The Journal of Technology Transfer (2021) 46:686–700
https://doi.org/10.1007/s10961-020-09796-4

Knowledge appropriability and directed technological change: the Schumpeterian creative response in global markets

Cristiano Antonelli[1,2] · **Christophe Feder**[2,3]

Published online: 22 May 2020
© Springer Science+Business Media, LLC, part of Springer Nature 2020

Abstract
When competition takes place in homogenous product markets between firms based in heterogeneous factor markets, the strategic introduction of biased technological change, directed towards the intensive use of factors that are locally and exclusively cheaper, can increase knowledge appropriability. The appreciation of the strategic direction of technological change widens the role of the Schumpeterian creative response in international trade and enables to grasp the central role of process innovations. The econometric analysis at the industry level of 13 OECD countries from 1995 to 2015 supports the hypotheses that openness to trade stirs the creative response and that process innovations, together with product innovations, account for the trade surplus.

Keywords Knowledge appropriability · Creative response · Schumpeter–Heckscher–Ohlin · Technological congruence · Process innovation

JEL Classification O33 · F15

1 Introduction

The limited appropriability of knowledge is a cornerstone of the economics of knowledge (Arrow 1962; Aghion et al. 2015). The introduction of directed process innovations that make intensive use of locally abundant factors that competitors cannot access can increase the appropriability of technological knowledge. Indeed, with the introduction of directed process innovations in the same product space, firms can take advantage of the positive effects of the limited exhaustibility and appropriability of knowledge in terms of localized pecuniary knowledge externalities. At the same time, firms can reduce the adverse effects

✉ Cristiano Antonelli
cristiano.antonelli@unito.it

[1] Dipartimento di Economia e Statistica, Università di Torino, Turin, Italy

[2] BRICK (Bureau of Research in Innovation Complexity and Knowledge), Collegio Carlo Alberto, Turin, Italy

[3] Dipartimento di Scienze Economiche e Politiche, Università della Valle d'Aosta, Aosta, Italy

of the limited knowledge appropriability in terms of spillovers to rivals. Competitors, in fact, can take advantage of knowledge spillovers but cannot replicate the specific cost conditions of innovators. The production cost for imitators-based in different factor markets—is larger than the production cost for innovators. The competitive advantage based upon the introduction of process innovation can last more than the competitive advantage based on product innovations.

The recent advances in the analysis of international trade provide an excellent context to explore and test the role of the introduction of process innovations directed to intensive use of locally abundant factors as a strategic tool to increase knowledge appropriability. In the standard theory of international trade, firms based in capital abundant countries exposed to the competition of cheap (labor-intensive) imports exit and enter other (capital-intensive) industries but do not change their technologies. The Schumpeterian creative response where firms try and innovate to cope with out-of-equilibrium conditions together with the recent advances of the economics of knowledge provide useful tools to grasp the role of product and process innovations in the economics of international trade (Antonelli 2017, 2019).

In the creative response approach to international trade, firms, challenged by increasing competition in domestic product markets, introduce product innovations and enter other industries (Scherer 1984; Aghion et al. 2011; Guarascio and Pianta 2017). In this paper, we articulate and test the hypothesis that process innovations do play—next to product innovations—an important role. Indeed, firms can bias the direction of technological change to increase their technological congruence[1] with locally heterogeneous factor markets, and to reduce production costs and increase the actual knowledge appropriability with positive effects on international competitiveness.

The empirical evidence of a recursive model where the dynamics of openness to trade affect research and development (R&D) expenditures, output elasticity, and productivity that, in turn, account for trade surplus in eight manufacturing industries and 13 OECD countries from 1995 to 2015 supports the hypotheses.

The plan of the paper is as follows. Section 2 presents the conceptual framework. Section 3 provides the empirical evidence. Section 4 concludes and gives some policy implications.

2 The theoretical framework

2.1 Directed technological change and knowledge appropriability

The induced technological change approach studies the determinants of the direction of technological change (Hicks 1932; Ruttan 1997; Acemoglu and Zilibotti 2001). Directed innovations are efficient when they improve the productivity of the cheapest factor that can be used by the firm (Acemoglu 2002 and 2010). Firms can direct their technological change only through process innovations.

This rich literature has not explored into depth the relationship between the direction of technological change and the knowledge appropriability. When competition takes place in

[1] The technological congruence is the level of coherence between their technology and own economic endowment (Abramovitz 1986; Zuleta 2012).

homogenous product markets between firms based in heterogeneous factor markets, the introduction of process innovations that direct technological change towards the intensive use of factors that are not only locally but also exclusively cheaper is an effective strategy to increase the appropriability of technological knowledge.

The increase of the use of locally abundant factors by means of the introduction of process innovations yields an increase in the levels of technological congruence which in turn increases the general efficiency of the production process (Antonelli and Quatraro 2010).

If the locally cheaper factor cannot be used, at the same cost conditions by competitors, the increased efficiency can be retained by the innovator and increases its profitability. Competitors can take advantage of the limited appropriability of knowledge, access the spillover of the technological knowledge that has been generated to support the introduction of the biased technological change—intensive of the locally cheaper factor for innovator—and imitate but cannot replicate the cost conditions of the innovator. The specific characteristics of the factor market into which the innovator is based cannot take place in the factor market of the imitator. The cost of the output of competitors is higher than the cost of innovators because the innovation is directed on a factor that is more expensive in their factor markets than in the innovator one, and competitors and imitators cannot replicate the cost conditions of the innovator.

The limited knowledge appropriability cannot prevent imitation. However, the difference in the factor market, magnified by its output elasticity, augments the appropriation of the rents stemming from the biased technological change. Rivals can imitate but cannot replicate the actual cost of innovators. The entry of competitive imitators no longer erodes the competitive advantage of innovators. The difference in costs of factors becomes an effective barrier to entry and a long-lasting source of competitive advantage and increased profitability.

The effects of the introduction of process innovations that bias technological change towards the intensive use of factors—that are locally cheaper—on the actual knowledge appropriability are stronger the more exclusive is the access to the innovator's factor market and the more the differential cost conditions are rooted in local factor markets.

The increased de-facto appropriability of knowledge rents and the stretching of the competitive advantage based upon the introduction of process innovations become a powerful incentive to direct technological change towards the intensive use of local and exclusive factors characterized by specific cost conditions that cannot be replicated.

The selective direction of technological change increases the actual levels of knowledge appropriability that, in turn, increase the profitability of innovation and hence the incentive to rely upon process innovations that direct technological change as a competitive tool within a Schumpeterian spiraling loop. The spiraling loop between the selective direction of technological change, the knowledge appropriability, and the rate of technological advance is stronger, the stronger the heterogeneity of factor markets into which competitors are based.

International trade and global competition characterized by competition in quasi-homogeneous product markets between rivals based in quite heterogeneous factor markets provide an excellent context to analyze the strategic direction of technological change as a tool to increase the knowledge appropriability and its effects on competitivity.

2.2 The creative response in international trade

The recent advances in the economics of international trade have stressed the role of technological change in international product markets. In the Heckscher–Ohlin (HO) framework, the entry of new labor abundant countries in international markets yields both the increase of imports of labor abundant goods by capital abundant countries and the reduction of the market price of labor abundant goods in the domestic markets of countries specializing in the production of capital abundant goods. Moreover, the imports of capital abundant goods with the reduct the market price of capital abundant goods in the domestic markets of countries specializing in the production of labor abundant goods.

The HO approach has all the elements of the technological congruence framework intrinsically. However, it assumes that the specialization of the trading countries is fully exogenous and static. There is no clue in the HO model about the determinants of the specialization and its change. The textbook version of the model assumes that specialization reflects the local endowments so that capital abundant countries specialize in capital abundant products and labor abundant countries in labor abundant ones. The HO approach does not allow the possibility that the change in technology and hence in specialization is the endogenous consequence of international trade.

A dynamic extension of the HO framework has been articulated with the integration of the Schumpeterian creative response. In a dynamic Schumpeter–Heckscher–Ohlin (SHO) framework, the entry of new countries in international product markets stirs the rate and biases the direction of technological change in incumbent competitors (Antonelli 2017, 2019).

The SHO framework unfolds two distinct approaches: (i) the challenge of competition in international product markets triggers the introduction of product innovations; (ii) the challenge of competition in international product markets triggers the introduction of process innovations that shape the direction of technological change.

The SHO approach that focuses the introduction of product innovations in international product markets is fully consistent with both the classic Schumpeterian rivalry and the HO approach and has been applied by an extensive literature (Scherer 1984). This SHO framework is fully consistent with the Schumpeterian rivalry: (i) firms compete through the introduction of new products; (ii) innovators enjoy transient rents that fund R&D expenditures; (iii) the entry of new competitors stirs the introduction of new waves of product innovations (Rivera Batiz and Romer 1991; Scherer and Huh 1992; Chen et al. 2017; Guarascio and Pianta 2017).

The SHO framework based on the introduction of product innovation is consistent with the predictions of the HO model about the increase of capital-intensive production in capital abundant countries exposed to the entry of new labor abundant competitors with increasing flows of inter-industrial international trade. The literature has much explored the inter-industrial effects of such dynamics. Domestic firms exposed to increasing competition from imported goods exit the market place and/or move away from the former product markets, introduce product innovations, and enter new industries where new firms are created. These dynamics account for the decline of the US manufacturing industry, where the competitive pressure of imports from the Far East has weakened its innovative capability (Bloom et al. 2016; Autor et al. 2020).

Within international supply chains, imported factors are used to support the exports of downstream industries. The dynamics trigger a structural change in importing economies with the decline of output in importing industries and the growth of output of exporting ones and reinforce vertical, inter-industrial trade between countries (Pahal and Timmer 2019; Del Prete et al. 2017; Boler et al. 2015; Aboal et al. 2017; Baldwin and Lopez-Gonzalez 2015; Castellani and Fassio 2019).

So far, the literature has paid little attention to the dynamic extension that focuses on the role of the introduction of process innovations and biased technological change in international trade. The analysis of the role of process innovations—that enable to introduce biased technological change directed to increase the output elasticity of locally abundant factors and high levels of technological congruence—enables to extend the scope of the classic Schumpeterian rivalry based on product innovations.

One of the major contributions of this paper is to highlight how not only product innovations but also process ones are a possible reaction of firms to the challenges of international trade. The focus on the role of process innovations extends the scope of investigation of the SHO framework. It enables to appreciate the effects of the augmented appropriability of knowledge triggered by the introduction of process innovations directed to take advantage of a global economy characterized by the dynamics of competition in quasi-homogeneous product markets among firms based in heterogenous factor markets.

2.3 Process innovations in the SHO framework

Globalization is characterized by competition in quasi-homogeneous product markets among firms, based in heterogeneous factor markets. The heterogeneity of factor markets is a resilient character of the global economy. Factor cost equalization is a slow process that takes place in the long-term. Many production factors are rooted in the specific and idiosyncratic characteristics of the different economic systems.

In a static context, with a given technology and hence a given mix of output elasticities, cost heterogeneity among competitors is itself an evident source of competitive advantage: firms select the factor intensity with standard procedures and make more intensive use of the factor that is locally cheaper. Moreover, cost heterogeneity is a source of barriers to entry and mobility with strong effects in terms of competitiveness and profitability for firms that enjoy the exclusive access to factors at a lower cost. In a dynamic context, however, technology can change purposely, and then cost heterogeneity becomes a powerful factor that shapes the endogenous introduction of directed technological change.

The creative response in international trade includes not only product but also process innovations. The latter enable to implement the strategic direction of technological change towards the augmented output elasticity of the factor that can be accessed and used at costs that are below the levels of competitors and are characterized by specific elements of exclusivity that impede their competitive use. The resilient heterogeneity of factor markets coupled with the introduction of directed technological change biased towards the use of locally abundant factors increases the appropriability of technological knowledge and the duration of the competitive advantage based on the introduction of innovations.

The introduction of biased technological change directed at increasing the output elasticity of the factor that is locally abundant has strong effects in terms of augmented total factor productivity and competitive advantage. The incentive to select the appropriate direction of technological change is augmented by its effects on the appropriability conditions of the benefits of the application of the new technological knowledge as determined by the relative access conditions to the factor. The appreciation of the strategic direction of technological change as a mechanism to increase the knowledge appropriability has major implications for the analysis of competition in global product markets.

2.4 The hypotheses

The combination of the trade and innovation theories is mutually fruitful: the HO model endogenizes the innovation process and becomes dynamic, and the Schumpeterian creative response can apply to competition among firms based in heterogeneous factor markets. Moreover, the integration of these two fields of research with the analysis of the role of directed technological change shows that both product and process innovations could emerge as a firm's creative reaction to international trade.

The competitiveness of countries is the endogenous outcome of the creative response of firms engaged in international competition and able to fund R&D activities to introduce both product and process innovations. Competition in international product markets stirs the creative response. The creative response is successful when firms have access to a large stock of technological knowledge—because of its limited appropriability and exhaustibility—enjoy low R&D cost. This creative response takes place in a limited portion of the space of products and techniques and triggers both product and process innovations.

The introduction of process and biased technologies yields: (i) a reduction of production costs that (ii) triggers a resilient and competitive advantage in the same industry and product market that (iii) is long-lasting because the intrinsic asymmetries of factor endowments and costs in local factor markets increase de-facto appropriability, and (iv) enables to increase their market shares in global markets in the very same industry, so as (v) to increase the exports, horizontal international trade, and trade surplus.

This dynamic differs and complements the alternative strategy that consists of the exit from the industries where the competition of imported goods is increasing, the introduction of product innovations, and the entry into new industries where local factor markets provide more abundant and relatively cheaper factors.

The analytical background elaborated so far enables us to spell out the basic hypotheses:

1) Both the flows of import and export measure the degree of involvement of local firms in international competition. The former, in fact, account for the penetration of foreign products in domestic markets and the latter for the extent to which domestic firms are involved in the competition with foreign producers in their domestic markets. The levels of trade openness provide a reliable and comprehensive measure of the extent to which the product markets of domestic firms are exposed to rivalry and competition. We assume that the larger the levels of openness to trade, the larger the pressure to activate the mechanisms of the creative response. The levels of innovative efforts are endogenous as the levels of openness to international trade determine them.

2) For given levels of openness to trade, firms are more likely to activate the mechanisms of the creative response the larger is the stock of knowledge available in their industries. Technological knowledge is intrinsically localized. Firms can benefit from pecuniary knowledge externalities if they can use knowledge items that are consistent and coherent with their knowledge base. The larger the knowledge externalities, the lower the costs of the generation of new knowledge. Hence, the larger the size of the industrial stock of knowledge, the lower knowledge costs and the larger the amount of innovative efforts that firms can fund and perform to feed the creative response and introduce process innovations in their product markets.

3) Innovative efforts yield the introduction of product and process innovations that affect the productivity of firms. The effects of innovative efforts are stronger, the stronger is the technological congruence, because of the larger and longer appropriability of the returns from innovation. Specifically, we expect to have larger levels of labor productivity, the larger the levels of innovative efforts, and the larger the technological congruence of the production processes as the result of the introduction of new technologies that make large use of the locally cheaper factors.

4) The increased levels of productivity exert direct positive effects on the trade surplus. The increase of trade surplus in their industrial product markets is, in fact, the eventual outcome of the creative response ignited by the openness to trade, when and if appropriate levels of the localized stock of knowledge are available and accessible in their industries

and support the innovative efforts that have made possible the introduction of new directed technologies with high levels of technological congruence. Competitors can imitate but cannot replicate—fully—the production costs of innovators.

3 The econometric analysis

3.1 Methodology and database

The hypotheses are tested on an industrial dataset to analyze the matching between openness to trade as the primary causal factor of the dynamics of the creative response, supported by the localized stock of industrial knowledge that accounts for the levels of productivity and performances in terms of trade surplus. Following the standard "CDM" approach suggested by Crépon et al. (1998), to solve the endogeneity problem, and Mairesse and Robin (2017), to correctly calculate the error terms, we test all the hypotheses in an econometric model with three regressions that implement the inclusion of an "international performance" equation that adds to the innovation equation and the productivity one.

This procedure, enriched by an "international performance" equation, is expected to test the chain of hypotheses that the industries, exposed to international competition both in domestic and international product markets—that have been able to switch the creative response relying on the localized stock of technological knowledge available within their industrial base and introduce process innovations with high levels of technological congruence—can increase their competitiveness and market shares both at home and abroad. The manufacturing data on the structural analysis (STAN) database allows testing these hypotheses.[2]

The STAN database follows the last revision of the international standard classification of productive activities (ISIC Revision 4). Therefore, all the manufacturing activities are classified in eight industrial macro-sectors: food products, beverages, and tobacco; textiles, wearing apparel, leather, and related products; wood and paper products, and printing; chemical, rubber, plastics, fuel products, and other non-metallic mineral products; basic metals and fabricated metal products, except machinery and equipment; machinery and equipment; transport equipment; and furniture, other manufacturing, repair and installation of machinery, and equipment.

From the STAN database at manufacturing industries, we can obtain the following comparable variables on 13 OECD countries from 1995 to 2015[3]: the gross output at current purchasing power parities (PPPs) in millions of dollars at 2010, Y; the investments at current PPPs in millions of dollars at 2010, I; the total employment and its total costs at current PPPs in millions of dollars at 2010, L and wL, respectively; the exports of goods at current PPPs in millions of dollars at 2010, X; the imports of goods at current PPPs in millions of dollars at 2010, M; and the R&D expenditures at PPPs in millions of dollars at 2010, *R&D*.

The data on R&D expenditures are available by industry, when the R&D expenditures of firms that have multiple lines of business are correctly split up in each line of

[2] http://www.oecd.org/industry/ind/stanstructuralanalysisdatabase.htm.

[3] More precisely, we have data from 1995 to 2015 for 11 countries: Belgium, the Czech Republic, Finland, France, Germany, Italy, Mexico, Norway, Portugal, Slovenia, the United Kingdom, and the United States. Moreover, we also have data for Canada from 1995 to 2014 and for Slovenia from 1997 to 2015.

own business, and by main activity, when their R&D expenditures are all allocated in the main business' line of the firms. When the firm produces a single product, or it produces multiple products but remains within one of the eight macro-sectors described above, no difference emerges between the two measures. Otherwise, the R&D expenditures allocated by industry are most informative but harder to be accounted for. Indeed, these data are poor: Belgium and the UK from 1995 to 2015; the Czech Republic from 2004 to 2015; France from 1995 to 2013; Italy and Portugal from 2008 to 2015; and Finland from 2010 to 2015. For the other six OECD countries, only R&D data by main activity is available. Fortunately, the difference between the two measures of the R&D expenditures is not very relevant, and then we measure the R&D expenditures by industry when they are available and by main activity otherwise.

Available data about wages, w, and capital rental costs, r, as well as about labor factor share, β, enable to measure of the slope of the isocost, w/r, and of the shape of the isoquant, $(1-\beta)/\beta$. Both variables are used to estimate the technological congruence of the eight manufacturing industries in 13 OECD countries.

We follow the inventory procedure (Hall 2005) to measure the capital intensity and the stock of R&D. Indeed, both investments, I, and R&D expenditures, $R\&D$, are flow variables. Assuming that they have an average duration of 5 years and a constant discount rate, we can measure the capital, K, and the stock of R&D, $\Sigma R\&D$:

$$K_t = I_t + 0.8I_{t-1} + 0.6I_{t-2} + 0.4I_{t-3} + 0.2I_{t-4}, \tag{1}$$

$$\Sigma R\&D_t = R\&D_t + 0.8R\&D_{t-1} + 0.6R\&D_{t-2} + 0.4R\&D_{t-3} + 0.2R\&D_{t-4} \tag{2}$$

From Y and L, we derive a standard measure of the labor productivity, $y = Y/L$, and then, by symmetry, we also measure: the capital intensity, $k = K/L$; the flow of R&D over labor, $RD = R\&D/L$; the stock of R&D over labor of 5 years, ΣRD; and the exports and the imports over labor, $x = X/L$ and $m = M/L$.

The trade surplus is a crucial variable to measure the competitiveness of firms in global product markets. From exports and imports over labor, we can measure the global market share for each industry s at year t in two ways:

$$TS_{s,t} = \frac{x_{s,t}}{m_{s,t}}, \tag{3}$$

$$NX_{s,t} = x_{s,t} - m_{s,t}. \tag{4}$$

When either export increases or import decreases, the global market share of the industry s in the country increases and well as the surplus of its trade balance, as described in (3) and (4). In the following, we will use both measures of trade surplus as robustness checks.

Finally, from Feder (2018), when the direction of technological change is congruent and hence efficient, it exerts positive effects on productivity. We then estimate the effects of the congruence of the direction of technological change:

$$DC = -\ln\left(\frac{1-\beta_i}{\beta_i}\frac{w_i}{r_i}\right)d\beta_i. \tag{5}$$

In (5), the interaction of the two variables w/r and $(1-\beta)/\beta$ can improve the performances of firms. The more congruent and efficient the direction of technological change, DC, the higher the levels of productivity. When the introduction of process and biased innovations directs technological change towards the increase of the output elasticity of the most abundant factor, production costs decrease.

Consistently with the SHO framework in Sect. 2, we rely upon a structured econometric approach that uses a bootstrapped three equations recursive system with fixed effects. In the first step of the empirical process, we test if the economic openness, $Open = x + m$, and the previous stock of R&D with an average duration of 5 years, ΣRD, affects the levels of innovation efforts, approximated with the flow of R&D, RD:

$$RD_t = \gamma_0 + \gamma_1 Open_t + \gamma_2 \Sigma RD_{t-1} + \sum \gamma YD + \varepsilon_1, \tag{6}$$

where YD is the dummy variable that drops the first year to avoid multicollinearity problems, and ε is the error term that captures all other effects not attributable to the previous variables. Following Mairesse and Robin (2017), we bootstrap (6) with 100 repetitions to correctly calculate the error terms in all the three steps of the empirical process.

In the second step of the three equations recursive system with fixed effects, following the technology production function (Griliches 1979, 1992),[4] labor productivity is the dependent variable; the independent variables are: the capital intensity, k; the direction of technological change, DC; and the instrumented variable, $\widehat{RD}$, as a proxy of the intensity of endogenized innovation efforts:

$$y_t = \alpha_0 + \alpha_1 \widehat{RD}_t + \alpha_2 DC_t + \alpha_3 \left(\widehat{RD}_t \cdot DC_t\right) + \alpha_4 k_t + \sum \alpha YD + \varepsilon_2, \tag{7}$$

where $\widehat{RD}$ is endogenously determined by the level of openness and the stock of knowledge available within the analyzed industry as estimated from (6):

$$\widehat{RD}_t = \hat{\gamma}_0 + \hat{\gamma}_1 Open_t + \hat{\gamma}_2 \Sigma RD^n_{t-1} + \sum \hat{\gamma} YD. \tag{8}$$

The factor intensity, $k = K/L$, could be affected by the unity of measure used in the database, and then an unappropriated unit of measure may bias the results. Zuleta (2012) suggests an empirical procedure to assign the right unit of measure of factors.[5] In (7), we assume that not only the intensity, $\widehat{RD}$, and the direction, DC, of innovation efforts but also their combination, $\widehat{RD} \cdot DC$, improve productivity.

Moving on to the last step of the three equations recursive system, we estimate:

$$Surplus_t = \delta_0 + \delta_1 \hat{y}_t + \sum \delta YD + \varepsilon_3, \tag{9}$$

where $Surplus$ measures the performances in the global market, estimated using either the trade rate described by (3) or the net trade described by (4) and $\hat{y}$ is the instrumented variable that derives from (7):

$$\hat{y}_t = \hat{\alpha}_0 + \hat{\alpha}_1 \widehat{RD}_t + \hat{\alpha}_2 DC_t + \hat{\alpha}_3 \left(\widehat{RD}_t \cdot DC_t\right) + \hat{\alpha}_4 k_t + \sum \hat{\alpha} YD. \tag{10}$$

Table 1 provides the main descriptive statistics. The variables are duplicated because, following Zuleta (2012), we also use the unit of measure of factors as an additional robustness check. Only TS is unaffected by the unit of measure of factors because it is a trade

4 Note that the levels of R&D expenditures are determined by the creative response and are endogenous.

5 See Zuleta (2012) and Feder (2018) for an in-depth analysis of the procedure to obtain variables with an unbiased unit of measure of factors.

Table 1 Descriptive statistics

	Factors' measure	Obs.	Mean	Std. Dev.	Min.	Max.
TS		2174	1.07	1.13	0.07	14.92
NX	From STAN (ISIC Rev. 4) database	2174	−7633.84	70,587.49	−389,174.06	460,559.63
Y/L		2174	239.22	128.77	44.53	957.71
Open		2174	281,705.27	385,341.35	1173.70	3,567,073.00
RD		2174	4012,057.52	6755,705.75	1356.80	45,275,636.00
K/L		1758	45.27	34.38	3.92	219.30
DC		1758	0.00	0.04	−0.21	0.17
ΣRD		1758	12,477,574.68	20,861,383.86	16,315.25	132,429,080.00
NX	From Zuleta (2012)'s method	2174	−505.93	10,863.81	−69,489.76	88,244.78
Y/L		2174	37.95	28.75	4.93	189.47
Open		2174	42,035.66	63,896.37	247.75	683,463.25
RD		2174	661,448.71	1270,998.97	268.69	10,414,889.00
K/L		1758	80.03	60.78	6.92	387.69
DC		1758	0.00	0.05	−0.24	0.20
ΣRD		1758	2,054,557.69	3,920,168.68	3,669.71	30,463,054.00

Source: STAN (ISIC Revision 4) and our elaborations

Table 2 Results of the first step of the three equations recursive system

Dependent variable	RD_t	RD_t
$Open_t$	0.521637*** (0.205608)**	0.771297*** (0.234998)**
ΣRD_{t-1}	0.317517*** (0.010365)**	1.665463*** (0.060401)**
Constant	245,396.182159*** (102,969.807361)**	587,738.703707*** (112,187.195366)**
Year Dummies	Yes	Yes
Factors' Measure	STAN Database	Zuleta's Method
R^2	0.9923	0.94053
Observations	1758	1758

Fixed effects panel model. Bootstrap Standard Errors are reported in parentheses (100 repetitions). Significant at *10%, **5%, and ***1%. Source: STAN (ISIC Revision 4) and our elaborations

ratio. Moreover, we observe that capital is always the most abundant factor. This evidence is provided directly from the STAN database for OECD countries.

3.2 Results

Table 2 shows the results of the first step of the three equations recursive system, described in (6), where the intensity of innovation efforts at the industrial level *RD* is endogenously determined by the level of openness and the stock of knowledge available within the analyzed industry. We can then conclude that both variables exert significant and positive effects on the intensity of current innovation efforts.

Table 3 Results of the second step of the three equations recursive system

Dependent variable	Y_t/L_t	Y_t/L_t	Y_t/L_t	Y_t/L_t
$\widehat{RD}_t$	0.000005*** (0.000001)**	0.000006*** (0.000001)**	0.000006*** (0.000001)**	0.000006*** (0.000001)**
DC_t	168.985303*** (23.486385)**	97.052554*** (27.781196)**	171.591771*** (23.692633)**	95.093776*** (27.925504)**
$\widehat{RD}_t \cdot DC_t$		0.000011*** (0.000004)**		0.000013*** (0.000004)**
K_t/L_t	1.098897*** (0.192452)**	1.126484*** (0.191531)**	1.027582*** (0.192695)**	1.050695*** (0.189923)**
Constant	148.478454*** (9.034488)**	146.626750*** (9.152565)**	149.140389*** (8.916183)**	147.051994*** (8.977701)**
Year Dummies	Yes	Yes	Yes	Yes
Factors' Measure	STAN database	STAN database	Zuleta's method	Zuleta's method
Observations	1758	1758	1758	1758

Fixed effects panel model. Bootstrap Standard Errors are reported in parentheses (100 repetitions). Significant at *10%, **5%, and ***1%. Source: STAN (ISIC Revision 4) and our elaborations

From previous empirical estimations, Table 3 shows the results of the second step of the three equations recursive system as proposed by (7). This evidence supports the hypothesis that, under the control of the standard capital intensity, both the congruent direction of technological change and the endogenous intensity—with respect to employment—of the current innovation efforts exert positive effects on productivity. These results confirm that Y/L is endogenous as it is itself the result of DC and $\widehat{RD}$. Following (7), we implement the structured econometric approach. The empirical evidence supports the hypothesis that when technological change is congruently directed and firms invest in innovation, the rate of productivity increases.

Analyzing OECD countries, capital is always the most abundant factor (see also Table 1). Therefore, from the positive coefficient of DC, we can also conclude that if w/r and $(1-\beta)/\beta$ increase, then also the productivity of firms increases. In other words, when in the manufacturing industry labor is more expensive and less productive than capital, the technology used by the industry is more coherent with its economic endowment, and then even with the same investments on technological change, the industry bears lower costs and then it is more productive. Table 3 also shows that the combined effect of the intensity and the direction of innovation efforts, $\widehat{RD} \cdot DC$, affects productivity in a positive and significant way.

Tables 4 and 5 show the results of the last step of the econometric process. More precisely, Table 4 assumes only the additional indirect effects on the surplus of the endogenous innovative efforts, $\widehat{RD}$, and of the technological congruence, DC. Vice versa, Table 5 also adds their combined effect, $\widehat{RD} \cdot DC$, on productivity and, indirectly, on surplus, as described in (9) and (10). The two proxies of the performance of each industry in global markets, i.e., the trade surplus TS and the net export NX, are the dependent variable of the endogenous level of Y/L: $\widehat{Y/L}$. The results enable to confirm that the introduction of new process innovations that bias the direction of technological change, increase the technological congruence of the innovators, exerts positive and significant effects on the global performance within the product markets of each industry. We can then conclude that also process innovations are a reaction of firms to the challenges of international trade.

Table 4 Results of the last step of the recursive system without the combined effect of the level and the direction of innovative efforts, $\widehat{RD} \cdot DC$

Dependent variable	TS_t	TS_t	NX_t	NX_t
$\widehat{Y_t/L_t}$	0.002030*** (0.000523)**	0.001900*** (0.000492)*	232.746306*** (55.312603)**	243.995093*** (55.141856)**
Constant	0.706751*** (0.090388)**	0.734102*** (0.087527)*	−52,761.339694*** (12,552.488418)**	−55,123.062941*** (12,531.347410)**
Year Dummies	Yes	Yes	Yes	Yes
Factors' Measure	STAN Database	Zuleta's Method	STAN Database	Zuleta's Method
Observations	1758	1758	1758	1758

Fixed effects panel model. Bootstrap Standard Errors are reported in parentheses (100 repetitions). Significant at *10%, **5%, and ***1%. Source: STAN (ISIC Revision 4) and our elaborations

Table 5 Results of the last step of the recursive system with the combined effect of the level and the direction of innovative efforts, $\widehat{RD} \cdot DC$

Dependent variable	TS_t	TS_t	NX_t	NX_t
$\widehat{Y_t/L_t}$	0.002008*** (0.000504)**	0.001862*** (0.000465)**	234.195318*** (55.360937)	247.236561*** (55.127209)**
Constant	0.711356*** (0.085385)**	0.741918*** (0.081259)*	−53,065.565050*** (12,499.427819)**	−55,803.620742*** (12,435.418639)*
Year Dummies	Yes	Yes	Yes	Yes
Factors' Measure	STAN Database	Zuleta's Method	STAN Database	Zuleta's Method
Observations	1758	1758	1758	1758

Fixed effects panel model. Bootstrap Standard Errors are reported in parentheses (100 repetitions). Significant at *10%, **5%, and ***1%. Source: STAN (ISIC Revision 4) and our elaborations

The evidence of the econometric test confirms that: (i) innovation efforts are endogenous and can be regarded as a creative response to the challenges of international trade. The larger the levels of openness to trade, the larger the R&D efforts of industries that can rely on a consistent stock of technological knowledge specific to their products; (ii) (more) capital abundant countries specialize in the production of (more) capital abundant goods; (iii) because of the high levels of localization of technological knowledge and technological change, (more) capital abundant countries introduce industry-specific (more) capital intensive technologies that enable to stick in the proximity of the original location in the space of techniques and products and remain within the boundaries of their product markets. The evidence, moreover, calls attention to the variety of factor intensities within the products of each industry. Summarizing, all the results support the hypotheses of the SHO process approach described in Sect. 2.4.

4 Conclusions and policy implications

The strategic direction of technological change towards the intensive use of local and exclusive factors that competitors cannot use at the same cost conditions is a powerful tool to increase both the actual appropriability of technological knowledge and the total efficiency of production activities.

The strategic bias of technological change induced by oligopolistic rivalry enables to stretch the duration of the effective appropriability of innovation rents when it can exploit the persistent cost asymmetries engendered by the exclusive access to rare factors that are rooted in the localized factor markets. Competitors, rooted in other factor markets, can imitate and replicate the knowledge base, but not the actual production conditions shaped by the specific and idiosyncratic conditions of their specific factor markets. The strategic use of process innovations biased towards the intensive use of locally and exclusive abundant production factors enables to increase the levels of the appropriability, delay the imitation of competitors, and stretch the duration of the competitive advantage. The positive effects on the appropriability and profitability of the introduction of process and biased innovations are a powerful incentive to direct strategically technological change.

The integration of the Schumpeterian creative response into the HO framework of international trade enables to grasp the endogenous dynamics of technological change and its interplay with international product markets. The creative response takes place when firms—that can take advantage of knowledge spilling from the local stock of knowledge—try and cope with out-of-equilibrium conditions through the introduction of innovations. The creative response includes both the traditional Schumpeterian rivalry that praises the introduction of product innovations as an alternative to price competition and the introduction of process innovations.

The traditional Schumpeterian rivalry is consistent with the HO framework. In the latter, capital abundant countries exposed to labor-intensive imports from labor abundant countries specialize in capital-intensive products. In the former firms introduce product innovations as a tool of oligopolistic rivalry, exit from their former industry, move towards other industries, introduce new products, and export, feeding inter-industrial flows of trade.

This paper has elaborated an extension of the Schumpeterian creative response to international trade theory, stressing the role of process innovations—next to product innovations—and the introduction of directed and localized technological change as a competitive tool in oligopolistic quasi-homogeneous product markets where competing firms are based in heterogenous factor markets.

Our analysis of the strategic role of the introduction of process innovations biased towards the intensive use of the locally abundant factor, in fact, enables us to stretch the traditional Schumpeterian rivalry and its application to analyzing international trade.

The globalization of product markets where rivals are based in heterogeneous factor markets calls attention on the role of the introduction of new process and biased technologies that are directed to make the most intensive use of locally abundant and hence cheaper factors, as a relevant strategy that extends the limits of the traditional Schumpeterian rivalry and yet applies its basic intuition on the endogeneity of technological change.

In this extended SHO framework, firms exposed to the aggressive entry into their product markets rely—also—on the introduction of process innovations to increase their levels of technological congruence and try to compete in the same product markets changing their production technologies and not only their products.

In the extended framework of Schumpeterian rivalry elaborated in this paper, firms based in heterogenous factor markets and exposed to the increasing globalization of product markets have a strong incentive to make strategic use of the direction of technological change biased towards the more intensive use of locally abundant factors. The introduction of new process and biased technologies that take advantage of factor costs asymmetries enables to increase the levels of technological congruence reducing costs, augmenting efficiency, increasing market share in global oligopolistic markets within the same industry.

The empirical evidence of the dynamics of factors, output elasticity, productivity, and international market shares of the manufacturing industries of 13 OECD countries from 1995 to 2015 supports the hypotheses.

The analysis implemented in this paper and the empirical evidence provide the foundations for understanding the interplay between international trade and the rate and direction of technological change. Firms try and cope with the entry of new competitors by means not only of the introduction of product innovations but also of the introduction of directed process innovations. The introduction of directed process innovations that increase the levels of technological congruence increases the actual appropriability of technological knowledge. Rivals can imitate the new directed technologies but cannot apply them with the same costs because of the intrinsic heterogeneity of global factor markets. Process innovations yield knowledge rents that last more than product innovations.

When the determinants of factor costs differential are endogenous at the system level, economic policies geared towards the identification and the selective support of the upstream activities that provide intermediary factors with significant cost differentials with respect to imitators and possible competitors helps to reinforce the direction of technological change towards the use of the factors that happen to be locally cheaper in downstream activities.

Acknowledgements Funding was provided by MIUR (Grant No. PRIN 20177J2LS9).

References

Aboal, D., Arza, V., & Rovira, F. (2017). Technological content of exports. *Economics of Innovation and New Technology, 26*(7), 661–682.

Abramovitz, M. (1986). Catching up, forging ahead, and falling behind. *The Journal of Economic History, 46*(2), 385–406.

Acemoglu, D. K. (2002). Directed technical change. *Review of Economic Studies, 69*(4), 781–809.

Acemoglu, D., & Zilibotti, F. (2001). Productivity differences. *Quarterly Journal of Economics, 116*(2), 563–606.

Aghion, P., Akcigit, U., & Howitt, P. (2015). Lessons from Schumpeterian growth theory. *American Economic Review, 105*(5), 94–99.

Aghion, P., Boulanger, J., & Cohen, E. (2011), *Rethinking industrial policy*. Bruegel Policy Brief, No. 2011/04.

Antonelli, C. (2017). Endogenous innovation: The creative response. *Economics of Innovation and New Technology, 26*(8), 689–718.

Antonelli, C. (2019). The creative response and international trade. *Structural Change and Economic Dynamics, 51,* 445–452.

Antonelli, C., & Quatraro, F. (2010). The effects of biased technological change on total factor productivity. *Empirical evidence from a sample of OECD countries, Journal of Technology Transfer, 35,* 361–383.

Arrow, K. J. (1962). Economic welfare and the allocation of resources for invention. In R. R. Nelson (Ed.), *The rate and direction of inventive activity: Economic and social factors* (pp. 609–625). Princeton: Princeton University Press for N.B.E.R.

Autor, D., Dorn, D., Hanson, G.H., Pisano, G., & Shu, P. (2020), Foreign competition and domestic innovation: Evidence from US patents. *American Economic Review* (forthcoming).

Baldwin, R., & Lopez-Gonzalez, J. (2015). Supply-chain trade: A portrait of global patterns and several testable hypotheses. *The World Economy, 38,* 1682–1721.

Bloom, N., Draca, M., & Van Reenen, J. (2016). Trade induced technical change? *The impact of Chinese imports on innovation, IT and productivity, Review of Economic Studies, 83*(1), 87–117.

Boler, E. A., Moxnes, A., & Ulltreveit-Moe, K. H. (2015). R&D international sourcing and the joint impact on firm performances. *American Economic Review, 105*(12), 3704–3739.

Castellani, D., & Fassio, C. (2019). From new imported inputs to new exported outputs. *Research Policy, 48*(1), 322–338.

Chen, Z., Zhang, J., & Zheng, W. (2017). Import and innovation: Evidence from Chinese firms. *European Economic Review, 94,* 215–220.

Crépon, B., Duguet, E., & Mairesse, J. (1998). Research and development, innovation and productivity: An econometric analysis at the firm level. *Economics of Innovation and New Technology, 7*(2), 115–158.

Del Prete, D., Giovannetti, G., & Marvasi, E. (2017). Global value chains participation and productivity gains for North African firms. *Review of World Economics, 153*(4), 675–701.

Feder, C. (2018). A measure of total input productivity with biased technological change. *Economics of Innovation and New Technology, 27*(3), 243–253.

Griliches, Z. (1979). Issues in assessing the contribution of research and development to productivity growth. *Bell Journal of Economics, 10,* 92–116.

Griliches, Z. (1992). The search for R&D spillovers. *Scandinavian Journal of Economics, 94*(Supplement), 29–47.

Guarascio, D., & Pianta, M. (2017). The gains from technology: New products exports and profits. *Economics of Innovation and New Technology, 26*(8), 799–804.

Hall, B. H. (2005). Measuring the returns to R&D: The depreciation problem. *Annales d'Economie et de Statistique, 79*(80), 341–382.

Hicks, J. R. (1932). *The theory of wages*. London: Macmillan.

Mairesse, J., & Robin, S. (2017). Assessing measurement errors in the CDM research–innovation–productivity relationships. *Economics of Innovation and New Technology, 26*(1–2), 93–107.

Pahal, S., & Timmer, M. P. (2019). Patterns of vertical specialization in trade: Long run evidence for 91 countries. *Review of World Economics, 155*(3), 459–486.

Rivera Batiz, L. A., & Romer, P. A. (1991). International trade with endogenous technological change. *European Economic Review, 35*(4), 971–1001.

Ruttan, V. W. (1997). Induced innovation evolutionary theory and path dependence: Sources of technical change. *Economic Journal, 107*(444), 1520–1529.

Scherer, F. M. (1984). *Innovation and growth: Schumpeterian perspectives*. Cambridge: MIT Press.

Scherer, F. M., & Huh, K. (1992). R&D reactions to high-technology import competition. *Review of Economics and Statistics, 74*(2), 202–212.

Zuleta, H. (2012). Variable factor shares, measurement and growth accounting. *Economics Letters, 114*(1), 91–93.

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.