect to models of public good provision models with only donation as method of provision.

As an example, primary benefits of greenhouse gas control in terms of a reduction of global warming may be followed by co-effects (the ancillary benefits) as less air pollution and reduced congestions in transport (Markandya and Rübbelke, 2004). By using an overlapping generation integrated assessment model, Bahn and Leach (2008) show that the reduction in sulphur dioxide emissions as a result of climate change mitigation policies leads to less morbidity and infant mortality, thus increasing the human capital stock accumulation. Primary and secondary benefits are also addressed in geographical terms by Pittel and Rübbelke (2010), where the authors analyse the implication of two alternative abatement solutions, where one type allows reducing solely local polluting emissions, while the other mitigates also global emissions.

A specific point is related to consumption and provision behaviours of environmental-friendly goods. Kotchen (2005) studies the comparative statics of environmental friendly consumption behaviour where green products are treated as impure public goods.[3] Kotchen and Moore (2007) investigate the incentive for households to participate to a green-electricity market, while van't Veld and Kotchen (2011) define as 'green clubs' – i.e., those programs in which firms voluntarily agree to respect environmental standards as for instance eco-labelling - as a situation in which pure non-rivality condition is respected while excludable reputation benefits are allowed. The central question they focus on is why firms might voluntarily commit themselves to exceed the regulatory requirements, when the environmental benefits generated by members of the green clubs are typically public goods.

Contributions explicitly addressing the role of technological choices in an impure public good framework are still spare. Barrett (2006) addresses the role of climate change treaties in promoting the joint supply of two public goods, climate change mitigation and the creation of new technologies as a knowledge stock which allows reducing mitigation costs. The policy implication is the need for an international coordination not only on mitigation actions but also on R&D planning. In the same line, Löschel and Rübbelke, (2009) consider the influence on impure public good provision in the case where alternative technologies are available, and Markandya and Rübbelke (2012) demonstrate that the impure public goods are provided in an inefficient way as long as there is no coordination among countries when alternative technologies are available. As mentioned by Rübbelke (2003), an important issue to be considered in this context is the choice of technologies adopted, which may strongly

[3] Kotchen (2006) focuses on the equilibrium results of a similar model, and analyses how green products affect environmnetal quality and social welfare.

influence the degree of complementarity between the private and public characteristics.

When focusing on technologies, an additional consideration is required as the knowledge itself has been recognized as an impure public goods. Knowledge capital typically has a public good property since it can be used in multiple locations simultaneously (Markusen and Maskus, 2002), and its benefits can be freely spread around if specific protection instruments are not well implemented (Scotchmer, 2004). More exactly, knowledge is ideally globally available but because the returns to some forms of knowledge can to some extent be appropriated (there is some degree of excludability), knowledge is often thought of as an impure public good (Stiglitz, 1999).

This last consideration leads to adopt a slightly different perspective, where the impure public good is the globally available stock of technology (or more generally of knowledge) rather than environmental protection. This brings also to investigate which mechanisms may explain how private agent's investment decision in developing new technologies due to the impure public good property influence other agents.

Thus, from a theoretical point of view, treating a 'technological' impure public good forces us to adopt a dynamic modelling approach in order to investigate investment decisions.

Concerning the empirical side, we follow the system of innovation approach as crucial for modelling ancillary (or spillover) benefits in a knowledge production framework. More precisely, although a firm-based approach could represent a better analysis of agents' behaviour (Bloom *et al.*, 2010), we believe that in our case the sector level approach is more appropriate for targeting and differentiating innovation and environmental policies that increase efficiency. Sector-based level behaviour is more effective in explaining structural change and economic dynamics (Bogliacino and Pianta, 2011), especially when environmental and innovation issues are jointly analysed (Costantini and Mazzanti, 2011). The core issue is to understand which drivers influence the investment decision of an economic sector by accounting for R&D spillover effects as well as emissions abatement options adopted by the other sectors.

We believe that the sector-based level is the most relevant to our purposes from both an applied and a conceptual perspective. With regard to the former, it allows good coverage at geographical level, while still maintaining a satisfactory degree of heterogeneity, for an investigation of spillover effects. In this sense, according to Wagner and Timmins (2009), assessment of the polluting behaviours is highly heterogeneous among sectors, whereas Cole *et al.* (2010) fully exploit the features of industry-based datasets to analyse how environmental performances and trade flows are driven by regulations and agglomeration economies. Thus, the sector or industry level of the analysis appears to be crucial to providing a more robust possibility of jointly exploring economic and environmental performances in depth without losing generality of results.

With regard to the theoretical layers of our research hypotheses, we refer to the paradigm of technological regimes early developed by Malerba and Orsenigo (1997). They observe that technological regimes may be a fruitful concept for studying how innovative activities are organised differently and industries evolve over time. More relevant for us, their main finding is that innovative activities are sector specific, insofar as the features of technological environments are common to groups of industries. They therefore find differences across sectors in the patterns of innovation and dynamic economic performance and similarities across countries. This is a key conceptual justification for studying sectors at various degrees of aggregation in a realm in which innovation plays a major role in linking economic and environmental performance over a long run scenario of investments by firms in private and public goods (Ambec and Lanoie, 2008; Jaffe and Palmer, 1997; Porter and van der Linde, 1995). According to Breschi *et al.* (2000), this reasoning is not aimed at excluding the relevance of national systems of innovation but affirms that an analysis based on sectors maximises the possibility of investigating the behaviour of agents in a dynamic innovative world.

3. The theoretical model

3.1 Model assumptions

The theoretical model analyses what happens to representative agents' investment decisions concerning R&D efforts in a context of a mixed public good. What makes our model different from the existing literature is that the choices made by agents concern investment and not consumption. This implies that our analytical framework must be dynamic. Consequently, analysis is on the reaction of the dynamic equilibrium solutions to changes in parameters.[4]

When a general knowledge-based interpretation is adopted, the private characteristic is given by higher productivity (or larger market shares or exploitation of monopolistic rents by the leader), and the public characteristic is given by the spillover effects caused by partial availability of global knowledge stock. If we assume an environmental point of view, we may well interpret the mixed good in a sense that the public characteristic is given by emissions abatement, whereas the private characteristic is given by higher resource efficiency.[5]

We assume that there is a finite set of economic sectors, indexed by $i = 1,..,I$. There is a large number of atomistic identical firms in each sector; we can therefore assume that each sector features one representative firm, labelled as firm i ($i = 1,...,I$). Each firm employs and invests in a kind of capital, *R*, which has the characteristics of an impure public good since it generates either a private characteristic (*z*) which has no effects on the other firms or a public characteristic (*a*) which may influence other firms' benefit.

In our case, the impure public capital good (*R*) can be represented by knowledge capital given by R&D stock. As a mere example, when the more stringent environmental approach is adopted, we can consider the private characteristic (*z*) as benefits arising from new production techniques that ensure higher energy efficiency, whereas the public characteristic (*a*) can be represented by energy-related emission intensity reduction. In other words, investing in R&D activities produces the same amount of goods with less energy consumption and consequently lower polluting emissions. While efficiency gains are clearly fully appropriable by the firm *i*, benefits from pollution abatement will also be advantageous for the other firms.

Since *R* has the characteristic of an impure public good, each unit of *R* is such that:

(1) $z = \alpha R \qquad \alpha > 0$ *given*,

(2) $a = \beta R \qquad \beta > 0$ *given*,

where α and β are exogenously given coefficients reflecting a simple process, whereas *z* and *a* are jointly generated in fixed proportion by one unit of *R*.

Therefore, we assume that whenever a firm invests in one unit of *R*, it invests in α given

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[4] We essentially propose in a dynamic framework some of the issues analysed by Cornes and Sandler (1994).

[5] We may address exemplificative benefits arising by abatement efforts from other firms. A decrease in polluting emissions will reduce environmental damage and related recovery costs (given by productivity losses due for instance to higher morbility of the employees). If some physical targets on emissions level are a binding constraint for production process, the higher availability of new technologies for emissions abatement

units of the private characteristic and in β given units of the public characteristic, and the two components of the stock are complements, hence increasing either one makes increasing the other more attractive (Milgrom and Roberts, 1995).

Moreover, since *a* also exerts effects on the other firms and vice versa, we define the total investment amount in the public characteristic by all firms but *i* as follows:

(3) $$A_{\neq i} = \sum_{j \neq i} a_j = \sum_{j \neq i} \beta R_j \qquad \forall i, j .$$

Hence, the whole quantity of the public characteristic (*A*) is given by the sum of the single contributions by each single firm as:

(4) $$A = \sum_{i=1}^{I} a_i = \sum_{i=1}^{I} \beta R_i = a_i + A_{\neq i} .$$

by assuming that all firms are equally productive in providing the public good.[6]

We adopt the Nash-Cournot assumption that the single firm *i* regards $A_{\neq i}$ as exogenously given.[7]

From eqs. (1)-(4) the investment of firm *i* in one unit of *R* has therefore three effects: (i) an increase in firm *i*'s private benefits due to the private characteristic ($z = \alpha R$); (ii) an increase in that firm's private benefits due to the public characteristic ($a = \beta R$); (iii) an increase in the total amount of public characteristic (*A*) available to all firms.

Let us now describe the optimisation problem in a dynamic setting. Firm *i*'s benefit function on the impure public capital good at time *t* (R_t) is represented as:

(5) $$B(R_t) = \left[\left(\beta R_t + A_{\neq} \right)^{\frac{\sigma-1}{\sigma}} + \left(\alpha R_t \right)^{\frac{\sigma-1}{\sigma}} \right]^{\frac{\sigma}{\sigma-1}} .$$

developed by other firms may help to increase the speed of diffusion process of environmental-friendly technologies and consequently reduce implementation costs.

[6] It would also be possible to include in the analysis the effect of differing productivities (Cornes and Sandler, 1989; Kotchen, 2009). Whilst important, this issue complicates the task of analyzing the reaction function in a dynamic setting. Therefore, in this paper we limit to the homogenous productivities case.

[7] For simplicity of notations, since in our analysis we always refer to firm *i*, we will omit the subscript *i* in the remaining test.

From eq. (2), we can re-write:

(6) $$B(R_t) = \left[(a_t + A_{\neq})^{\frac{\sigma-1}{\sigma}} + (\alpha R_t)^{\frac{\sigma-1}{\sigma}}\right]^{\frac{\sigma}{\sigma-1}},$$

where $\sigma \in (0,+\infty)$ is the elasticity of substitution between the two benefit components: (i) the public component given by the contribution of firm *i* (*a*), and the contribution of all the other firms ($A_{\neq}$); (ii) the private component (αR). As already mentioned, we are interested in the relationship of complementarity/substitutability between the two benefit components. Consequently, we state that when $\sigma > 1$ the two components (A and αR) are (gross) substitutes, whereas for $\sigma < 1$ the two components are (gross) complements, while we ignore the Cobb-Douglas case of $\sigma = 1$.

We can see two different relevant complementarities: a technical complementarity defined by the impure public good's joint provision of private and public characteristics and an economic complementarity that relates specifically to the benefit function specification.

Firm *i*'s cost function of the R&D investments at time *t* is defined as:

(7) $$K(I_t) = p(I_t)I_t,$$

with

$$p(I_t) \geq 0, \ \frac{\partial p(I_t)}{\partial I_t} > 0, \text{ and } \frac{\partial^2 p(I_t)}{\partial I_t^2} \geq 0,$$

where $p(I_t)$ is the real price of the investment resources in R&D at time *t*. We assume that $p(I_t)$ is non-decreasing in I_t. This captures in reduced form the idea that there is an increasing opportunity cost for the other firms of employing scientists and engineers to develop new knowledge (Goulder and Mathai, 2000; Goulder and Schneider, 1999).

With regard to the firm *i*'s adjustment cost function of R&D capital stock, it is defined, at time *t*, as $C(R_t)$, with $\frac{\partial C(R_t)}{\partial R_t} > 0$, and $\frac{\partial^2 C(R_t)}{\partial R_t^2} \geq 0$.

3.2 Equilibrium solutions

Each firm has an infinite lifespan and discounts the future with the discount factor ρ in its net benefit maximisation function. R_t is the state variable and I_t is the costate variable.

For simplicity of analysis, we assume that net benefit $\Pi(R_t)$ is defined as gross benefits minus R&D cost as:

(8) $$\Pi(R_t) = B(R_t) - C(R_t).$$

Formally, the optimisation problem of firm i becomes:

$$Maximise \int_0^\infty [\Pi(R_t) - K(I_t)]e^{-\rho t}dt$$

s.t.:

$$\dot{R}_t = I_t - \delta R_t,$$
$$R_{t=0} = R_0,$$

where δ is the standard capital depreciation rate and the current-value Hamiltonian associated with the optimisation problem is given by:

$$H_C(R_t, I_t, l_t) = \Pi(R_t) - K(I_t) + l_t(I_t - \delta R_t).$$

The optimality conditions in terms of the current Hamiltonian are $\frac{\partial H_C}{\partial I_t} = 0$, $\dot{R}_t = \frac{\partial H_C}{\partial l_t}$, $\dot{l}_t = \rho l_t - \frac{\partial H_C}{\partial R_t}$.

Assuming that $f(x) = (K'(x))^{-1}$, the optimality equation of the current-value Hamiltonian, the state and costate equations become:

$$I_t = f(l_t)$$
$$\dot{R}_t = f(l_t) - \delta R_t;$$

$$\dot{l}_t = -\Pi'(R_t) + (\delta + \rho) l_t .$$

The equations for the equilibrium are:

$$R^* = \frac{1}{\delta} f(l^*)$$

and

$$l^* = \frac{1}{(\delta + \rho)} \Pi_R(R^*),$$

from which we obtain:

$$(9) \qquad R^* = \frac{1}{\delta} f\left(\frac{1}{(\delta + \rho)} \Pi_R(R^*) \right).$$

3.3 *The reaction function*

The present section is devoted to analysis of the reaction function between one firm's investment in R&D and another firms' investment in the public characteristic, $A_{\neq}$.

By differentiating eq. (8), with respect to $A_{\neq}$ we get:

$$(10) \qquad R^*_{A_{\neq}} = \frac{\xi}{1 - \xi \Pi_{RR}(R^*)} B_{RA_{\neq}}(R^*),$$

where, given the assumption $f' = \frac{1}{K''} > 0$:

$$\xi = \frac{1}{\delta(\delta + \rho)} f'\left(\frac{\Pi_R(R^*)}{\delta + \rho} \right) > 0 .$$

Moreover, from eq. (8) we have $\Pi_{RR}(R^*) = B_{RR}(R^*) - C_{RR}(R^*)$, with:

$$B_{RR}(R) = -\frac{\alpha^2 A_{\neq}^2 \left[(\beta R + A_{\neq})^{\frac{\sigma-1}{\sigma}} + (\alpha R)^{\frac{\sigma-1}{\sigma}} \right]^{\frac{2-\sigma}{\sigma-1}}}{\sigma (\beta R + A_{\neq})^{\frac{\sigma+1}{\sigma}} (\alpha R)^{\frac{\sigma+1}{\sigma}}} < 0 .$$

Since by assumption $C_{RR}(R) \geq 0$, for $R = R^*$ we get $\Pi_{RR}(R^*) < 0$, from which we obtain $\frac{\xi}{1-\xi\Pi_{RR}(R^*)} > 0$.

Finally, since we also get:

$$B_{RA_{\neq}}(R) = \frac{\alpha A_{\neq}}{\sigma} \frac{\left[(\beta R + A_{\neq})^{\frac{\sigma-1}{\sigma}} + (\alpha R)^{\frac{\sigma-1}{\sigma}} \right]^{\frac{2-\sigma}{\sigma-1}}}{(\beta R + A_{\neq})^{\frac{\sigma+1}{\sigma}} (\alpha R)^{\frac{1}{\sigma}}} > 0 ,$$

for $R = R^*$ we obtain the following:

Proposition 1. *In equilibrium the reaction function has positive slope*:

$$R^*_{A_{\neq}} = \frac{\xi}{1-\xi\Pi_{RR}(R^*)} B_{RA_{\neq}}(R^*) > 0 .$$

We can therefore specify the behaviour of the reaction curve in three special cases, depending on the parameters α and σ. In particular, expanding the previous relation by means of a Taylor series up to the dominant order around $\alpha = 0;\ \sigma = +\infty$ or $\sigma = 0$, we obtain the following propositions:

Proposition 2. *When the private component of R&D is very small* ($\alpha \to 0$):

$$R^*_{A_{\neq}} \sim \frac{\xi_{\alpha\to 0}}{1+\xi_{\alpha\to 0} C_{RR}(R^*)} \frac{A_{\neq}}{\sigma R^*} \begin{cases} \left(\beta R^* + A_{\neq}\right)^{\frac{1-2\sigma}{\sigma}} \left(\alpha R^*\right)^{\frac{\sigma-1}{\sigma}} \textit{ if } \sigma > 1 \\ \frac{1}{\left(\beta R^* + A_{\neq}\right)^{\frac{\sigma+1}{\sigma}}} \left(\alpha R^*\right)^{\frac{1}{\sigma}} \textit{ if } 0 < \sigma < 1 \end{cases} .$$

Hence: $R^*_{A_{\neq}} \to 0$.

Proposition 3. *When the two sorts of benefit are substitutes* ($\sigma \to \infty$):

$$R^*_{A_{\neq}} \sim \left[\frac{\xi_{\sigma\to\infty}}{1+\xi_{\sigma\to\infty} C_{RR}(R^*)} \frac{\alpha A_{\neq}}{(\beta R^* + A_{\neq})(\beta R^* + A_{\neq} + \alpha R^*)} \right] \frac{1}{\sigma}.$$

Proposition 4. *When the two sorts of benefit are complements* ($\sigma \to 0$):

$$R^*_{A_{\neq}} \sim \left[\frac{\xi_{\sigma\to 0}}{1+\xi_{\sigma\to 0} C_{RR}(R^*)} \frac{\alpha A_{\neq}}{\sigma} \right] \begin{cases} \left(\dfrac{\alpha R^*}{\beta R^* + A_{\neq}} \right)^{\frac{1}{\sigma}} if\ \alpha R^* < \beta R^* + A_{\neq} \\ \left(\dfrac{\beta R^* + A_{\neq}}{\alpha R^*} \right)^{\frac{1}{\sigma}} if\ \alpha R^* > \beta R^* + A_{\neq} \end{cases}.$$

Propositions 3 and 4 show that the reaction curve is more sensitive (firm *i*'s investments in R&D react more promptly to the other firms' decisions on the public characteristic) for smaller values of the elasticity of substitution. In the first case ($\sigma \to \infty$), the reaction function is a power function. In the second case ($\sigma \to 0$), the reaction function is exponential. The effect of complements and substitutes cases are therefore assessed on a relative basis.

From these results, we can make some interesting considerations about one firm's investment decisions in R&D and the other firms' investment decisions in the public characteristic in a dynamic framework.

The first relevant consideration comes from Proposition 1: in equilibrium the reaction function between one firm's investments in R&D and other firms' investments in the public characteristic is positive.

The first question that deserves an answer is what does a positive reaction function imply?

If we adopt a knowledge-based view, we may well interpret our theoretical results in a realm of consolidated knowledge spillovers. When the single firm's investment decisions in the knowledge capital good are influenced by the part of the global knowledge stock that is freely appropriable, we recognise the fact that the existence of a fully appropriable (private) benefit of the mixed good may positively influence the knowledge accumulation process.

Let us then adopt an environmental view where the public component is given by emissions abatement. Since according to eq. (2) whenever a firm invests in one unit of R&D, it invests in β units of emissions abatement too, a positive reaction between one firm's investment in emissions abatement and other firms' investment in emissions abatement must also exist. This leads to clear implications for the free riding problem. It means that each firm reacts positively to the other firms' investment in emissions abatement since the investment in emissions abatement by each firm is increased by the other firms' investments. This leads to an individual equilibrium choice of emissions abatement that can go beyond legal and contractual obligations. We can conclude that this cooperative behaviour is stimulated by the cumulativeness of past investment in this mixed good, including its public characteristic.

This result may help to explain why in some cases environmental performance of firms goes beyond the effective abatement target implemented by regulatory policies. When a private (fully appropriable) component is part of the mixed good and the public component is strictly complementary, it may well be that the overall result is an emission level that is lower than the policy target. This result may open discussion on the relevant policy issue of optimal environmental targets, but it goes beyond the scope of this paper.[8]

Consequently, the second question is why is the reaction function positive?

R&D is a mixed capital good by assumption and the technological consequence is the complementarity between the private characteristic (αR) and the public characteristic (βR). In actual fact, the only case in which the firm's investment in R&D does not react with respect to $A_{\neq}$ is when the private characteristic of R&D is very small, that is when $\alpha \to 0$ (see Proposition 2 above). If R&D was a pure public capital, the single firm's R&D investment would not react positively to the other firms' investment in the public component.

Moreover with Proposition 3 and 4, we see that the reaction of R with respect to $A_{\neq}$ is stronger when the private and the public components of the benefit function are complements than when the two components are substitutes. In the first case, an increase in the other firms' investment in the public component increases the single firm's marginal benefit of accumulating the complementary private component. Therefore, each firm now wishes to increase its own investment of the private component and, consequently, the overall mixed capital good. In this way, through the extra investment in R&D, each firm

[8] This discussion also shows potential and fruitful connections between this theoretical framework and notions of appropriability, complementarity and cumulativeness that are pre-conditions of innovation along typical Schumpeterian patterns of creative accumulation (Breschi *et al.*, 2000). In the dynamics of these technological regimes, imitative behaviours and spillovers (Malerba, 2006) can consolidate positive reaction functions both considering agents belonging to a national industry or sectors located in different countries.

determines an increase in its investment in the public component too.

4. The empirical framework

4.1. Modelling strategy

In order to empirically test the positive slope of the reaction function, we rely on analytical instruments available in the knowledge spillovers literature. More precisely, we refer to knowledge spillovers as a key driver for the internal knowledge production function where technology produced by other firms (or sectors[9]) can be generally defined as the efforts in innovative activities (our mixed good) or disentangled in its public component (our $A_{\neq i} = \sum_{j \neq i} a_j = \sum_{j \neq i} \beta R_j$). To this end, specific attention should be paid to how spillovers coming from decisions by other firms are modelled.

In this empirical framework, our agents are given by *I* manufacturing sectors. The public component of the mixed good can be represented either by a general knowledge spillover effect or a more specific environmental spillover effect, here modelled as total emissions of each sector in the sense that if total emissions are decreasing, given a certain level of value added, we implicitly assume that emission intensity is decreasing as well. In this sense, if the reaction function is positive, we expect to find a positive sign for the coefficient estimated for $A_{\neq}$ when knowledge spillovers are considered and a negative sign if an environmental spillovers effect is under scrutiny.

Let us now consider how to shape spillover effects by accounting for recent advancements in the economics of innovation discipline. Very broadly, knowledge spills from one agent to another in a twofold manner (Glaeser *et al.*, 1992). In a Jacob-type externality frame, we argue that knowledge produced by other sectors may be a useful input for the domestic knowledge production function of each sector. In a Marshall-type externality setting, knowledge only flows across homogeneous sectors. We can disentangle these two effects since our dataset has both a sector and a cross-country dimension. We control for Jacob type externality considering potential effects of R&D choices by other sectors located in the same country, whereas we account for Marshall-type externalities by considering the potential influence of innovation decisions by similar sectors located in other countries. Accounting

[9] In the theoretical model, we assume that each sector features one representative firm, labelled as firm *i*.

for R&D spillovers allows us to disentangle the effects strictly related to abatement decisions more easily from the more general innovative behaviour captured here by knowledge externalities.

We can rely on the concepts of cognitive proximity and absorptive capacity to capture the public component of the cumulated knowledge stock. Especially when a Jacob-type externality is considered, there is growing consensus on the need to account for the notion of cognitive proximity since the probability that innovation spills from one sector to another strongly depends on the absorptive capacity of the receiving sector and knowledge will be more likely to diffuse when competences and knowledge stocks of the inventors and adopters are closely related (Antonelli *et al.*, 2011; Boschma and Iammarino, 2009). Conversely, when Marshall-type externalities are the conceptual framework used to model the public component, geographical distance may also influence the strength of innovation spillovers since face to face contacts and all other features related to personal exchanges (such as language contiguity or transportation facilities) may influence the absorptive capacity (or in other words, the ability to transform knowledge produced abroad into own innovative capacity).

With regard to cognitive proximity, Frenken *et al.* (2007) propose adopting an index that captures the technological relatedness between industrial sectors by computing the similarity between two sectors' input mix. In line with Los and Timmer (2005), we have taken the amount of capital stock (K) and number of employees (L) for each sector as inputs, resulting in a similarity matrix for technological relatedness (tr) computed on the basis of capital labour ratios. In our exercise we have C countries ($c = 1,2,...,C$) and I sectors ($i = 1,2,...,I$).[10] The resulting weighting system for aggregating innovation efforts in a Jacob-type setting results in the form:

$$(11) \qquad tr_{ci}^{ck} = \left(\frac{\left| (K/L)_{ci} - (K/L)_{ck} \right|}{\sqrt{(K/L)_{ci} + (K/L)_{ck}}} \right)^{-1} \qquad \forall\ sector\ k \neq i$$

whereas for intra-sector Marshall-type externalities we have:

[10] For the sake of simplicity, we omit the temporal dimension from mathematical notations but all variables relate to the time span 1995-2006.

(12) $$tr_{ci}^{si} = \left(\frac{\left|(K/L)_{ci} - (K/L)_{si}\right|}{\sqrt{(K/L)_{ci} + (K/L)_{si}}} \right)^{-1} \quad \forall \; country \; s \neq c$$

The final knowledge stock produced "abroad" results in several alternative measures according to the weighting system adopted. When Jacob-type externalities are scrutinised, the public component is approximated by a spillover effect modelled as the sum of R&D stock by the other *I-1* sectors (at country level) weighted by eq. (11), as follows:

(13) $$T_{\neq i} = \sum_{k=1, k \neq i}^{I} \left[\left(tr_{ci}^{ck} \right) R_{ck} \right]$$

When inter-country Marshallian-type spillovers are investigated, there are, according to Bode (2004), several alternative criteria for transforming geographical distances into spatial weights. For the sake of simplicity, we have only considered the pure inverse distances, assuming that the intensity of inter-country knowledge spillovers may be subject to spatial transaction costs in the sense that the intensity of influences between any two regions diminishes continuously with increasing distance. In this case, we consider that the smaller the distance between country *c* and any other region *s*, the higher the weight assigned to *s* with respect to its influence on *c*. Hence, the weight assigned to each country *s* ($\forall s \neq c$) is proportional to the inverse distance between *c* and *s*. Summing up, the sum of R&D efforts by the other *C-1* countries (at sector level) may be aggregated on the basis of a cognitive proximity criterion given by eq. (12):

(14) $$T_{\neq c}^{1} = \sum_{s=1, s \neq c}^{C} \left[\left(tr_{ci}^{si} \right) R_{si} \right]$$

or alternatively, R&D efforts may also be aggregated on the basis of a geographical proximity criterion, resulting in a double weighting system:

(15) $$T_{\neq c}^{2} = \sum_{s=1, s \neq c}^{C} \left[\left(tr_{ci}^{si} d_{cs}^{-1} \right) R_{si} \right]$$

where d_{cs}^{-1} stands for the inverse of the pure geographical distance (km) between economic centres.

Summing up, we can interpret the chosen weighting system as an empirical quantification of the value assumed by the parameter β in the theoretical model.

Since geographical distance may also influence to which extent abatement efforts in the same sector outside the country will play a role in the domestic investment decisions in the mixed capital good by sector *k*, we have applied the same geographical weighting system as for R&D. Accordingly, the public component of the mixed capital good provided by homogeneous sectors located in other countries is given by:

(16) $$E_{\neq c}^{1} = \sum_{s=1, s\neq c}^{C} e_{si}$$

when geographical distances are ignored, or alternatively by:

(17) $$E_{\neq c}^{2} = \sum_{s=1, s\neq c}^{C} \left[\left(d_{cs}^{-1} \right) e_{si} \right]$$

if we consider that the degree of influence of the public component on the reaction function decreases with distance. When inter-sector influences are considered, the public component results as the simple sum of abatement efforts by the other sectors in the same country as:

(18) $$E_{\neq i} = \sum_{k=1, k\neq i}^{I} e_{ck}$$

Summing up, we have one type of knowledge spillovers given by eq. (13) and one environmental spillovers given by eq. (18) when inter-sector relationships are considered, whereas we can test two versions of knowledge spillovers as eqs. (14)-(15) and environmental spillovers as eqs. (16)-(17) when we account for inter-country relationships.

4.2. The dataset

In order to construct an analytical framework of this type, we exploit an original dataset that derives from a combination of EUROSTAT and OECD sources at sector as well as country level. Our panel includes 15 EU countries (Austria, Belgium, Czech Republic, Denmark, Finland, France, Germany, Greece, Hungary, Italy, Netherlands, Portugal, Spain, Sweden, United Kingdom) and 23 manufacturing sectors covering all industries classified at the 2-digit ISIC Rev 3 level, in a time span between 1995 and 2006. Polluting emissions at sector level are based on the NAMEA approach (National Accounting Matrix including Environmental Accounts) available from EUROSTAT,[11] whereas all data for R&D, value added, capital and labour are taken from EUROSTAT and OECD-STAN. Data on bilateral geodesic distances are available from the Centre d'Etudes Prospectives et d'Informations Internationales (CEPII).

The innovative efforts should be modelled as changes in the knowledge stock, which is coherent with the temporal dynamics developed by equilibrium solutions in the theoretical model. Accordingly, the knowledge stock for R&D expenditures is as follows:

$$R_{ci(t)} = R_{ci(t-1)} \cdot (1-d) + I_{ci(t)}$$

given that the initial stock is measured by $R_{ci(t_0)} = I_{ci(t_0)} / (g+d)$ where g is the sector-specific average annual growth rate of constant price R&D expenditures throughout the period and d = 0.15 is the standard depreciation rate for R&D-based knowledge stock (Keller, 2004).

We focus on two main environmental externalities, related to CO2 and NMVOC emissions, as representative of two distinguished diffusion patterns, a global one (CO2) and a more localised one (NMVOC). The comparison of results is aimed at highlighting potentially different sector strategies in this mixed good framework and accounting for differences between global and local externalities since the public benefits associated with the former are in principle more influential because the relative magnitude of the public component of the mixed good is larger than in the local externality case.

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[11] NAMEA contains data on different polluting and greenhouse gas emissions (CO2, CH4, NMVOC, CO, SOx, NOx). The first NAMEA was developed by the Dutch Central Bureau of Statistics and analysed by Ike (1999), Keuning *et al.* (1999), Steenge (1999), and Vaze (1999) in relation to the possible policy implications deriving from sector-specific environmental performance. In the NAMEA tables, environmental pressures, in particular air emissions, and economic data (value added, final consumption expenditures and full-time equivalent job) are assigned to the economic branches of resident units directly responsible for environmental and economic phenomena.

4.3. The econometric strategy

The final equation to be estimated should account for both sector-specific as well as country features in order to detect all potential drivers affecting the knowledge production function that can be interpreted in a national or sectoral system of innovation realm. More importantly, our theoretical results tell us how investment decisions on innovative efforts move over time, forcing us to adopt a dynamic panel estimator. Moving from eq. (5), the final log linear equation to be empirically estimated in a panel context is thus given by:

$$R_{cit} = \alpha_0 + \phi y_{cit} + \beta_1 E_{\neq it} + \beta_2 T_{\neq it} + \eta_i + \gamma_c + \varepsilon_{cit}$$

when inter-sector spillovers are scrutinised, or alternatively:

$$R_{cit} = \alpha_0 + \phi y_{cit} + \beta_1 E^{1,2}_{\neq ct} + \beta_2 T^{1,2}_{\neq ct} + \eta_i + \gamma_c + \varepsilon_{cit}$$

when intra-sector cross-country spillovers are under investigation.[12]

According to the theoretical model, we can proxy the total value of the mixed capital good by sector i located in country c as $R \approx R_{cit}$ where the private component of the mixed good as the appropriable part of R&D investments is given by value added of each sector ($\alpha R \approx y_{cit}$), whereas the public component is given by knowledge or environmental spillovers.[13]

Since the theoretical model is set as an intertemporal maximisation problem, our estimation technique should account for equilibrium growth rates rather than working with linear variables. According to Becker and Pain (2008) and Ulku (2007), the best way to deal with dynamic estimation in a panel context when a knowledge production function is under investigation is to adopt a panel error correction model as the recently developed system GMM (sys-GMM) proposed by Arellano and Bover (1995) since it allows for increasing

[12] In both specifications, all variables are expressed in log terms.

[13] Remembering that when environmental externalities are under scrutiny, our public component is expressed as total emissions per unit of value added (as a sort of emission intensity measure), according to the theoretical model, the reaction function is found to be positive if the coefficient is negative, revealing that decreasing emission intensity (given by abatement efforts) by the other agents positively influence internal investment behaviour in innovative activity.

efficiency when we work with a dependent variable that is highly persistent over time as well as with potential endogeneity of some explanatory variables.

Generally speaking, a dynamic panel estimator is appropriate when the dependent variable is quite persistent over time, which is exactly our case.[14] More precisely, the sys-GMM estimator seems to be more efficient than simple Arellano-Bond GMM (diff-GMM) since the latter has finite sample bias and poor precision when the series are strongly persistent. Moreover, as shown in Bond *et al.* (2001), when the number of time series observations is small whereas N is relatively large (in our case 12 and 354, respectively), there are dramatic efficiency gains from using the system rather than the difference GMM.

Although our dataset is large in its NxT matrix and thus in principle fully coherent with sys-GMM, inconsistency should always be considered (Kiviet, 1995; Judson and Owen, 1999). Hence, we have applied the comparative strategy suggested by Bond (2002) as a rule of thumb since sys-GMM is highly recommended when the value of the coefficient of the lagged dependent variable using a sys-GMM is in between the values of the same coefficient estimated with fixed effects as the lower bound and OLS as the upper bound, whereas diff-GMM gives an underestimation of the coefficient which is what we verify when performing these estimations on our empirical model.[15]

5. Empirical results

We first test the positive slope of the reaction function from an inter-sector perspective where Jacob-type externalities are considered, accounting for both polluting emissions (Table 1). As a general consideration, our modelling strategy is to include only necessary explanatory variables in order to reduce potential multicollinearity arising from adding many covariates to GMM estimators. More importantly, since in our theoretical model the public component is generally defined, without explicit characterisation in terms of knowledge vs. environmental externalities, we have tested the two spillover effects both separately and jointly.[16]

[14] Wooldridge F-test equal to 129.86***, with H0=absence of autocorrelation of the residuals rejected.

[15] All results for robustness checks are available upon request from the authors. As a general remark, all estimations with sys-GMM provide coefficients for the lagged dependent variable respecting the intermediate position in the variation range for different estimators as suggested by Bond (2002).

[16] From a general point of view, the robustness of results relies on an AR test on residual terms for the temporal structure and a Sargan test on overidentifying instruments for endogeneity issues. Statistical

Turning to an interpretation of our results in the light of the theoretical model, we can see that the value added ($y_{cit} = ValAd_i$) of sector i in country c positively relates to R&D investments. This is to be expected as common evidence in this stream of economics of innovation literature (Becker and Pain, 2008) since the larger profit gains at sector level are, the more likely it is that competitive advantage will be maintained on the innovation side in well-known Schumpeterian monopolistic behaviour. This is exactly what we expected from our benefit function of the representative agent where a positive reaction function between the private component and the mixed capital good is clearly addressed.

Regarding inter-sector spillovers, Column 1 in Table 1 shows that the main test on $A_{\neq}$ modelled as eq. (13) leads us to confirm the theoretical result that R&D spillovers ($T_{\neq i}$) are part of a mixed good technology with a positive and statistically robust coefficient.

Table 1 – CO_2 and NMVOC abatement decisions within country

	KNOW-spill	CO2		NMVOC	
	(1)	(2)	(3)	(4)	(5)
$R_{i(t-1)}$	0.852 ***	0.871 ***	0.850 ***	0.864 ***	0.860 ***
	(152.58)	(189.98)	(259.87)	(188.39)	(228.03)
$ValAd_i$	0.028 ***	0.102 ***	0.115 ***	0.078 ***	0.067 ***
	(11.10)	(42.62)	(69.73)	(30.78)	(35.78)
$T_{\neq i}$	0.059 ***		0.046 ***		0.027 ***
	(8.03)		(13.39)		(7.92)
$E_{\neq i}$		-0.188 ***	-0.150 ***	-0.080 ***	-0.075 ***
		(-6.07)	(-8.19)	(-5.26)	(-7.62)
Constant	2.050 ***	2.397 ***	0.782 ***	1.913 ***	1.703 ***
	(5.62)	(6.92)	(3.62)	(7.33)	(11.71)
Country fixed effects	Yes	Yes	Yes	Yes	Yes
Sector fixed effects	Yes	Yes	Yes	Yes	Yes
No Obs.	3,391	3,391	3,391	3,391	3,391
Wald test	79,213	107,795	275,772	102,934	192,664
AR (1)	-3.366 (0.0)	-3.481 (0.0)	-3.478 (0.0)	-3.478 (0.0)	-3.448 (0.0)
AR (2)	-1.890 (0.1)	-1.970 (0.0)	-1.956 (0.1)	-1.968 (0.1)	-1.937 (0.1)
Sargan test	120.07 (0.2)	120.80 (0.2)	177.80 (0.1)	138.96 (0.1)	171.05 (0.1)

Notes: Two-step robust specification has been used. Robust t-statistics in absolute value are shown in brackets. (**), (***) Significant p-value at the 5%, 1%, respectively. AR(1) and AR(2) are tests-with distribution N(0, 1) on the serial correlation of residuals. Sargan Chi-square test for over identification of restrictions.

Let us then quantify the role of a public component modelled as environmental externalities. From Columns 2 and 4 (Table 1) we show that the test on $A_{\neq}$ modelled

robustness of coefficients for the lagged dependent variable respecting the rule of thumb mentioned above gives us final justification for using sys-GMM.

according to eq. (18) leads us to do not reject the theoretical result for environmental spillovers as well. According to Proposition 1, the covariate $E_{\neq i}$ shows that there is a positive influence of other sectors' emissions abatement efforts over internal R&D investment choice.[17]

For both pollutants we can see that coefficients for $T_{\neq i}$ and $E_{\neq i}$ remain statistically robust and with the expected sign when knowledge and environmental spillover effects are jointly introduced, whereas their magnitude decreases slightly when only one spillover effect is introduced. The fact that persistence over time is slightly reduced (coefficient for the lagged dependent variable is lower in Columns 3 and 5) shows that a joint spillover effect allows better explaining R&D investment decisions.

We can also see that coefficients for $E_{\neq i}$ are always higher than those related to $T_{\neq i}$ for both CO2 and NMVOC, revealing the strong and persistent positivity of the reaction function with respect to the specific environmental externality under scrutiny. Since coefficients represent elasticities, we should interpret this last piece of evidence carefully. In fact, we can only say that an increase in abatement efforts by the other agents will increase the propensity to invest in R&D activities by each agent and that this impulse is greater than in knowledge spillovers. A potential explanation of this specific result may pass through the effect on the coefficient relative to the private component ($y_{cit} = ValAd_i$) which increases when environmental spillovers are included. When the public component is explicitly considered as an environmental spillover effect, the coefficient for the private component is higher for both pollutants. We can interpret this statistical evidence as a sign of an higher influence of the public component on the marginal benefit related to the private component, which dynamically fosters investments in R&D. Moreover, this effect is higher for CO2 emissions which we consider by definition the environmental externality with higher technical complementarity and lower substitutability in the benefit function.

Turning to cross-country intra-sector spillover effects, Tables 2 and 3 show results for CO2 and NMVOC respectively. It is then a sector-specific effect which should capture the spillover arising from partnership and technological flows occurring within the same economic branch.

[17] By using a difference-based estimation method, we can interpret the coefficient as an elasticity in terms of the reaction of investment choice in R&D with respect to changes in emissions level (i.e., abatement efforts) of the other agents (where agents in this specification correspond to other sectors in the same country). This proves that the spillover effect associated with the abatement carried out by other sectors increases investment in the mixed capital good.

Columns 1 and 2 in Table 2 reveal that environmental spillovers do not play any role in influencing R&D investments when CO2 abatement efforts are under scrutiny. This evidence is hardly surprising if we think about the pervasiveness of the emission source, i.e. energy consumption, in all manufacturing sectors. In other words, in this case an environmental national system of innovation seems to prevail over a sectoral one.

Table 2 – CO2 abatement decisions (outside the country, same sector)

	(1)	(2)	(3)	(4)	(5)	(6)
$RT_i(t\text{-}1)$	0.882 ***	0.889 ***	0.851 ***	0.872 ***	0.847 ***	0.870 ***
	(154.25)	(147.63)	(117.00)	(157.92)	(111.45)	(150.02)
$ValAd_i$	0.058 ***	0.027 ***	0.055 ***	0.056 ***	0.065 ***	0.051 ***
	(17.19)	(7.37)	(18.17)	(18.04)	(20.80)	(15.80)
$E^1_{\neq c}$	0.019		0.001	0.019		
	(1.16)		(0.09)	(1.39)		
$E^2_{\neq c}$		-0.005			0.004	0.019
		(-0.14)			(0.25)	(0.95)
$T^1_{\neq c}$			0.102 ***		0.121 ***	
			(5.53)		(6.70)	
$T^2_{\neq c}$				0.043 ***		0.070 ***
				(3.66)		(5.82)
Constant	2.688 ***	2.277 **	0.714	1.715 ***	-0.85	0.908 **
	(2.69)	(2.30)	(1.23)	(2.81)	(-1.86)	(2.23)
Country effects	Yes	Yes	Yes	Yes	Yes	Yes
Sector effects	Yes	Yes	Yes	Yes	Yes	Yes
No Obs.	3,391	3,391	3,391	3,391	3,391	3,391
Wald test	55,487	52,018	72,588	78,251	75,700	81,157
AR (1)	-3.432 (0.0)	-3.384 (0.0)	-3.409 (0.0)	-3.514 (0.0)	-3.404 (0.0)	-3.596 (0.0)
AR (2)	-1.951 (0.1)	-1.923 (0.1)	-1.973 (0.1)	-2.014 (0.1)	-1.986 (0.1)	-2.048 (0.1)
Sargan test	100.31 (0.1)	103.94 (0.1)	127.57 (0.1)	116.02 (0.4)	124.19 (0.2)	118.74 (0.3)

Notes: Two-step robust specification has been used. Robust t-statistics in absolute value are shown in brackets. (**), (***) Significant p-value at the 5%, 1%, respectively. AR(1) and AR(2) are tests-with distribution N(0, 1) on the serial correlation of residuals. Sargan Chi-square test for over identification of restrictions.

When knowledge spillovers are also included, we can see that the public component shaped as the appropriable part of the knowledge stock accumulated by the same sector located in other countries is the only one that influences the reaction function. As a general result, it is worth noting that technological relatedness plays a crucial role in explaining the influence of knowledge stock produced by the same sector located in other countries on domestic R&D investment decisions, whereas geographical proximity alone does not explain knowledge flows. In fact, the inclusion of the geographical distance in the weighting system only influences the magnitude of the effect, but the positive sign of the coefficient remains robust.[18] As far as the technological relatedness matrix is concerned, this result reveals that

[18] As a robustness check we have estimated knowledge spillovers by considering a pure geographical distance matrix. Coefficients in this case are always not statistically robust, reinforcing our choice of modelling the b

sector homogeneity in terms of capital labour ratio similarity is also effective when inter-country spillovers are considered. If we consider the panel of countries examined here as well as the macro aggregation of manufacturing sectors, we may well expect the same sector in Germany and Hungary to have an input mix that is different enough to give strength to technological relatedness.

In Table 3, as far as the NMVOC abatement spillover effects are concerned, we observe that the public component shaped as a specific environmental externality influences the reaction function, with an expected and statistically robust negative sign. In this case, the distance-based weighting system reinforces the influence of other agents' behaviour on internal R&D investment decisions, meaning that some forms of transactional barriers due to geographical features have a role to play.

If we jointly consider a knowledge and environmental externality spillover effect, the R&D investments are positively influenced by the public component irrespective of the spillover specification adopted. In this case, the knowledge effect seems to prevail over the environmental externality effect, reinforcing our previous result on CO_2 emissions since a sectoral system of innovation seems to be crucial.

The different evidence for CO_2 and NMVOC when testing the mixed good hypothesis at EU level for inter-country effects in the same manufacturing sector highlights the plausible role of policy in creating a framework (targets, expectations, etc.) for cooperative behaviours. To some extent, within the European Union, CO_2 abatement targets are generally decided at country level and then distributed among sectors in a national bargaining process. In addition, the current energy mix as well as other structural features of sectors are all factors influencing this bargaining outcome since CO_2 emission cuts must pass through a reduction in energy consumption (which is highly pervasive in terms of the number of sectors influenced by the policy strategy) or the impulse to renewable energies (which is a policy option based on a national strategy). To this purpose, the role of energy efficiency in abating CO_2 could also explain why its significance is higher with respect to CO_2 within national boundaries (as results in Table 1 clearly reveal), given that more efficient processes are diffusible and compatible with different sectors.

Table 3 – NMVOC abatement decisions (outside the country, same sector)

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coefficient in the theoretical model relying on the cognitive proximity framework. Results for a different specification not reported in Tables 2-3 are also robust since we only include $E_{\neq c}$ or we test $E_{\neq c}$ jointly with the two alternative $T_{\neq c}$.

	(1)	(2)	(3)	(4)	(5)	(6)
$RT_i(t-1)$	0.886 ***	0.877 ***	0.853 ***	0.870 ***	0.856 ***	0.868 ***
	(164.53)	(159.30)	(173.20)	(217.83)	(164.07)	(200.49)
$ValAd_i$	0.073 ***	0.068 ***	0.092 ***	0.073 ***	0.098 ***	0.095 ***
	(25.00)	(23.78)	(41.85)	(32.33)	(47.30)	(39.80)
$E^1_{\neq c}$	-0.018 **		-0.028 ***	-0.019 **		
	(-1.97)		(-4.09)	(-2.50)		
$E^2_{\neq c}$		-0.034 ***			-0.037 ***	-0.040 ***
		(-3.44)			(-5.21)	(-5.28)
$T^1_{\neq c}$			0.085 ***		0.070 ***	
			(7.93)		(7.13)	
$T^2_{\neq c}$				0.069 ***		0.044 ***
				(11.05)		(7.57)
Constant	1.354 ***	1.784 ***	-0.316	0.271	-0.229	0.352
	(2.99)	(4.56)	(-1.09)	(0.95)	(-0.97)	(1.66)
Country effects	Yes	Yes	Yes	Yes	Yes	Yes
Sector effects	Yes	Yes	Yes	Yes	Yes	Yes
No Obs.	3,391	3,391	3,391	3,391	3,391	3,391
Wald test	98,801	78,937	174,406	210,488	180,205	185,889
AR (1)	-3.445 (0.0)	-3.444 (0.0)	-3.497 (0.0)	-3.659 (0.0)	-3.505 (0.0)	-3.604 (0.0)
AR (2)	-1.964 (0.1)	-1.961 (0.1)	-2.008 (0.1)	-2.071 (0.1)	-2.012 (0.1)	-2.062 (0.1)
Sargan test	121.45 (0.1)	113.67 (0.1)	159.61 (0.1)	159.04 (0.2)	165.01 (0.1)	161.03 (0.1)

Notes: Two-step robust specification has been used. Robust t-statistics in absolute value are shown in brackets. (**), (***) Significant p-value at the 5%, 1%, respectively. AR(1) and AR(2) are tests-with distribution N(0, 1) on the serial correlation of residuals. Sargan Chi-square test for over identification of restrictions.

On the contrary, for NMVOC emissions, the implementation of policy targets are rather sector-based, notwithstanding the fact that early adoption at EU level of emission reduction targets for this specific pollutant may also help to explain these divergent results.[19]

6. Conclusions

We analyse investment decisions in innovation activities in a context where technology is characterised by mixed good features. Mixed good can be defined as the total amount of R&D accumulated stock. We pay attention to the reaction function between one agent's investment decision in the mixed good and the other agents' investment decisions in the public component of the mixed good.

The dynamic theoretical investigation shows that the only case in which the agent's investment in R&D does not react with respect to the aggregated public component provided by other agents is when the private component of R&D is very small. When the

[19] Policies targeting emissions (including NMVOC) have been present at national and EU level for decades, up to the new CAFE Directive introduced in 2008. NMVOC were targeted by EU Directives 99/13/EC and 94/63/EC and are of special importance in chemical, metallurgical and ceramic industries, but also in other manufacturing sectors, often giving rise to hot spots in densely agglomerated areas such as industrial districts (Belis-Begouignan and Oltra, 2004).

private and the public component are complements in the benefit function, an increase in the other agents' investment in the public component increases the marginal benefit of accumulating the complementary private component. In this way, through the extra investment in R&D, the representative agent also determines an increase in its investments in the public component.

Empirical analysis gives robust results on theoretical findings, related to the positivity of the reaction function. While results for knowledge externalities are consistent with a large body of literature on this issue, empirical findings on the role of environmental externalities are quite original.

Investments in R&D for each manufacturing sector positively react to environmental abatement decisions of the other sectors, and the reaction is higher than in the case of knowledge externalities. A comparison between different diffusion paths for global vs. local environmental externalities provides insightful additional suggestions. When considering CO_2 emissions, the sector R&D is mainly triggered by national interactions, which is coherent with the national systems of innovation framework. The result is also consistent with the fact that CO_2 abatement technologies heavily regard energy efficiency that provides joint private and public benefits. Thus, the fact that a sector positively reacts by investing more when others have abated is theoretically justified by the nature of the good and by the specific content of technology involved. The fact that NMVOC abatement efforts by other sectors impact R&D investments positively also from abroad means that, in some cases, a realm of sectoral systems of innovation is also relevant.

Overall, an investment in R&D that takes the form of a mixed public good might help fostering a general environmental-friendly behaviour, although this effect is likely to be strongly emission-specific as well as sector-specific.

These conclusions deserve some considerations. First of all, we show the existence of a "pro-social" behaviour *de facto* which is not explained by altruism, but is accounted for by the complementarity between the two characteristics of the impure public capital good.

Secondly, we also show that if the private characteristic tends to zero, this behaviour is no longer ensured. Hence, with regard to what specifically concerns a reduction in negative environmental externalities, we can rely on agents' voluntary (or extra-targets) behaviour only when they perceive benefits also arising from a complementary private characteristic.

This leads to some relevant policy implications. When a policy target is implemented (which can be oriented to a more general innovation impulse or to a specific environmental purpose), it could be achieved more easily if a "pro-social" behaviour were somehow triggered. More importantly, this behaviour may also help to foster a win-win solution where the achievement of environmental targets goes hand in hand with an increase in the competitive advantages driven by innovation dynamics. To this purpose, the reasoning behind the optimal policy mix should also include issues on the role of technical complementarity between the private and public characteristics. A pure environmental regulation approach may be less effective than a mixed approach where specific innovation incentives are ancillary measures to environmental targets.

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