FUNDAMENTAL R&D SPILLOVERS AND THE INTERNATIONALIZATION OF A FIRM'S RESEARCH ACTIVITIES

By

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Fundamental R&D Spillovers and the Internationalization of a Firm's Research Activities

Abstract

A conceptual framework is proposed for analyzing how differences in national R&D stocks can impact on a firm's decision to internationalize its R&D activities. A central finding is that the integration of product markets can generate an added incentive to undertake R&D abroad. A three-stage analysis of a non-cooperative game is proposed, which entails cost-reducing process innovation in an international model of duopoly. Each firm's technological efficiency depends not only on its investment in applied R&D, but also on its absorption of domestic and foreign fundamental R&D, as well as the extent to which the latter are substitutes or complements. In a first stage, a firm's absorption of foreign fundamental R&D can be impacted by a decision to localize R&D activities abroad. The interrelation between this decision and initial production costs is also explored.

***JEL classification codes*: F15, F23, O3**

Key words: **fundamental R&D, spillovers, international location, economic integration**

I. Introduction

It has long been recognized that research and development, at the level of both countries and firms, can play a critical role in explaining their economic performance as reflected, for example, by trade and investment shares, as well as endogenous economic growth. Increasing attention has also been given to the potential for R&D spillovers impacting on diverse dimensions of national and international economic performance. Branstetter (1998) and Mohnen (1999) have offered recent surveys of the latter literature, while Griliches (1992), Nadiri (1993), and Mohnen (1996) have considered the more general role of R&D externalities. Yet, the extent to which the localization of R&D activities has become globalized remains a subject of relatively less attention for which there has been little formal modeling.[1] Indeed, the relative lack of attention to the determinants of knowledge flows contrasts with the vast literature relating to the international mobility of products, services and factors of production. For the most part, existing investigations of the globalization of R&D activities have been confined to empirical and policy analysis – often involving case studies and firm surveys. Certain of these studies highlight the role that distinctive national innovative environments can have in attracting R&D-related foreign direct investment. In particular, Florida (1997) found that a key consideration accounting for the establishment of foreign-affiliated R&D laboratories in the U.S was an objective to have access to scientific and technical

[1] However, Sanna-Randaccio and Veugelers (2002) have recently offered a formulation of the trade-offs that a multinational enterprise faces when envisaging the decentralization to foreign subsidiaries of certain R&D activities traditionally undertaken by the parent firm.

human capital, while Granstrand (1999) emphasized the excellence of American universities as a driving force attracting Japanese R&D.[2]

Clearly, if the internationalization of R&D activities enhances firms' technological competitiveness, the interrelation between R&D and industrial performance is rendered inherently more complex. Traditionally, the literature on multinational enterprises has highlighted how intangible assets due to distinctive technological innovations in home countries can explain the "compensating advantage" of corporations in foreign markets.[3] Yet, to the extent that the localization of firms' R&D activities becomes internationalized, there are apparent measurement issues. This suggests potential methodological limitations in studies of R&D productivity and the determinants of foreign direct investment, which have been largely reliant on national R&D statistics.[4] Furthermore, existing empirical analysis of international R&D spillovers, such as those proposed by Coe and Helpman (1995), as well as by Coe, Helpman and Hoffmaister (1997), has not made sufficiently explicit either the microeconomic underpinnings of the analysis, nor the structural mechanisms by which alternative sources of fundamental and applied R&D affect international economic performance. Presumably reduced form econometric estimates of technological spillovers are sensitive to the underlying specifications for such structural mechanisms.

[2] Representative other studies on the internationalization of R&D include the contributions by Brockhoff (1998), Grandstrand (1999), Kuemerle (1997), Lefebvre and Madeuf (1999, 2001), Niosi (1999), Patel (1997), as well as Serapio and Dalton (1999).

[3] The extensive literature on multinational corporations is synthetically discussed by Caves (1996).

[4] See, for example, the studies by Crepon, Duquet, and Mairesse (1998), Griliches (1992), Griliches and Mairesse (1990), Mairesse (1994) and Mansfield (1994) relating to productivity and R&D. The survey of empirical studies offered by Caves (1996) underscores the role of technological advantages in home countries as major determinants of foreign direct investment.

The objective of the present research is to offer a conceptual framework for understanding the conditions under which a firm will be prompted to localize certain R&D activities abroad. A central concern is with economic integration in goods markets as a factor, which can explain the globalization of R&D. This issue of the interrelation between product market integration and the internationalization of firms' R&D activities appears to have been largely neglected in existing analytical research. Indeed, one characterization of the state of existing research is offered by Globerman (1997), who suggested that it is "less clear how increased international economic integration will affect incentives to decentralize R&D activities geographically, and the relevant literature is rather confusing on this issue." (p. 150)

As discussed in more detail in the next section, a variety of factors can account for the globalization of both fundamental and applied R&D. With regard to the former, there have been revolutionary decreases in international transactions costs resulting from new information and other technologies. In this paper, however, the focus is on globalization of R&D via corporations' decisions to localize innovative activities abroad. Both demand-side and supply-side factors can account for the increased pressures for the globalization of firms' R&D activities. The former include the need to adopt applied R&D to the distinctive preferences of consumers in different markets.[5] While recognizing the eventual role of such demand-side factors, the focus in this research will be on the role of a specific supply-side factor in influencing firms' decisions to localize

[5] Gaussens (2000) has offered an analysis of certain demand-side factors in driving firms to localize R&D activities abroad, so as to attract customers and, thereby, maintain their international competitiveness.

R&D abroad.[6] In particular, the concern is with a need to acquire more advanced and/or complementary forms of fundamental R&D, which are nationally distinctive.

The organization of the rest of this paper is as follows. The next section starts by reviewing a number of heuristic empirical issues relating to the characteristics of technological innovation, along with its creation and diffusion. This then offers a point of departure for a more formalized framework, which is proposed for analyzing issues of how differences in national stocks of fundamental R&D can impact on the international location of a firm's R&D activities. The proposed analysis entails a three-stage analysis of a strategic game involving a duopoly model of cost-reducing process innovation. A firm's technological efficiency is understood to depend not only on its investment in applied R&D, but also on its absorption of domestic and foreign fundamental R&D. In this paper's third section an analysis of a more specific formulation of the model leads to a series of central analytic propositions regarding the conditions under which a firm will localize its R&D activities abroad. More specifically, the analysis explores the interrelation between the decision to internationalize R&D, the degree of international market segmentation, and firms' relative initial competitive positions in terms of their production costs. The central findings are shown to be robust to alternative specifications regarding whether national stocks of fundamental R&D are substitutes or complements. In a concluding section the principal contributions of this research are summarized, while a number of conceivable extensions of the analysis are also identified.

[6] The distinction made here between demand and supply-side factors is analogous to that suggested by Kuemmerle (1997). In particular, he identified two primary objectives for classifying new R&D sites abroad: "home-base-augmenting sites" and "home-base-exploiting sites". He contended that the former were designed "to tap knowledge from competitors and universities around the globe," whereas the latter were aimed "to support manufacturing facilities in foreign countries or to adapt standard products to the demand there" (p. 62).

II. General Analytic Framework

A. Introduction

The point of departure for our analysis is a certain number of salient heuristic observations regarding the nature of R&D. These motivate the principal modeling assumptions that will be subsequently invoked. First, it can be noted that both fundamental and applied R&D have been historically characterized by a high degree of concentration and locational specificity in firms' countries of origin. Second, the globalization of firms' R&D activities appears, in general, to have developed much more slowly than has been the case for other activities, such as those related to production and marketing. Taken together, these observations point to a potential national specificity of R&D. Nonetheless, it needs to be recognized that the extent to which R&D has assumed global dimensions depends on the specific categories of innovative activity. Notably, it is potentially important to distinguish between fundamental and applied R&D, as well as between product and process innovation.

Government sponsored R&D, which can entail universities, public research institutes, and joint ventures between public institutions and industry, is undoubtedly a principal source of fundamental R&D. There are marked international disparities in both the levels and nature of government sponsored R&D. To the extent that these distinctive characteristics generate a diffusion of knowledge, which assumes geographical dimensions, they can be viewed as giving rise to national stocks of fundamental R&D. Nonetheless, such stocks may have varying degrees of comparability

across countries. When such national stocks of fundamental R&D entail characteristics, which are substitutes, certain countries may assume technologically dominant positions.

Fundamental R&D can be considered as constituting a form of international semi-public good, whereby certain foreign firms may be excluded from fully benefiting from technological spillover effects generated from other countries' stocks. In particular, the transfer of fundamental R&D from a country's public sector to firms involves inherent access and transaction costs, which may be termed "learning" costs. Hence, it can be contended that optimal absorption of fundamental R&D by the private sector is enhanced by geographic proximity to national public-sector sources of fundamental R&D and involves private sector investment costs.[7] Alternatively, fundamental R&D, arising in a given country, can be considered to generate positive knowledge externalities, which spillover to the private sector both nationally and internationally. It is a reasonable presumption that such spillover effects are heightened by firms localizing R&D activities (labs) in a given source country.[8] Indeed, the acquisition of fundamental R&D can be regarded as a necessary condition defining the capacity of firms to create new products, processes and services. Thus, applied R&D may be understood to entail the conversion at the firm level of basic knowledge into process and product improvement. In sum, at an initial level of simplification, firms can

[7] The process of transferring fundamental R&D can be impacted by government technology policies, which aim at promoting its diffusion to the private sector. A clear example was the US government's transfer of internet technology, which had arisen from research sponsored by the Department of Defense.

[8] National and international R&D spillovers can arise through the dissemination of fundamental knowledge in the form of scientific presentations and publications. Such knowledge may be diffused asymmetrically across countries due to differences in educational and research environments, as well as governments' willingness to share proprietary knowledge internationally. In addition, fundamental R&D spillovers undoubtedly capture certain aspects of human capital markets for scientists and engineers. In particular, they can arise through different degrees of labor market mobility, as well as through national disparities in the quality of scientific training. Together these considerations suggest a national specificity of fundamental knowledge.

be viewed as principally undertaking two distinct R&D tasks: absorbing fundamental R&D and investment in applied R&D for their commercial use.[9] [10]

The foregoing considerations highlight the inherent complexities of modeling the internationalization of firms' R&D activities. Our analysis proposes an initial modeling framework that highlights certain key aspects of the R&D globalization process. As such, the analysis entails simplifying assumptions, while only considering certain dimensions of the inherently complex overall process corresponding to the internationalization of R&D. In particular, while recognizing that the extent to which R&D stocks in different countries are either complements or substitutes is critical to defining firms' strategic international location decisions, the focus here will be on a scenario where stocks of fundamental R&D are substitutes. Similarly, while remarking the potential role that applied R&D spillovers between firms may contribute to explaining international industrial performance, the concern will be with international spillovers of fundamental R&D. Their interrelation with applied spillovers is left for subsequent investigation.[11]

[9] In fact, certain corporations also undertake path-breaking fundamental research. However, such basic innovations may be either a necessary for undertaking more applied R&D, or a byproduct of research, rather than a principal objective.

[10] As intangible assets, absorbed levels of fundamental R&D and investment in applied R&D can be transferred, to varying degrees, within firms - both nationally and internationally. However, there are potentially high transaction costs and potential risks associated with transferring technologies between firms.

[11] Other supply-side rationale for localizing R&D abroad include the need to internalize positive externalities from applied R&D spillovers, competitive advantages gained by access to lower-paid, but nonetheless highly skilled researchers, as well as industrial restructuring linked to market integration.

B. Characterization of the Innovation Processes

A duopoly model of international technological competition in cost-reducing process innovation is proposed, where reference will be made to a domestic and foreign country, and an asterisks is used to distinguish variables related to the latter. It is hypothesized that there is a representative firm in each country, where the domestic and foreign firms are designated, respectively, by the subscripts *i* and *j*.

There are two forms of R&D activity - fundamental and applied. Government and university sponsored R&D is understood to be the principal source of fundamental knowledge creation and to generate national R&D stocks. Firms can be viewed as principally undertaking two distinct R&D tasks. These consist of absorbing fundamental R&D and, then, investing in applied R&D.[12] The latter entails the conversion by firms of fundamental R&D into process innovations.

The two countries' fundamental R&D stocks, which are taken to be exogenously given and are denoted by X and X*, are potentially distinctive in terms of their levels and composition. In light of their geographical separation and an assumption that firms must invest in order to absorb fundamental knowledge, these national R&D stocks have certain features of international semi-public goods. More specifically, the proposed analysis distinguishes between alternative scenarios in which the two countries' fundamental knowledge stocks are either substitutes or complements. If the two stocks

[12] There may be firm-specific allocative decisions regarding both the extent of absorption of fundamental knowledge from public sector sources and investment in fundamental knowledge creation. As a result, firms' fundamental R&D stocks could differ across firms, sectors, and countries. Consequently, there is the potential for fundamental R&D spillover effects across firms with different degrees of locational specificity depending on the importance of cluster effects at regional, national and international levels. Nonetheless, our focus will be on a paradigm where it is the public sector, which is the principal source of differences in national R&D stocks.

are substitutes, but one is larger than the other, there will be a technological gap between the two countries.

Each firm has access to an overall fundamental technology base, which is an amalgam of the national R&D stock in its own country and international spillovers of fundamental knowledge. It is postulated that there are two key decisions by either firm, which determine its overall resources of fundamental knowledge. The first of these is whether the firm is willing to locate its R&D activities abroad, thereby enabling it to internalize higher international spillovers of fundamental knowledge. The second concerns how much it is willing to invest in absorbing the available national and foreign fundamental knowledge stocks.

More specifically, when the two countries' R&D stocks are substitutes, a representative (domestic) firm's potential fundamental knowledge base is given by:[13]

$$x_i = \max [X, X + \lambda (X^* - X)] \quad \text{where } \lambda \in [0, 1]$$

Note that λ corresponds to the fundamental R&D spillover parameter in the case of the domestic firm. For expositional simplicity, it will be assumed for this case of substitutability that the fundamental knowledge stock in the foreign country is higher than that in the domestic country, and that the localization decision by the domestic firm is the only one envisaged. Alternatively, in the case of complementary R&D stocks, the potential technological bases for the domestic and foreign firms are given by:

$$x_i = X + \lambda X^* \quad \text{where } \lambda \in [0, 1]$$

$$x_j = \lambda^* X + X^* \quad \text{where } \lambda^* \in [0, 1]$$

[13] In order to economize notation, analogous equations for the two firms will only be presented for the domestic one.

Note that unlike the case of substitutability it is now not necessary to make any hypothesis regarding the relative values of the R&D stocks, X and X*.

Note that the value of the positive spillover parameter, λ, depends on whether that firm localizes part of its R&D activities abroad. In particular, the spillover parameter equals λ_0, if the firm does not locate R&D labs in the foreign country. However, if it does undertake R&D abroad it has a easier access to an expanded fundamental knowledge base, which is captured by a higher value for the spillover parameter, such that $\lambda_1 > \lambda_0$. For expositional clarity, x_i^0 and x_i^1, are used to distinguish, respectively, the fundamental knowledge base of a firm before, x_i [λ_0], and after, x_i [λ_1], it has established R&D activities abroad.

A firm's actual capacity to mobilize fundamental knowledge, which is denoted by z_i, is impacted by several factors. First, this innovative capacity depends on the firm's fundamental knowledge base, which as discussed, is generated both nationally and through international R&D spillovers of fundamental R&D. Second, a firm's acquisition of fundamental R&D depends on its expenditures, designated as γ_i, which aim at absorbing that available R&D stock. Third, a firm's success in acquiring fundamental knowledge is determined by the actual absorption process.[14] Taken together, these three factors result in the following function determining a firm's actual, fundamental knowledge capacity:

$$z_i = \theta(\gamma_i)\, x_i$$

[14] The functional form, $\theta(\gamma_i)$, capturing the process by which a firm absorbs fundamental knowledge, can have a country specificity. This corresponds in part to the efficacy of the structure of university-industry linkages and to government policies designed at promoting the transfer of basic R&D to industry.

Decreasing returns are assumed, so that $\theta' > 0$ and $\theta'' < 0$. The foregoing specification also captures the semi-public nature of fundamental R&D, since transferring it from the public sectors to firms involves inherent access and transaction costs that may be viewed as "learning" or, alternatively, absorption costs.

A firm's overall investment in R&D, ρ_i, entails a combination of both the foregoing flow expenditures on absorbing fundamental knowledge stocks and its applied (flow) R&D budget, β_i, such that:

$$\rho_i = \gamma_i + \beta_i$$

Its effective technological efficiency, e_i, is understood to depend on its overall expenditures on R&D, their allocation between fundamental and applied research, as well as the prevailing technology transforming these investments into reductions in cost. The functional relation capturing this technology process is assumed to be common to both countries, so that:

$$e_i = \Phi [z_i, \beta_i] = \Phi [\theta(\gamma_i) x_i, \beta_i]$$

This function is assumed to be increasing and concave in the two arguments, z and β. Note that this formulation offers a view of a firm's overall international technological efficiency in which R&D is an intangible asset which, while specific to each firm, can be used on a worldwide basis within a given corporate structure. Implicitly, there is an optimization issue concerning the internal allocation of a firm's expenditures between domestic and foreign R&D sites. However, as a simplification, the analysis abstracts from such issues, since otherwise solutions are quite intractable. Nonetheless, the proposed model highlights the role that a firm's decision to localize its R&D activities

abroad can have by generating a higher propensity to absorb fundamental knowledge and, thereby, a higher productivity of investments in applied research and development.

Efficient management of technological resources requires that a firm optimally allocate its overall expenditures between fundamental R&D absorption and the associated applied transformation of R&D into process innovations. For a given value of technological efficiency, ê, this corresponds to the following minimization problem:

Min ρ_i

with respect to γ_i **,** β_i

subject to

$\Phi\,[\theta(\gamma_i)\,x_i,\ \beta_i] = \hat{e}_i$

This yields the following efficient R&D expenditure function:[15]

$r_i = r(e_i, x_i)$ **where** $\frac{\partial r_i}{\partial e_i} \geq 0$ **and** $\frac{\partial r_i}{\partial x_i} \leq 0$

Thus, more R&D expenditures, r_i **, are necessary in order to achieve increased technological efficiency,** e_i **, while access to a larger base of fundamental R&D,** x_i **, dampens the need for a firm's overall R&D expenditures. As a consequence, there is an apparent tradeoff between sunk costs linked to increased absorption capacity, due to**

[15] This function can be regarded as yielding "effective levels" of process R&D, given that a firm's applied R&D decisions are positively impacted by national public support for fundamental R&D. An equivalent production function for effective technological efficiency, after cost minimization, could be characterized as having the following general representative form:

$$e_i = e_i(r_i, x_i)$$

$$\text{where } \frac{\partial e_i}{\partial r_i} \geq 0\,,\ \frac{\partial e_i}{\partial x_i} \geq 0\,, \text{ and } \frac{\partial^2 e_i}{\partial r_i \partial x_i} \geq 0\,.$$

localizing R&D abroad, and a firm's overall flow expenditures on R&D. Consistent with the concavity hypothesis characterizing the effective technological efficiency function, $e_i = \Phi [z_i , \beta_i]$, the following second-order conditions are taken to apply for the efficient R&D expenditure function:

$$\frac{\partial^2 r_i}{\partial e_i^2} \geq 0, \frac{\partial^2 r_i}{\partial x_i^2} \geq 0 \text{ and } \frac{\partial^2 r_i}{\partial e_i \partial x_i} \leq 0$$

In addition, for tractability it will also be assumed that:

$$\frac{\partial^3 r_i}{\partial e_i^2 \partial x_i} \leq 0$$

In sum, a firm's overall R&D effort is viewed, in the current paradigm, as comprising two key elements: i. the absorption of fundamental R&D, and ii. its conversion into applied process innovations. Together, these entail the conversion of fundamental R&D breakthroughs into reductions in variable costs of production, such that for the representative firm (*i*), with an ouput level of q_i , the following cost function applies:

$$c_i (q_i , e_i)$$

$$\text{where } \frac{\partial c_i}{\partial q_i} \geq 0, \frac{\partial c_i}{\partial e_i} \leq 0, \text{ and } \frac{\partial^2 c_i}{\partial q_i \partial e_i} \leq 0$$

Note that increased technological efficiency reduces the marginal cost of production.

C. The Basic Framework of International Technological Competition

The proposed analysis of international duopolistic competition in process innovation entails sequential decisions, which can be treated as three distinct stages in a non-cooperative game:

1. international localization decision in order to acquire fundamental R&D from a technologically dominant country;

2. R&D decisions by competing international duopolists, which entail both overall levels of R&D expenditure and their allocation between the absorption of fundamental R&D and its conversion, via applied R&D, to process innovation; and finally,

3. product-market competition between two firms.

As in the research of Spencer and Brander (1983), a standard metholodogy of backward induction is used to analyze the determinants of such international technological competition. However, unlike existing research, the proposed analysis admits the additional possibility of firm' initially localizing their R&D activities abroad in order to absorb fundamental R&D from abroad.

More specifically, in the final stage the duopolists will determine their output levels, q_i and q_j , in light of their relative technological competitiveness and demand conditions in the two markets. The general form of the two firms' objective functions is given by:

$$\Pi_i = R_i (q_i , q_j) - c_i (q_i , e_i) - r_i (e_i , x_i)$$

$$\Pi_j = R_j (q_i , q_j) - c_j (q_j , e_j) - r_j (e_j , x_j)$$

The revenue functions, R_i and R_j, depend on the demand characteristics in the two national markets, as well as on the extent of market segmentation. Standard

assumptions regarding the form of demand functions will be made, while the national markets are understood to be either fully or partially integrated internationally. In the former case only a single overall demand function needs to be specified, whereas in the latter scenario two distinct national demand functions are identified, which can be eventually served by firms from both countries. The extent of international market segmentation is then captured by a parameter, δ , which represents the additional costs of exporting, rather than selling in the home market.[16] Under Cournot-Nash assumptions, the outcome of output competition in this final stage will be reduced form solutions of the general form:

$$q_i^* = q_i (e_i , e_j)$$

$$q_j^* = q_j (e_i , e_j)$$

In the intermediate stage, the competing international duopolists simultaneously determine their overall levels of effective technological efficiency, e_i and e_j , under Nash assumptions, while efficiently allocating these R&D budgets between absorbing fundamental knowledge stocks and undertaking applied cost innovations.[17] These investment and allocative decisions are undertaken while anticipating the associated implications for their relative cost competitiveness in the final stage of output competition. These effective technological efficiency decisions are in turn dependent on the firms' access to fundamental R&D stocks at home and abroad, which are potentially

[16] Although national markets are often segmented by asymmetric trade and other costs, a simplifying assumption of uniform export costs between the two national markets is made.

[17] Since there is a dualism between levels of technological efficiency and corporate R&D expenditures, ananalytically equivalent formulation is in terms of overall levels of r_i and r_j . Again, the latter entail expenditures on both absorbing fundamental R&D and on its conversion, through applied R&D, to process innovation.

impacted by eventual decisions in the first period to localize R&D activities in the foreign country. The generic form for the associated reduced form solutions is given by:

$$e_i^* = e_i\,(x_i\,,\,x_j\,)$$

$$e_j^* = e_j\,(x_i\,,\,x_j\,)$$

In the first stage, differences between countries in their stocks of fundamental R&D are understood to potentially generate an incentive for firms to localize R&D activities abroad in order to obtain access to, and thereby absorb, fundamental R&D in the foreign country. Both cases of substitutability and complementarity in the two countries' R&D stocks will be considered. In the first scenario of substitutability, the foreign country is understood to be in a technologically dominant position, so that $X^* > X$. In a second scenario, where the fundamental R&D stock of the foreign country is complementary to that available in a firm's home country, the analysis will be limited to a situation where only the international localization decision of the domestic firm is considered and there is no strategic locational response by its foreign competitor. Thus, the considerably more complex framework of a full game-theoretic analysis at this first stage is left for further research.

There are apparent market access costs, along with associated learning costs, entailed by localizing abroad in order to absorb foreign fundamental R&D. When only unidirectional localization decisions are considered, so that the analysis relates to entry into the foreign country, the sunk costs of localizing R&D activities abroad are captured, for the representative domestic firm i, by an exogenous variable, S_i. The decision to localize R&D activities abroad will depend on whether the anticipated gain in profits, resulting from access to an expanded fundamental knowledge base and the associated

increase in the firm's technological efficiency, are higher than the sunk costs of setting up a R&D lab abroad. This leads to the following critical inequality condition:

$$\Delta\Pi_i = \Pi_i(x_i^1, x_j) - \Pi_i(x_i^0, x_j) > S_i$$

As previously noted, the change in the value for the endogenous spillover parameter, λ, plays a key role in impacting the potential gains from internationalizing a firm's R&D activities. Indeed, the potential change in a firm's operating profit, resulting from its localizing its R&D activities abroad, is at the center of much of the subsequent analysis. Nonetheless, such a change in a firm's operating profits, $\Delta\Pi_i$, is potentially impacted by not only changes in the spillover parameters, λ_0 and λ_1, but also both absolute and relative changes in the stocks of fundamental knowledge in either country, X and X*. [18]

III. Model Analysis and Determination of Central Analytic Propositions

A. Further Model Specifications

In order to undertake a more detailed analysis of the model, linearity assumptions are made for both the demand and cost functions. In particular, the demand function, when the national markets are fully integrated, is given by:

$$Q = a - p$$

When there is market segmentation, the domestic and foreign demand functions are, respectively:

$$Q_1 = a_1 - b_1 p_1$$

$$Q_2 = a_2 - b_2 p_2$$

[18] An effect of the information technologies has undoubtedly been to facilitate the diffusion of fundamental and applied knowledge. Within the proposed framework of substitutable R&D stocks, this could be interpreted as a

Note that the sum of the slopes, $b_1 + b_2$, equals one, which is numeraire used for the slope of the global demand function. It will also be assumed that the price sensitivity of demand in the two markets is not too different. More specifically, that the following inequality conditions apply:

$$\tfrac{1}{2} \leq b_1 / b_2 \leq 2$$

The linear cost functions for the firms reflect the reduction of costs resulting from increases in their levels of effective technological efficiency:

$$c_i (q_i , e_i) = (c_i^0 - e_i) q_i$$

International market segmentation is then understood to arise from the additional costs, of selling q_i* to a foreign market, instead of at home. These impact directly on an exporting firm's cost function, such that:

$$c_i (q_i^*, e_i) = (c_i^0 - e_i + \delta) q_i^*$$

For such a case of market segmentation, it will be demonstrated in Annex I that the expression for a firm's profit at the Cournot-Nash equilibrium is equivalent to that which would be obtained with a global demand function, except that the associated value of the intercept, a_i' , is lower than in the fully integrated scenario. In particular, it is shown that when the domestic exporter, faces additional trade costs of δ , that:

$$a_i' = a + \delta b_i - 2 \delta b_j$$

Note that the foregoing restriction on the price sensitivity of demand in the two markets is a necessary condition for $a_i' < a$.

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narrowing of the technological gap, X* - X. For a scenario of complementary, the globalization of technological know-how may have resulted in an expanded set of distinctive national R&D stocks.

B. General Characterization of the Duopoly Equilibrium

A detailed analysis of the three stages of international duopolistic competition is essential in order to establish the cental propositions of this research. Using backward induction, we start by characterizing the final stage of product market competition, where given their degree of technological competitiveness, each firm simultaneously determines its output and sales, q_i , under Cournot-Nash assumptions.

In light of earlier specifications, the profit of firm i then corresponds to:

$$\Pi_i = (p - c_i) q_i - r_i = M_i - r_i$$

For notational simplicity, the symbol M_i is used to identify a firm's revenues net of variable costs, but not including the fixed costs, r_i , of a firm's R&D expenditures. The latter are determined by the values of e_i and x_i , which are taken as given in this final stage of output competition.

In light of the linear demand function, $Q = a - p$, it is straightward to ascertain the following characteristics of the Cournot – Nash equilibrium:

$$q_i = 1/3 [a - 2 c_i + c_j]$$

and

$$M_i = 1/ 9 [a - 2 c_i + c_j]^2$$

Turning now to the second stage, the R&D decisions of the two firms, e_i and e_j , or equivalently r_i and r_j , can be analyzed. In light of the linear cost functions, $c_i = c_i^0 - e_i$ and $c_j = c_j^0 - e_j$, the following variable is first defined:

$$\alpha_i = a - 2 c_i^0 + c_j^0 .$$

Consequently, the third stage equilibrium production and profit of firm *i* are:

$q_i = 1/3 [\alpha_i + 2 e_i - e_j]$

and

$\Pi_i = = M_i - r_i = 1/9 [\alpha_i + 2 e_i - e_j]^2 - r_i (e_i , x_i)$

Non-cooperative equilibrium for competition between the two firms in their effective technological efficiencies, e_i and e_j , is specified, for firm *i* , by the condition :

$$\frac{\partial M_i}{\partial e_i} = \frac{4}{9}(\alpha_i + 2e_i - e_j) = \frac{\partial r_i}{\partial e_i}$$

Similarly, the reaction function for firm j corresponds to the relation:

$$\frac{4}{9}(\alpha_j + 2e_j - e_i) = \frac{\partial r_j}{\partial e_j}$$

These two equations yield the equilibrium values of e_i and e_j , as functions of each of the firms' potential knowledge bases, x_i and x_j .

The corresponding second-order conditions are:

$$k_i = \frac{9}{4}\frac{\partial^2 r_i}{\partial e_i^2} - 2 \geq 0$$

Actually, a more restrictive assumption is invoked. Specifically, it is supposed that the parameters of function r_i are such that $k_i > 1$. As will be seen later, this guarantees that the optimal level of each firm's technological efficiency, e_i , is an increasing function of its potential knowledge base, x_i .

A consequence of equilibrium in the second stage is that the profit of firm i is a function of both firms' knowledge bases, x_i and x_j . In the initial stage, firm *i* will decide whether to localize abroad or not. Such foreign localization entails an increase in the domestic firm's operating profit, Π_i . In a scenario of substitutable R&D stocks, this is

due to x increasing from $x_i^0 = X + \lambda_0 (X^* - X)$ to $x_i^1 = X + \lambda_1 (X^* - X)$. With complementary stocks, the corresponding values of x are: $x_i^0 = X + \lambda_0 X^*$ and $x_i^1 = X + \lambda_1 X^*$.

C. Central Analytic Results for Fully Integrated Markets

In this sub-section a series of propositions will be demonstrated on the basis of a more detailed analysis of the three stages of the model. First, we consider how changes in the level of firm's fundamental knowledge stock impact on the equilibrium values of the duopolists' levels of technological efficiency, production and profits. In particular, a further analysis of the second stage yields the following:

***Lemma 1*:**

An increase in that firm's fundamental knowledge base, x_i , due to an increase in either the level of its home stock of fundamental knowledge, X, or in the international spillover parameter, λ , will, *ceteris paribus*, increase its effective technological efficiency, e_i , quantity of sales, q_i, and its profits, Π_i . In contrast, the comparable values for its competitor, e_j , q_j , and Π_j decrease.

The demonstrations of these results are based on an analysis of the effects of marginal variation of the domestic firm' knowledge base, dx_i , assuming that its competitor's knowledge base, x_j , remains constant. Differentiation of the equilibrium conditions characterizing each firm's reaction function in the second stage yields:

$$k_i de_i + de_j = -\frac{9}{4}\frac{\partial^2 r_i}{\partial e_i \partial x_i} dx_i$$

$$de_i + k_j de_j = 0$$

This can be simplified to:

$$de_i = \frac{k_j}{k_i k_j - 1}\left(-\frac{9}{4}\frac{\partial^2 r_i}{\partial e_i \partial x_i}\right) dx_i$$

$$de_j = \frac{-1}{k_i k_j - 1}\left(-\frac{9}{4}\frac{\partial^2 r_i}{\partial e_i \partial x_i}\right) dx_i$$

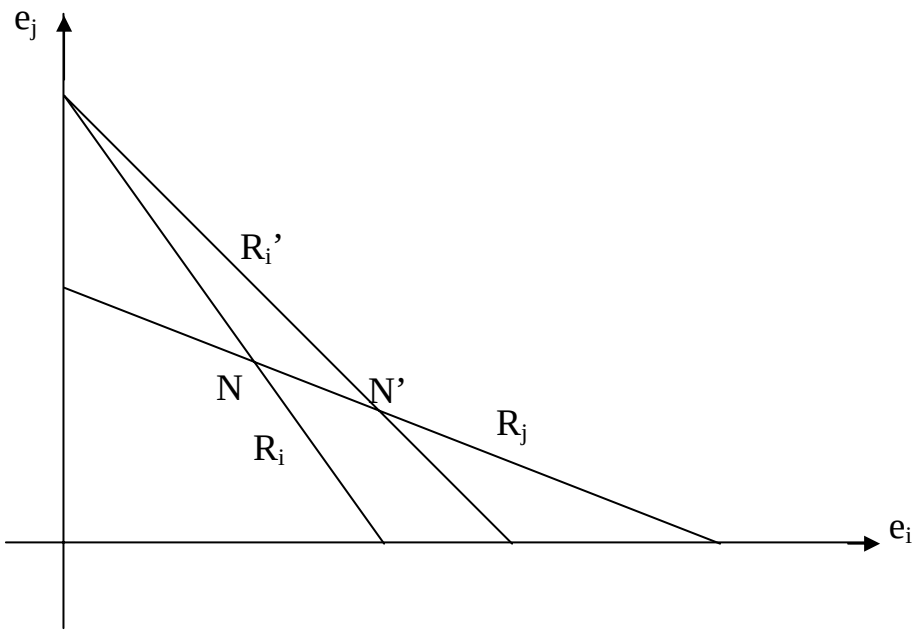
In light of earlier assumptions that the second-order cross derivatives of the function r_i are negative, it is easy to see that:

$$\frac{de_i}{dx_i} \geq 0 \text{ , } \frac{de_j}{dx_i} \leq 0 \text{ , } \frac{dq_i}{dx_i} = \frac{1}{3}\left(2\frac{de_i}{dx_i} - \frac{dej}{dx_i}\right) \geq 0 \text{ , } \frac{dq_j}{dx_i} \leq 0$$

The foregoing effects are illustrated by the changes in the reaction functions, R_i and R_j , and associated Nash equilibria, N and N′, as shown in Figure 1.

Figure 1

The Competitive Gain in Effective Technological Efficiency Resulting from an Increase in the Domestic Firm's Knowledge Base



Furthermore, it follows that:

$$\frac{\partial \Pi_i}{\partial x_i} = 2q_i\left(\frac{\partial q_i}{\partial e_i}\frac{\partial e_i}{\partial x_i} + \frac{\partial q_i}{\partial e_j}\frac{\partial e_j}{\partial x_i}\right) - \frac{\partial r_i}{\partial e_i}\frac{\partial e_i}{\partial x_i} - \frac{\partial r_i}{\partial x_i} = 2q_i\frac{\partial q_i}{\partial e_j}\frac{\partial e_j}{\partial x_i} - \frac{\partial r_i}{\partial x_i}$$

$\frac{\partial \Pi_i}{\partial x_i} \geq 0$ **, since** $\frac{\partial q_i}{\partial e_j} \leq 0, \frac{\partial e_j}{\partial x_i} \leq 0, \frac{\partial r_i}{\partial x_i} \leq 0$

Similarly, it can be readily shown that an increase in the domestic firm's fundamental knowledge base decreases the profitability of its foreign competitor:

$$\frac{\partial \Pi_j}{\partial x_i} = 2q_j\left(\frac{\partial q_j}{\partial e_i}\frac{\partial e_i}{\partial x_i} + \frac{\partial q_j}{\partial e_j}\frac{\partial e_j}{\partial x_i}\right) - \frac{\partial r_j}{\partial e_j}\frac{\partial e_j}{\partial x_i} = 2q_j\frac{\partial q_j}{\partial e_j}\frac{\partial e_j}{\partial x_i} \leq 0$$

Because of the model's basic symmetry, it is also the case that:

$$\frac{\partial \Pi_i}{\partial x_j} \leq 0$$

Consequently, the domestic firm's profits, Π_i **, is an increasing function of** x_i **and a decreasing function of** x_j **.**

The analysis will now focus on the first stage when the domestic firm decides whether to localize its R&D activities abroad. As already discussed, the associated critical condition applies:

$$\Delta \Pi_i = \Pi_i(x_i^1, x_j) - \Pi_i(x_i^0, x_j) > S_i$$

A consequence of Lemma 1 is that, a larger incremental spillover effect, $\lambda_1 - \lambda_0$, generated by localizing R&D activities abroad, will generate heightened net profits, i.e. d $\Delta \Pi_i > 0$. It is apparent that such a gain in profits can also be generated by a reduction of the sunk costs of setting up R&D activities abroad, S_i.

Based on Lemma 1 it is possible to establish two key propositions, which relate to how changes in the domestic firm's profits depend on its national fundamental R&D stock, X, for the alternative scenarios of substitutability and complementarity between this domestic stock and the foreign one.

***Proposition 1*:**

Let us consider a scenario where international stocks of fundamental R&D are substitutes and a firm comes from a country, which is a technological follower.

The impact on a firm's profits from its localizing R&D activities abroad, $\Delta \Pi_i$, as a result of an increase in its national fundamental R&D stock, X, is potentially ambiguous. Notably, d $\Delta \Pi_i$ / d X depends on initial value of the fundamental R&D spillover parameter before R&D activities are localized abroad, λ_0, and on the associated gain in the international spillover parameter, $\lambda_1 - \lambda_0$. For sufficiently high values of λ_1, the gains from setting up R&D activities abroad, $\Delta \Pi_i$, will, *ceteris paribus*, decrease and tend to zero when there is convergence between the domestic and foreign fundamental knowledge stocks, i.e. $X \rightarrow X^*$.

Consequently, for any given value for the sunk costs of setting up R&D activities abroad, S_i , there exists a critical value of the national fundamental R&D stock, $\overline{X}$, *beyond* which the firm will not localize its R&D activities abroad. This critical value depends positively on the incremental spillover effects, $\lambda_1 - \lambda_0$, resulting from setting up R&D operations abroad.

Alternatively, it is apparent that there always exists a sufficiently large sunk cost value, S_i , such that the firm will not set up R&D activities abroad.

The demonstration of the foregoing proposition, which is rather straightforward, is provided in Appendix I.

The incremental spillover effects, $\lambda_1 - \lambda_0$, can be interpreted as representing the differential return to acquiring tacit knowledge, which results from setting up R&D activities abroad. On the one hand, the substantial reduction in international transactions costs, due to advances in information technologies, along with other factors contributing to economic globalization, may have facilitated the international diffusion of fundamental knowledge. In the proposed model this can be interpreted, *ceteris paribus*, as an increase in the initial spillover parameter λ_0 . On the other hand, the heightened pace of technological change may be reflected by larger differentials in countries' stocks of fundamental knowledge, X* - X. Such an idea is undoubtedly reflected in policy debates regarding the "digital divide". An apparent implication of Proposition 1 is that such offsetting effects, associated with economic globalization, may have ambiguous implications on the rationale for localizing R&D abroad.

We now examine how changes in the fundamental R&D stock impact on a firm's decision to localize R&D abroad for the case of complementary stocks in the two countries. It should be noted that an increase in a country's fundamental knowledge stock now entails simultaneous increases in the knowledge bases of both the domestic and foreign firms.

***Proposition 2*:**

Let us consider a scenario where international stocks of fundamental R&D are complements.

The impact on a firm's profits from its localizing R&D activities abroad, $\Delta \Pi_i$, as a result of an increase in its national fundamental R&D stock, X, is again potentially ambiguous. However, given certain technical assumptions on the second derivatives of profit function in relation to a firm's fundamental knowledge base, x_i , it can be demonstrated that $\Delta \Pi_i$ is an increasing function of X. Therefore, for any given value for the sunk costs of setting up R&D activities abroad, S_i , there exists a critical value of the national fundamental R&D stock, $\overline{X}$, *under* which the firm will not localize its R&D activities abroad.

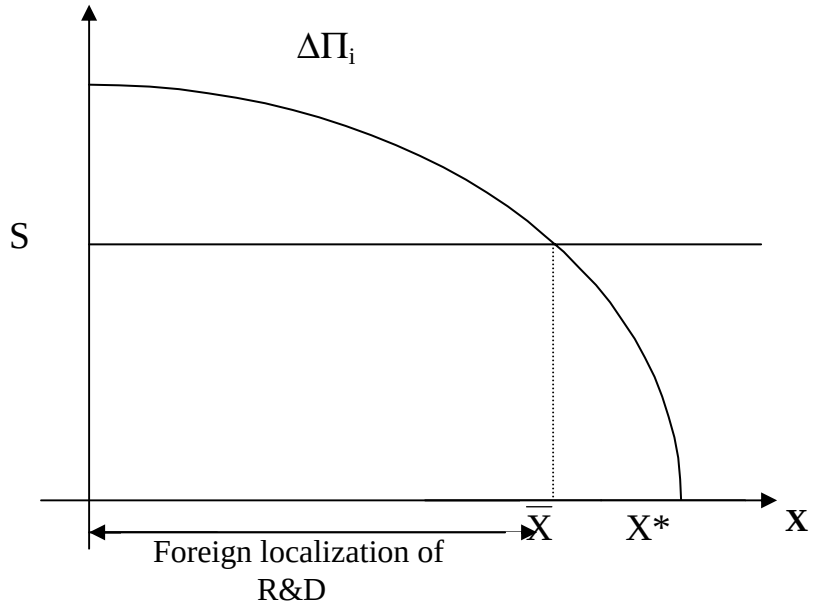
Appendix II provides the demonstration of this second proposition. Note that both Propositions 1 and 2 point to a critical value of a country's R&D stock, $\overline{X}$, which demarcates sub-sets of values of X for which a firm will either undertake R&D activities abroad, or not do so. However, as suggested by Figures 2a,b, the underlying

mechanisms are quite different in the alternative scenarios of R&D substitutability and complementarity. More specifically, the curves corresponding to the incremental change in profits, $\Delta \Pi_i$, are, respectively, decreasing and increasing functions of the national R&D stock, X. In the former case of substitutability, the additional technological advantage arising from locating abroad clearly declines as the two countries' R&D stocks converge. Under complementarity, there are two offsetting effects on the home country's relative technological competitiveness. While the direct impact of an increase in that country's R&D stock is to enhance its fundamental knowledge base, x_i , there is also an indirect effect, due to an associated technological spillover to the foreign country. The latter results in an increased value of x_j . The technical assumptions underlying Proposition 2 ensure that the direct effect increasingly dominates the indirect one, so that the associated incremental profit function in Figure 2b is upward sloping.

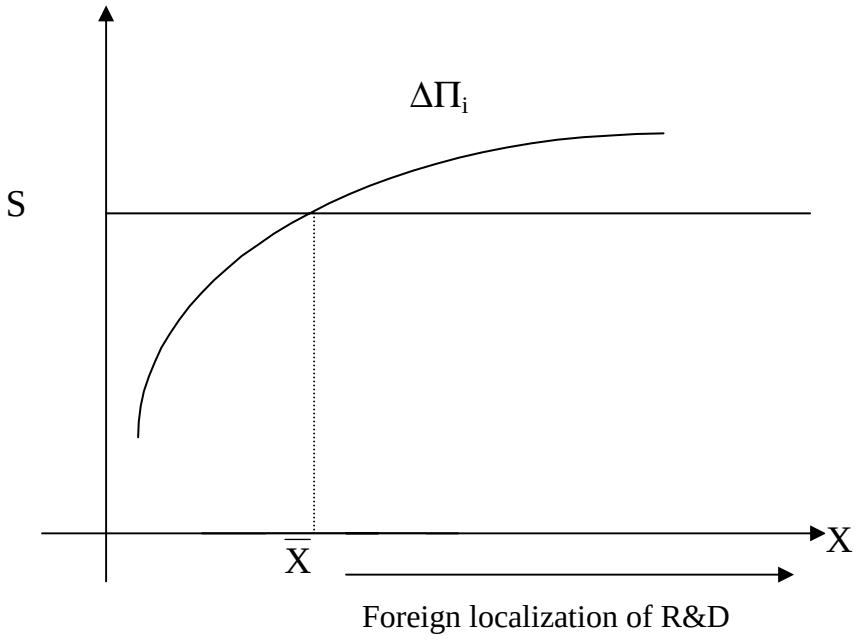
Figures 2a,b

A Comparison of Conditions for Localizing R&D Activities Abroad under Alternative Scenarios Regarding the Relation between the National Stocks

a) Substitutability



b) Complementarity



D. The R&D Locational Effects of Variations in Demand and of Changes in Intial Production Costs

In this sub-section, the impact of changes in initial demand and production conditions on a firm's propensity to localize R&D activities abroad will be characterized. The formal analysis starts by considering, for given levels of the fundamental knowledge bases x_i and x_j, the effects of variations in a representative variable, z, which impacts on the equilibrium values of the two firms' levels of effective technological efficiency e_i and e_j. Such variations generate a change in the profit of the representative firm *i*. The following lemma summarizes the principal results:

***Lemma 2*:**

If $\frac{d\Pi_i(x_i, x_j)}{dz}$ **is an increasing (decreasing) function of x_i, a rise (fall) in the value of z modifies the threshold for the critical value of a country's R&D stock,** $\overline{X}$**, such that the representative firm is more inclined to localize R&D activities abroad.**

The demonstration of the foregoing result starts with the Taylor expansion for the derivative of the incremental effect on profits due to a change in z:

$$\frac{d\Delta\Pi_i}{dz} = \frac{d\Pi_i(x_i^1, x_j)}{dz} - \frac{d\Pi_i(x_i^0, x_j)}{dz} = (x_i^1 - x_i^0)\frac{d}{dz}\left[\frac{\partial\Pi_i(x, x_j)}{\partial x_i}\right]$$

with $x \in \left[x_i^0, x_i^1\right]$.

If $\frac{d}{dz}\left[\frac{\partial \Pi_i(x, x_j)}{\partial x_i}\right] = \frac{\partial}{\partial x_i}\left[\frac{d\Pi_i(x, x_j)}{dz}\right] \geq 0$ **then,** $\Delta\Pi_i$ **is increasing with z . Thus, when z increases, the curve representing the evolution of** $\Delta\Pi_i$ **, as a function of X, moves upward. Consequently, the threshold value a country's R&D stock,** $\overline{X}$**, moves to the right (left) for the case of substitutable (complementary) R&D stocks, as shown in Figure 2a (2b).**

The specific variables which are understood here to correspond to z are the demand parameter *a* and the initial marginal production costs c_i^0 **and** c_j^0 **. In Appendix III it is demonstrated that under some specific assumptions** $\frac{d\Pi_i}{da}$**,** $-\frac{d\Pi_i}{dc_i^0}$ **and** $\frac{d\Pi_i}{dc_j^0}$ **are increasing functions of** x_i **. This leads to the following proposition:**

***Proposition 3*:**

The initial demand conditions, represented by the parameter *a*, as well as the marginal costs of production for the domestic and foreign firm, c_i^0 **and** c_j^0**, play critical roles in determining whether a firm will localize R&D activities abroad.**

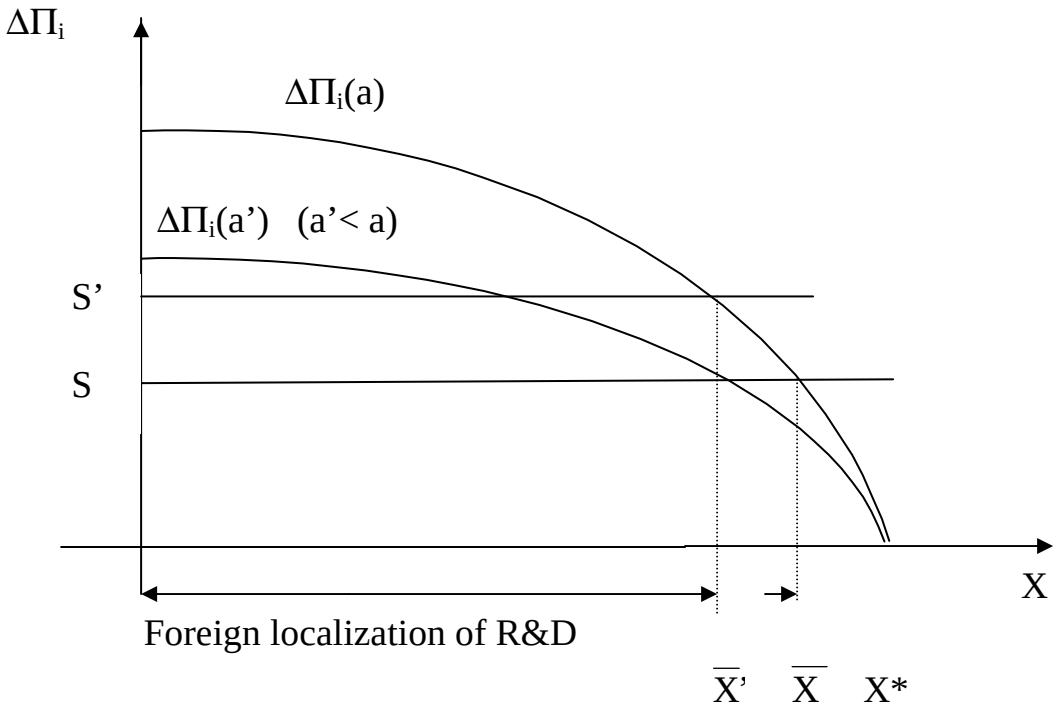
For both scenarios of substitutable or complementary international stocks of fundamental R&D, either an increase in demand, a fall in the initial marginal production cost of firm *i* , or a rise in the initial marginal production cost of firm *j* *widens* the range of values of the national fundamental R&D stock, X, for which the representative firm *i* will localize its R&D activities abroad.

In other words, when the domestic firm is relatively more competitive in terms of its initial marginal costs of production, or demand conditions are more favorable, the representative firm has a greater incentive to set up R&D in the foreign country. The foregoing analysis is illustrated in Figure 3a,b by the upward movement of the change in profit function, Δ_i , for an increased value of the parameter *a* relative to an value of *a'*. Nonetheless, it is apparent that there are different adjustment mechanisms, depending on whether the national stocks of R&D are either substitutes or complements. As shown in Figure 3a, for a given level of sunk costs, S, and under the substitutability assumption, heightened demand generates a higher threshold value of X, $\overline{X}$, beyond which the firm will not localize abroad. Alternatively, the impact of expanded demand costs is to increase the critical values of sunk costs which warrant internationalizing R&D activities – from S to S'. Figure 3b illustrates the alternative scenario of complementarity in the national stocks of fundamental R&D. Since an increase in demand again generates an upward shift in the incremental profit function, the threshold value of X, below which the domestic firm will not localize its activities abroad, decreases with expanded demand. The effect of such increased demand on the critical values of sunk costs is analogous to that under substitutability.

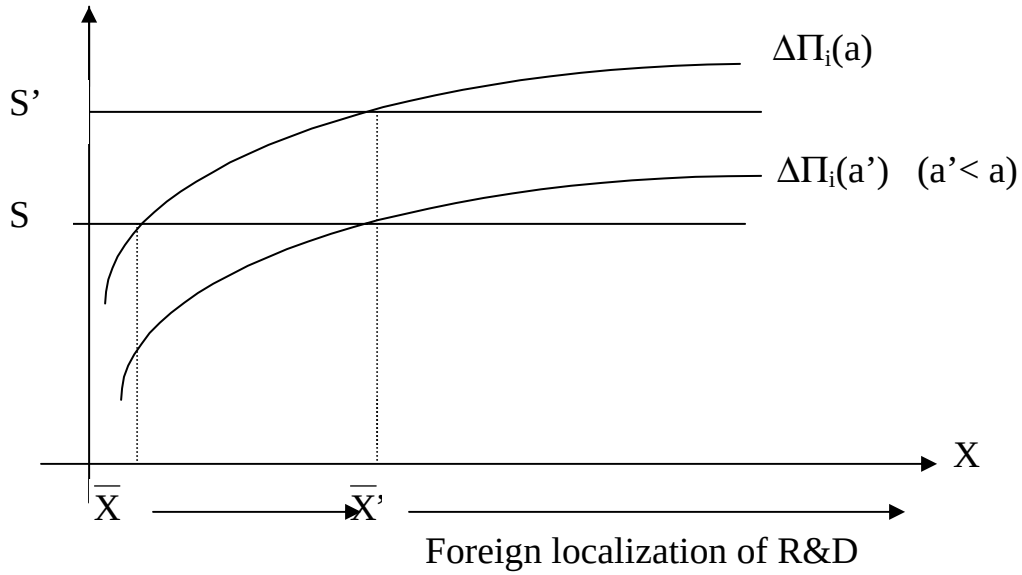
Figures 3a,b

The Impact of Increased Demand on the Incentive to Undertake R&D Activities Abroad for Alternative Scenarios Regarding the National R&D Stocks

a) Substitutability



b) Complementarity



The explanation for the findings, summarized in Proposition 3, is again that, *ceteris paribus*, reductions in a firm's domestic marginal production costs, as well as increases in the marginal costs of its foreign competitor, induce a greater incentive for the domestic firm to produce. With such a larger production base, there is a higher return from increases in the firm's technological knowledge base. In this regard, our analysis highlights the associated rationale for internationalizing a firm's R&D activities, in order to absorb more fundamental R&D from abroad and reduce marginal production costs.

E. Reduced Product Market Segmentation and the International Location of R&D

In this subsection the focus is on a central issue of how changes in the extent of international market segmentation impact on the incentive for R&D activities to become more globalized. A central proposition characterizes the interrelation between the impact of such reductions in trade costs and a firm's incentive to localize R&D activities abroad for both scenarios of substitutability and complementary between national and foreign stocks of fundamental R&D. More specifically, the analysis focuses on the implications of reducing international trade costs, which is captured in the analysis by changes in a parameter, δ. This represents the additional costs of a firm's exporting, rather than selling in the home market.

In Appendix IV it is shown that, when markets are segmented, the variable cost margin for the representative firm *i* is similar to that with unified markets, except that the demand parameter *a* must be replaced by a new coefficient, $a_i^{'}$. This is defined by the equation $a_i^{'} = a_i + a_j - \delta\beta_i$, where $\beta_i = 2b_j - b_i$. Consequently, the equations characterizing the equilibrium values for e_i and e_j are similar to those obtained in sub-section IIIB, describing the general characterization of the duopoly equilibrium. However, the expressions for α_i and α_j will be replaced by new parameters, which are represented by $\alpha_i^{'}$ and $\alpha_j^{'}$, where the following formulas apply: $\alpha_i^{'} = a_i^{'} - 2c_i^0 + c_j^0$ and $\alpha_j^{'} = a_j^{'} - 2c_j^0 + c_i^0$. It can be seen that heightened (reduced) market integration, as reflected by a lower (higher) value for the trade cost parameter, δ, results in higher (lower) values for the demand parameters, $a_i^{'}$, $a_j^{'}$ and also for $\alpha_i^{'}$ and $\alpha_j^{'}$. More precisely, the variation in the degree of market segmentation $d\delta$ entails the following relation: $\frac{d\alpha_i^{'}}{\beta_i} = \frac{d\alpha_j^{i}}{\beta_j} = -d\delta$.

It is shown in Appendix III that a decrease in trade costs induces firm *i* to seek higher levels of technological efficiency, $de_i / d\delta < 0$ if the following condition is met: $k_j\beta_i - \beta_j > 0$. In that case the marginal variation of the representative firm's profit resulting from a decrease of the trade costs is positive and an increasing function of x_i.

The foregoing reasoning leads to a central finding in this research.

***Proposition 4*:**

Let us consider a scenario where two national markets are segmented due to trade costs, $\delta > 0$, of serving markets abroad, instead of at home.

If the demand conditions in the two countries are such that $k_j\beta_i - \beta_j > 0$, the range of X values, for which a firm will localize R&D abroad, increases as trade costs are reduced. However, the directional effects of these range changes in X differ for the alternative scenarios of substitutability and complementarity in the national stocks of fundamental R&D.

In particular, when foreign demand is at least as sensitive to price changes as in the domestic country, so that $b_j \geq b_i$ and $\beta_j \leq \beta_i$, the above inequality condition is automatically satisfied, so that trade liberalization always generates a higher propensity to localize R&D activities abroad. This follows from the assumption that $k_j \geq 1$.

Thus, a central finding, which is conveyed in Proposition 4 and the foregoing discussion, is that the probability of undertaking R&D in the foreign country is higher with the increased integration of markets. The basic intuition relates to how an expanded potential market creates an added profit incentive to improve a firm's technological competitiveness. A key insight is that the heightened profit associated with expanded foreign demand is itself an increasing function of a firm's technological efficiency, which, in turn, depends on its technological base. *Ceteris paribus*, the latter is enhanced through the increased absorption of foreign fundamental R&D by localizing R&D activities abroad. Alternatively, undertaking R&D activities abroad engenders

sunk costs of access to a distinctive foreign technological environment. Following the integration of product markets, there are associated economies of scale, due to the spreading of such costs across a larger number of consumers. It can be noted that the foregoing intuition offers an insight regarding the interpretation of the condition relating demand in the two markets, specifically, $k_j\beta_i - \beta_j > 0$**. Specifically, if foreign demand is relatively more price sensitive, then this inequality is necessarily satisfied, and increased trade liberalization will be associated with a higher opportunity cost of not localizing R&D activities abroad, since the domestic firm can thereby gain a competitive advantage abroad, which is enhanced for higher values of** β_j**.**

In sum, reductions of a firm's trade costs or domestic marginal production costs, as well as increases in overall demand or in the marginal costs of its foreign competitor, induce, *ceteris paribus*, a greater incentive for the domestic firm to produce. With such a larger production base, there is a higher return from increases in the firm's technological knowledge base. In this regard, our analysis highlights the associated rationale for internationalizing a firm's R&D activities, in order to absorb more fundamental R&D from abroad and reduce marginal production costs.

IV. Conclusion

An apparent lacuna in existing empirical and policy investigations of the interrelation between firms' research and development activities and their international industrial performance is the lack of an adequate analytical perspective for

understanding the factors leading to the globalization of R&D. Indeed, most research relating to the internationalization of R&D has entailed policy and empirical studies, which rely heavily on case studies, questionnaire surveys, and/or national data sources. The central contribution of the current research is to offer a conceptual framework for understanding factors relating to the interrelation between product market integration and the incentive firms have to localize R&D abroad. The analysis has highlighted how distinctive national R&D environments, as represented by national stocks of fundamental knowledge, can impact on the interrelated decisions of firms as to how much they should invest in absorbing fundamental R&D, undertaking applied R&D, as well as where such activities should be located.

Promising directions for further investigation include the extension of the analysis of complementary national R&D stocks to consider a more complex game-theoretic setting. Ongoing investigation of scenarios, where firms from more than one country can localize their R&D activities abroad, suggests a number of Nash equilibria.[19] Another avenue for further inquiry concerns the impact of increased oligopolistic competition, or other industrial structures, on the extent to which R&D activities become globalized.

The possibility of applied R&D spillovers between firms, which may have varying degrees of locational specificity, is another apparent direction for research. Furthermore, the effects of applied spillovers are undoubtedly interrelated with the extent of fundamental R&D spillovers, as well as processes whereby firms transform

[19] In such an extended framework, certain outcomes are characterized by a form of Prisoners' Dilemma where *ex ante* decisions to localize abroad turn out to be unprofitable *ex post*, so that there is excessive globalization of R&D activities.

fundamental knowledge into process innovations.[20] Ultimately, such research can contribute to the literature on multinational corporations by identifying the role of R&D, in relation to other determinants of production costs, for determining firms' international locational decisions. In this regard, it should be noted that models of foreign direct investment have often emphasized R&D as an intangible asset, which can yield compensating advantages in foreign markets. In contrast, a general thrust of the present research is to underscore how the nature of a firm's R&D performance may be impacted by the decision to localize abroad.

The paradigm proposed in this paper can offer a basis for understanding how government support for fundamental R&D can impact on the evolution of countries' international competitiveness and technological innovativeness of their firms. In particular, the analysis of national R&D stocks could also consider welfare implications of alternative government technological, educational and industrial policies. Such an extension might thereby offer an explanation for divergent levels and paths of such stocks, as well as to different rates of national investment in the creation, and in the absorption, of fundamental knowledge.[21]

A possible limitation of the existing analysis is that it does not consider endogenous industrial structures, which could be altered by the globalization of R&D activities. Owen and Ulph (2002) have offered a general framework for analyzing how

[20] In terms of the analysis proposed in this paper, one approach for modeling applied spillover effects, which are not locationally specific, is to include symmetric additive terms in the effective technological efficiency functions. Within the context of our model, including such applied spillover effects potentially impacts on the second stage of the proposed strategic game, thereby influencing the conditions which determine whether the domestic firm undertakes R&D activities abroad.

the welfare consequences of different degrees of international economic integration can be determined by configurations of sunk, and other, costs. Analogous development of the model proposed here could, for example, offer a basis for examining how the rationale for research joint ventures (RJVs) might depend on locational factors reflecting distinctive national R&D environments. Finally, as already emphasized, a conceptual framework for factors accounting for the globalization of R&D is a critical prerequisite for undertaking empirical analysis of national and international R&D spillovers, along with their relation to global industrial performance. A key insight of this research is that the productivity of private sector investments in R&D is conditioned by firms' capacity to absorb both domestic and foreign spillovers from fundamental R&D. Thus, empirical applications of the proposed analysis also appear as a pressing research priority.

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Appendix I

After localizing abroad, the incremental operating profit of firm *i* is given by:[22]

$$\Delta\Pi_i = \Pi_i (x_i^1 , x_j) - \Pi_i (x_i^0 , x_j)$$

where $x_i^1 = X + \lambda_i^1 (X^* - X)$, $x_i^0 = X + \lambda_i^0 (X^* - X)$,

$(\lambda_i^0,\lambda_i^1) \in [0,1]^2$, $\lambda_i^1 > \lambda_i^0$

Derivation of the foregoing with respect to X yields the following two equivalent expressions:

$$\frac{\partial\Delta_i}{\partial X} = (1 - \lambda_1) \frac{\partial\Pi_i}{\partial x_i} (x_i^1, x_j) - (1 - \lambda_0) \frac{\partial\Pi_i}{\partial x_i} (x_i^0, x_j)$$

or

$$\frac{\partial\Delta_i}{\partial X} = (1 - \lambda_1)\left[\frac{\partial\Pi_i}{\partial x_i} (x_i^1, x_j) - \frac{\partial\Pi_i}{\partial x_i} (x_i^0, x_j)\right] - (\lambda_1 - \lambda_0) \frac{\partial\Pi_i}{\partial x_i} (x_i^0, x_j)$$

Using a Taylor expansion, the term in brackets in the foregoing expression, can be written as:

$$\frac{\partial\Pi_i}{\partial x_i}(x_i^1, x_j) - \frac{\partial\Pi_i}{\partial x_i}(x_i^0, x_j) = (x_i^1 - x_i^0)\frac{\partial^2\Pi_i}{\partial x_i^2}(x_i , x_j) = (\lambda_1 - \lambda_0)(X^* - X)\frac{\partial^2\Pi_i}{\partial x_i^2}(x_i , x_j)$$

with $x_i \in [x_i^0 , x_i^1]$.

Following substitution, this leads to:

$$\frac{\partial\Delta_i}{\partial X} = (\lambda_1 - \lambda_0)\left[(1 - \lambda_1)(X^* - X) \frac{\partial^2\Pi_i}{\partial x_i^2} (x_i , x_j) - \frac{\partial\Pi_i}{\partial x_i} (x_i^0, x_j)\right]$$

It has already been demonstrated that $\frac{\partial\Pi_i}{\partial x_i}(x_i , x_j) \geq 0$. **It will now be assumed that Π_i is convex in x_i, so that** $\frac{\partial^2\Pi_i}{\partial x_i^2}(x_i , x_j) \geq 0$. **It follows that for λ_1 near to 1 and/or X near to X*, the first term of the expression in the brackets will be small and the derivative of Δ_i will be negative. However, if λ_1 is small and X sufficiently small in relation to X*, the derivative may become positive. In the latter case, when X increases, the incremental profit of firm 1, Δ_i, will reach a maximum before decreasing.**

It should be remembered that the condition warranting localization abroad is given by:

$$\Delta_i = \Pi_i (x_i^1, x_j) - \Pi_i (x_i^0, x_j) > S_i$$

It has been shown that the incremental profit of firm 1 can initially be an increasing, and then subsequently a decreasing function of the fundamental knowledge stock, X. For such a case, there are at least some values of sunk costs, S_i , such that there will be lower and upper bounds to the knowledge stock, $\overline{X}' < X < \overline{X}$, beyond which localization abroad will not occur. Note that if the home knowledge stock is very low, the incremental profit generated by foreign localization may also be very low, since the domestic firm has too much of a competitive disadvantage to compete viably even when setting up R&D operations in the foreign country. Hence, localization abroad will not take place.

[22] For notational simplicity the symbol Δ_i is used to indicate changes in the *i*th firm's profits.

Appendix II

In the case of complementarity between the domestic and foreign R&D stocks, the domestic firm's profit function is given by:

$\Pi_i = \Pi_i (x_i , x_j)$

where now

$x_i = X + \lambda_i X^*$ **and** $x_j = X^* + \lambda_j X \quad (\lambda_i , \lambda_j) \in [0,1]^2$

It has already been shown that: $\frac{\partial \Pi_i}{\partial x_i} \geq 0$, $\frac{\partial \Pi_i}{\partial x_i} \leq 0$. **The following additional hypotheses will now be made:**

$\frac{\partial^2 \Pi_i}{\partial x_i^2} \geq 0$, $\frac{\partial^2 \Pi_i}{\partial x_i \partial x_j} \leq 0$, **and** $\frac{\partial^2 \Pi_i}{\partial x_i^2} + \frac{\partial^2 \Pi_i}{\partial x_i \partial x_j} \geq 0$

Note that the last of the foregoing three inequalities guarantees that the absolute value of the second-order cross derivative is smaller than the second-order own effect.

The incremental profit generated by localizing R&D abroad is:

$\Delta\Pi_i = \Pi_i (x_i^1 , x_j) - \Pi_i (x_i^0 , x_j) = \Delta\Pi_i (X, X^*, \lambda_i^0, \lambda_i^1 , \lambda_j)$

where $x_i^1 = X + \lambda_i^1 X^*$, $x_i^0 = X + \lambda_i^0 X^*$

It can now be demonstrated that, given X*, $\Delta\Pi_i$ **is an increasing function of X :**

$$\frac{\partial \Delta\Pi_i}{\partial X} = \left[\frac{\partial \Pi_i(x_i^1, x_j)}{\partial x_i} \frac{\partial x_i}{\partial X} + \frac{\partial \Pi_i(x_i^1, x_j)}{\partial x_j} \frac{\partial x_j}{\partial X} \right] - \left[\frac{\partial \Pi_i(x_i^0, x_j)}{\partial x_i} \frac{\partial x_i}{\partial X} + \frac{\partial \Pi_i(x_i^0, x_j)}{\partial x_j} \frac{\partial x_j}{\partial X} \right]$$

$$= \Phi_i(x_i^1, x_j) - \Phi_i(x_i^0, x_j)$$

where

$$\Phi_i(x_i , x_j) = \frac{\partial \Pi_i (x_i , x_j)}{\partial x_i} + \lambda_j \frac{\partial \Pi_i (x_i , x_j)}{\partial x_j}.$$

Thus, it follows that: $\frac{\partial \Phi_i}{\partial x_i} = \frac{\partial^2 \Pi_i}{\partial x_i^2} + \lambda_j \frac{\partial^2 \Pi_i}{\partial x_i \partial x_j}$. **Since** $0 \leq \lambda_j \leq 1$**, the assumptions regarding the second derivatives of the profit function imply that** $\frac{\partial \Phi_i}{\partial x_i} \geq 0$**, and hence** $\frac{\partial \Delta\Pi_i}{\partial X} \geq 0$.

Appendix III

A. The Effects of Changes in Demand and Production Costs for a Unified Market

The concern here is with the incidence of marginal variations of parameters *a*, C_i^0 and C_j^0, upon the second stage equilibrium values of research efforts and firm *i* 's profit.

By differentiating equilibrium conditions, one has:

$$\frac{4}{9}(d\alpha_i + 2de_i - de_j) = \frac{\partial^2 r_i}{\partial e_i^2} de_i$$

$$\frac{4}{9}(d\alpha_j - de_i + 2de_j) = \frac{\partial^2 r_j}{\partial e_j^2} de_j$$

or equivalently,

$$k_i\, de_i + de_j = d\alpha_i$$
$$de_i + k_j\, de_j = d\alpha_j$$

From this result, it follows that:

$$(k_i k_j - 1)de_i = k_j\, d\alpha_i - d\alpha_j$$
$$(k_i k_j - 1)de_j = k_i\, d\alpha_j - d\alpha_i$$

The derivative of firm *i* 's profit with regard to α_i is given by:

$$\frac{d\Pi_i}{d\alpha_i} = 2q_i \frac{dq_i}{d\alpha_i} - \frac{\partial r_i}{\partial e_i}\frac{de_i}{d\alpha_i}$$

$$= 2q_i\left(\frac{\partial q_i}{\partial \alpha_i} + \frac{\partial q_i}{\partial e_j}\frac{de_j}{d\alpha_i}\right) + \left(2q_i \frac{\partial q_i}{\partial \alpha_i} - \frac{\partial r_i}{\partial e_i}\right)\frac{de_i}{d\alpha_i} = 2q_i\left(\frac{\partial q_i}{\partial \alpha_i} - \frac{1}{3}\frac{de_j}{d\alpha_i}\right)$$

The variations in firm *i*'s profits, associated with marginal variations of three relevant parameters, can now be made explicit. These concern, respectively, the position of demand (*a*) and the basic unit costs of the two firms (C_i^0 and C_j^0) :

a) variation of a :

$$d\alpha_i = d\alpha_j = da\,,\ \frac{\partial q_i}{\partial a} = \frac{1}{3}$$

$$\frac{d\Pi_i}{da} = \frac{2}{3}q_i\left(1 - \frac{de_j}{da}\right) = \frac{2}{3}q_i \frac{k_i(k_j - 1)}{k_i k_j - 1} \geq 0$$

b) variation of C_i^0 :

$$d\alpha_i = -2dc_i^0\,, d\alpha_j = 0\,,\ \frac{\partial q_i}{\partial c_i^0} = -\frac{2}{3}$$

$$\frac{d\Pi_i}{dc_i^0} = -\frac{2}{3}q_i\left(2 + \frac{de_j}{dc_i^0}\right) = -\frac{2}{3}q_i \frac{k_i(2k_j + 1)}{k_i k_j - 1} \leq 0$$

c) variation of C_j^0 :

$$d\alpha_i = 0\,, d\alpha_j = -2dc_j^0,\ \frac{\partial q_i}{\partial c_i^0} = \frac{1}{3}$$

$$\frac{d\Pi_i}{dc_j^0} = \frac{2}{3} q_i(1 - \frac{de_j}{dc_j^0}) = \frac{2}{3} q_i\left(1 + \frac{2k_i + 1}{k_i k_j - 1}\right) = \frac{2}{3} q_i \frac{k_i(k_j + 2)}{k_i k_j - 1} \geq 0$$

Now, the direction of variation of these three derivatives with respect to x_i can now be specified. First, if we make the simplifying assumption that R&D expenses, r_i , are a quadratic function of efficiency, e_i . It is easy to see that in that case, k_i and k_j are only depend on, and decrease with, respectively, x_i and x_j .
Since the expression k_i /(k_i k_j –1) is decreasing with k_i, it is then an increasing function of x_i, and the same is true for $\frac{d\Pi_i}{da}$, $\left|\frac{d\Pi_i}{dc_i^0}\right|$, $\frac{d\Pi_i}{dc_j^0}$.

When this assumption is released, the analysis becomes much more difficult, since k_i and k_j depend on x_i also through e_i and e_j . More precisely, one has:

$$k_i = \frac{9}{4}\frac{\partial^2 r_i}{\partial e_i^2} - 2$$
$$k_j = \frac{9}{4}\frac{\partial^2 r_j}{\partial e_j^2} - 2$$

so that, by differentiating, it follows that

$$\frac{dk_i}{dx_i} = \frac{9}{4}\frac{\partial^3 r_i}{\partial e_i^3}\frac{de_i}{dx_i} + \frac{9}{4}\frac{\partial^3 r_i}{\partial e_i^2 \partial x_i}\frac{de_j}{dx_i}$$
$$\frac{dk_j}{dx_i} = \frac{9}{4}\frac{\partial^3 r_j}{\partial e_j^3}\frac{de_j}{dx_i}$$

Note that it has already been assumed that $\frac{\partial^3 r_i}{\partial e_i^2 \partial x_i} \leq 0$ **. Furthermore, is is known that** $\frac{de_i}{dx_i} \geq 0$ and $\frac{de_j}{dx_i} \leq 0$. **Accordingly, if we make the new assumption that** $\frac{\partial^3 r_i}{\partial e_i^3} \leq 0$ and $\frac{\partial^3 r_j}{\partial e_j^3} \leq 0$ **(which means that R&D expenses do not grow too fast with e_i), it can be established that k_i is still a decreasing function , while k_j is an increasing function of x_i . If, as previously, k_i /(k_i k_j –1) is decreasing with k_i, the property that** $\frac{d\Pi_i}{da}$, $\left|\frac{d\Pi_i}{dc_i^0}\right|$ and $\frac{d\Pi_i}{dc_j^0}$ **are increasing with x_i still holds.**

C. The Reduction of Traded Costs with Segmented Markets

The foregoing analysis can be transposed by replacing α_i and α_j , by α'_i and α'_j, and by observing that $d\alpha'_i = -\beta_i\, d\delta$ and $d\alpha'_j = -\beta_j\, d\delta$. It then follows that then when δ varies :
(k_i k_i - 1)de_i = (k_j β_i – β_j) d(-δ)
(k_i k_i - 1)de_j = (k_i β_j – β_i) d(-δ)

It can be seen from these formulas that when the export cost δ decreases, this does not entail necessarily an increase in the research efforts of both firms. It is possible that only one firm benefits from it. For instance, if $k_j < \frac{\beta_j}{\beta_i}$ **, we have de_i < 0 and de_j > 0 (for then β_j/β_i < 1, so that k_i β_j – β_i > 0). In the opposite case,**

where $k_j > \frac{\beta_j}{\beta_i}$, it follows that $de_i > 0$, but the sign of de_j is indeterminate, since it depends on the value of k_j. The corresponding variation of firm *i*'s profit is

$$\frac{d\Pi_i}{d(-\delta)} = \frac{2}{3} q_i(\beta_i - \frac{de_j}{d(-\delta)}) = \frac{2}{3} q_i\left(\beta_i - \frac{k_i\beta_j - \beta_i)}{k_i k_j - 1} \right) = \frac{2}{3} q_i \frac{k_i(\beta_i k_j - \beta_j)}{k_i k_j - 1}$$

We can see that there is now a condition for profit to grow when the export cost δ diminishes. This condition may be written

$$k_j > \frac{\beta_j}{\beta_i} = \frac{2b_i - b_j}{2b_j - b_i}$$

When it is met, $\frac{d\Pi_i}{d(-\delta)} > 0$ and the analysis proceeds analogously to that in the previous cases. In particular, under the same conditions as before, $\frac{d\Pi_i}{d(-\delta)}$ is an increasing function of x_i.

Appendix IV

Let q_i and q_i^* represent, respectively, the sales levels of the domestic firm, respectively, in its home and export markets, then when markets are segmented, the variable cost margin of firm i is:

$$M_i^s = (p_i - c_i)\, q_i + (p_j - c_i - \delta)\, q_i^*,$$

The two firms are understood to compete in quantities upon the two markets, so that at the Cournot-Nash equilibrium, the sales of firm i amount to:

$$q_i = 1/3\, [a_i - 2b_i c_i + b_i (c_j + \delta)]$$

$$q_i^* = 1/3\, [a_j - 2b_j (c_i + \delta) + b_j c_j]$$

Accordingly, the variable cost margin of firm i is given by:

$$M_i^s = 1/b_i\, q_i^2 + 1/b_j\, q_i^{*2} = 1/9b_i\, [a_i - 2b_i c_i + b_i (c_j + \delta)]^2 + 1/9b_j\, [a_j - 2b_j (c_i + \delta) + b_j c_j]^2 .$$

If the following definition is adopted, $\gamma_i = 2c_i - c_j$, then it follows that:

$$M_i^s = 1/9b_i\, [a_i + b_i (\delta - \gamma_i)]^2 + 1/9b_j\, [a_j - b_j (2\delta + \gamma_i)]^2 = b_i / 9\, [a_i / b_i + \delta - \gamma_i]^2 + b_j / 9\, [a_j / b_j - 2\delta - \gamma_i]^2$$

After the two markets are fully integrated, the global demand function is specified by: $Q = a - p$, where $a = a_i + a_j$. The new Cournot equilibrium is characterized by $q_i = 1/3\, [a - 2c_i + c_j]$, and the variable cost margin of firm i is given as:

$$M_i = 1/9\, [a - 2c_i + c_j]^2 = 1/9\, [a - \gamma_i]^2$$

Redefining terms, such that $a_i' = a + \delta b_i - 2\delta b_j$, the latter expression can be alternative expressed as:

$$M_i^s = 1/9\, (b_i + b_j)\, \gamma_i^2 - 2/9\, [a_i + a_j + \delta b_i - 2\delta b_j]\, \gamma_i + 1/9\, [a_i^2 / b_i + a_j^2 / b_j]$$

$$= 1/9\, [a_i' - \gamma_i]^2 + 1/9\, [a_i^2 / b_i + a_j^2 / b_j - a_i'^2]$$

By comparing M_i^s and M_i , it can easily be seen that the passage from segmented markets to integration can be interpreted as an upward move of the demand function, from a_i' to a, since, with our assumptions about b_i and b_j , $a_i' < a$. The other terms also introduce a difference between M_i^s and M_i . Yet, since they are independent of the cost structure and, hence, the R&D decisions, they do not impact the progress of the game.