

PRELIMINARY PAPER

Complementarity between internal knowledge creation and external knowledge sourcing in developing and least developed countries

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Abstract: In order to catch up with the technological frontier, firms in developing countries have been striving hard to promote technological advancement through internal R&D effort (make) as well as through external sourcing (buy). The adoption and learning process requires firms to set up effective strategies to catalyze the speed of their catching-up. This study uses the complementarity approach to investigate the intricate relationship between in-house R&D and external technological sourcing. Our empirical evidences exhibit the existence of complementarity between these two innovation strategies in developing countries. However, we also discover that the synergic effect is mainly due to the association of unobserved characteristics. The results also highlight the significant role of external technological acquisition, particularly for firms in least developed countries.

Keywords: make and buy, complementarity, R&D, adoption.

1. Introduction

Innovation is a process of invention and discovery; it is also a process of learning and adopting of new technologies and techniques. Attempting to achieve continuous productivity growth, firms utilize and advance technologies to create new products and services through innovation. Unambiguously, much of the economic and social progress of the past few centuries has been benefited from technology inventions and achievements. The vital role of innovation which is thought to be brought about through research and development (R&D) activities carried out by profit-seeking entrepreneurs was elaborated in the endogenous growth theory (shumpter, *** Aghion and Howitt, 1998; Grossman and Helpman, 1991).

According to Coe, Helpman and Hoffmaister (1997) a large part of the world's R&D activity is carried out by firms located in developed countries, particularly the more powerful member countries of the OECD. And the significant performance of R&D in explaining firm productivity of developed economies has been demonstrated in a number of empirical studies (Griliches, 1984; Kleinknecht and Mohnen, 2002).

However, when we turn our attention to innovation in developing countries, new dimensions of meaning to the concept of "innovation" were uncovered. An obvious problem in trying to relate innovation studies in industrialized countries to technology policy issues in developing countries is that comparatively little technological innovation is taking place in developing countries, especially if innovation is define strictly as the first commercial introduction of a product or process in the international market. Several studies had contributed to conceptualize innovation and technological change in developing economies (see Fransman, 1984). Innovation in this context is distinguished as a learning and adopting process to catch-up technological frontier.

Due to the low level of human capital and vulnerable infrastructure, in-house innovative activities are severely constrained for a majority of firms in developing countries. Innovation emerges through various sources. Internally, Firms depend on the conventional innovation inputs, in-house R&D. Externally, most of firms in developing countries also reply on external acquisition such as investing in new machinery and equipments, licensing, or hiring qualified personnel with relevant knowledge. The internal and external sources are nonexclusive and interacted in the learning process. Cohen and Levinthal (1989) introduced the notion of "absorptive capacity" to describe the substantial role of a stock of prior knowledge to effectively absorb external know-how. This in-house making process will at the same time accommodate firms to build up their own technological capability which is vital to facilitate the learning

process. Simultaneously, external knowledge acquisition may facilitate the efficiency of in-house R&D activities. Such a mutual interaction implies the complementarity between these activities. This view claims for the existence, within the innovation process, of synergic effects making the simultaneous adoption of different inputs more valuable than the separate investment in each of them.

This paper will be based on firm level analysis using data across 23 developing and least developed countries¹. Two interesting findings are drawn from the empirical analysis. Firstly, in order to search for the most important technological sources, we directly estimate the partial effects of in-house R&D and external sourcing strategies in firms' production function. Two types of technological input decision are distinguished. First, firms can obtain new technologies by conducting in-house R&D (we define this as "MAKE"). In addition, they can acquire new technologies which are externally accessible and attracted to them, such as licensing, hiring new personnel, or through trade fairs and study trip (we define this as "BUY"). Our results show that firms in least developed countries rely more on external sources and firms in middle-income countries are more depend on in-house R&D to promote the productivity growth. Secondly, by adopting three different methodologies introduced in previous literatures, we systematically test the complementary versus the substitute relationship between MAKE and BUY. The model adopted in the empirical analysis is econometrically feasible to distinguish between complementarity and correlation induced by unobserved heterogeneity. The findings imply there is significant inter-dependent relationship between innovation strategies in middle-income economies. However, this association is mostly due to the induced co-movement effect by unobserved heterogeneity.

The paper is structured in 6 sections. In the next section we briefly review the key feature of innovation strategies in developing countries and the complementarity in innovation studies. In section 3 we present the empirical model and methods to quantitatively assess complementarity. And we describe our data and identify variables in section 4. In section 5 we show the empirical results and elaborate interpretations with respect to the empirical findings. In the last section, we will present the conclusion.

¹ The classification of developing (middle-income) and least developed countries (LDCs, low-income) is taken from "World Bank country classification 2005".

2. MAKE and BUY strategies in developing countries: complementarity versus substitutability

2.1 Something more than R&D?

Cooper (1989) explained considerably on the differences between innovation in industrialized economies and characteristics of innovation in developing countries. He pointed out that it is a rather limited view of innovation theories only concerned with the initial introduction of products or processes. The catch-up phase is crucial too in any firm where innovation appears in particular for two reasons. First, the expectation of the catch-up speed has substantial influence on the behaviour of innovative firms. Firms will always put effort on strengthening their technological capability in order to preempt learning and imitation. Second, it is important to consider catch-up and other processes that might be involved in the technological diffusion process. Most firms in developing countries are attempting to reach the technological frontier instead of creating products and processes that are new to the market. Thus, to understand the circumstance in developing countries, we must grasp the objective conditions determining the learning and adoption process.

Literature on developing countries customarily distinguishes two main types of innovation: 'make', which focuses on R&D done through in-house development or cooperative activities with suppliers, customers or university/research institutes; and 'buy', which involves transactions of skilled personnel, new machinery (embodied buy), or license agreements with foreign innovative firms (disembodied buy). For the most part even the most technologically advanced firms in developing countries are committed to be involved in external sourcing activities (Freeman, 1989). This is partly due to their limited technical resources, and partly because of their comparatively limited production experience. However, it does not mean that R&D is not important for firms. During the learning and catch-up process, firms are required to have a certain level of technological basis to facilitate the assimilation of new technologies. Cooper (1989) mentioned that failure of learning processes in developing countries is in fact quite common because firms in developing countries that receive technology via external sources are quite often unconcerned about how to develop and appropriate this internal capability. The fact that firms should integrate internal and external knowledge to form more efficient combinations of knowledge suggests the possibility of synergies and system effects (Arora and Gambardella, 1990; Cockburn and Henderson, 1998; Granstrand et al., 1992).

The paradigm of open innovation demonstrated that the knowledge that a firm uncovers in its research cannot be restricted to its internal pathways to market; similarly, its internal pathways to market cannot necessarily be restricted to using the firm's internal knowledge; firms should make the best use of internal and external knowledge (Chesbrough, 2003). This perspective strengthens that external knowledge can create significant value for firms. In parallel, it also highlights that firms organize its internal R&D from the reason of identifying, understanding, selecting from, and connecting to the wealth of available external knowledge. This interdependent relationship naturally consistent with the complementarity idea and suggests there might be synergy between internal and external knowledge sourcing.

2.2 Complementarity in innovation activities

The notion of complementarity is commonly referred in standard price theory, where, for example, two goods are complements if raising the price of one of them lowers the consumption of the other. Here we broaden this conception that permits analysis of complex economic phenomena, organizational structures and government policies. Milgrom and Robert (1990) say that a group of activities are complements if doing more of any subset of them increases the return to doing more of any subset of the remaining activities. It corresponds to positive mixed-partial derivatives of some payoff function in a differentiable framework: the marginal returns to one variable are increasing in the levels of the other variables.

A growing number of empirical studies in both economic and management literature have estimated the complementarity versus substitubility. Here, we briefly review those which are used in innovation activities. Arora and Gambardella (1990) test the synergetic effects among four different external sourcing strategies of large chemical and pharmaceutical firms. After controlling heterogeneity of firms, the results also show the complementarity between all types of external sourcing strategies. Veugelers (1997) find that external sourcing strategy stimulate internal research activities. It seems that external knowledge sources leverage the innovative productivity of in-house R&D. This results is consistent with previous research by Lokshin, Belderbos and Carree (2006). Mohnen and Roller (2005) use the Community Innovation Survey (CIS) data to test the complementarity between different obstacles faced by firms. Their results show that lack of internal human capital is complementary to all the other obstacles in almost all industries. In a recent study by Cassiman and Veugelers (2006), using the methodology developed by them, they systematically examined the relationship between firms' internal R&D

and disembodied innovation strategies. The empirical results presented that a strong synergy effect of in-house R&D and disembodied sourcing strategy exists in Belgian manufacturing firms. Some evidence of substitutability is also found in previous research, such as Basant and Fikkert (1996). They analyse the interaction between internal R&D and Licensing agreements and found they are substitute sources in the innovation process. Fernandez-Bagues (2004) also found substitutability evidence between internal and external pharmaceutical R&D projects.

Compared to developed countries, relevant studies in developing countries are relatively scarce. Since the learning and catch-up is the main objective in developing countries, we are hoping that our study on firms' technological strategy choosing and the performance of those strategies will help firms to address effective innovation management policies and ultimately improving benefit their performance.

3. Methodology: Measuring Complementarity

In this section we present our empirical model in which complementarity in technological acquisition strategies can be identified. Before we go any further, two types of complementarity should be distinguished. The first one is the complementarity under the framework of achieving a specific economical goal. It is a synergy between activities which will lead to a better performance in terms of that specific economic indicator. For instance, complementarity between innovation sourcing strategies in productivity growth; complementarity between R&D cooperation strategies in innovation output. The second type of complementarity we are trying to elaborate is the complementarity between economic activities in the general sense of utility maximization. In this framework, no specific objective function is defined. It is based on the interpretation that firms' choice of adopting activities simultaneously will in one way or another accomplish the optimal utility goal. Hence, the assumption required to make here is that firms are believed to make rational choice base on their individual understanding of maximizing utility of these activities. Due to the fact that it is a general behaviour of adoption and decision making, we define this type of mutual effects as behaviour complementarity.

3.1 Complementarity: definition

The study of complementarities between activities is based on the theory of supermodularity and first introduced in economics analysis by Vives (1990).

Definition: suppose there are two endogenous technological acquisition activities y_1, y_2 and Z is a vector of exogenous variables. The objective function/utility function $f(y_1, y_2, Z)$ is supermodular if the following inequality holds for all values of the other arguments of f :

$$f(y_1^h, y_2^h; Z) - f(y_1^l, y_2^h; Z) > f(y_1^h, y_2^l; Z) - f(y_1^l, y_2^l; Z) \quad (2a)$$

Supermodularity (2a): y_1 and y_2 are complements. Where the superscript h(high) and l(low) denotes the level of y . If y is in continuous term, this inequality restriction implies that the incremental effect of one activity (y_1) on the objective function increases condition on the increasing of another activity (y_2). If y_1 and y_2 are discrete variables, the superscript 'h' will simply tells the presence of y while superscript 'l' represents the absence of y . Then the interpretation would be that the presence of one strategy (y_2) increases the marginal return of the other strategy (y_1) when other exogenous effects are controlled.

$$f(y_1^h, y_2^h; Z) - f(y_1^l, y_2^h; Z) < f(y_1^h, y_2^l; Z) - f(y_1^l, y_2^l; Z) \quad (2b)$$

Submordularity (2b): y_1 and y_2 are substitutes. In the case that y is in continuous term, the marginal return of activity y_1 on the objective function will be decreasing if activity y_2 increases its level. If y is discrete variable, this inequality function means that the presence of one strategy (y_2) decreases the return of the other strategy (y_1) when other exogenous effects are controlled.

Three different methods are adopted in the empirical analysis. Production approach, adoption approach and Quantile approach. We specifically highlight the second one because it not only points out that there has been a significant misspecification lied on the conventional Correlation approach, but also econometrically feasible and, especially, enables us to distinguish the correlation induced by unobserved heterogeneity from complementarity. The Quantile approach will be used as a robustness test.

3.2 Production approach (PROD)

In empirical studies, one of the most popular approaches applied to investigate complementarity between economic activities is to direct estimating the cross partial returns in the production function. It has been explicitly demonstrated in several empirical studies (Cassiman and Veugelers, 2006; Mohnen and Roller, 2003; Belderbos et al., 2006).

In order to implement the PROD approach, the objective function which activities embodied in will have to be established first. Our objective function is transformed from the conventional

Cob-Douglas production function. Suppose that innovation is determined by internal and external acquisition strategies chosen by individual firm i , strategies are represented by $y_{ji} = (y_{mi}, y_{bi})$, “m” denotes make, “b” means buy and $m, b \in j$. With substantial impacts on production efficiency, innovations carry out in firms and indexed by the log Cobb-Douglas production function $f(K, L, y_{ji}, Z)$.

$$\ln f(K, L, y, Z; \cdot) = \alpha K_i + \beta L_i + \theta y_{ji} + \chi Z_i + e_i \quad (1)$$

K and L are the standard input variables represent capital and labour. Z_i includes a category of control variables which capture the organization and institutional characteristics; θ is a vector of coefficients that measures the marginal return to adoption of strategies y_{ji} the possible combinations between them. χ stands for a vector of parameters which measure the partial effects of elements in Z .

PROD Approach: observe the existence of complementarity directly by the regression of objective function on exclusive combinations of innovation activities.

Production function (1) can be rewritten as below

$$\ln f(K, L, y, Z; \cdot) = \alpha K_i + \beta L_i + \theta_{00}(1 - y_{bi})(1 - y_{mi}) + \theta_{10}y_{bi}(1 - y_{mi}) + \theta_{01}(1 - y_{bi})y_{mi} + \theta_{11}y_{bi}y_{mi} + \chi Z_i + e_i \quad (3)$$

y_{ji} is a binary choice and takes value 1 if it is chose by firm i . θ_{11} stands for the cross-partial returns of choosing both MAKE and BUY jointly, the same criteria can be applied to θ_{10} , θ_{01} , θ_{00} . The production function is supermodular and y_{bi} and y_{mi} are complement only if

$$\theta_{11} - \theta_{01} - \theta_{10} + \theta_{00} > 0 \quad (4a)$$

It tells that the presence of one innovation activity will higher the marginal returns of another activity compare with performing them in isolation. On the other hand, they are interpreted as substitution if

$$\theta_{11} - \theta_{01} - \theta_{10} + \theta_{00} < 0 \quad (4b)$$

In order to investigate the partial returns to MAKE and BUY respectively, we chose a simplified alternative form to express the objective function. First, a set of coefficients need to be defined,

$$\begin{aligned}
\theta_0 &= \theta_{00} \\
\theta_b &= \theta_{10} - \theta_{00} \\
\theta_m &= \theta_{01} - \theta_{00} \\
\theta_{bm} &= \theta_{11} + \theta_{00} - \theta_{10} - \theta_{01}
\end{aligned} \tag{5}$$

Then we write the production function as the following simple form

$$Lnf(K, L, y, Z, \dots) = \alpha K_i + \beta L_i + \theta_0 + \theta_b y_{bi} + \theta_m y_{mi} + \theta_{bm} y_{bi} y_{mi} + \chi Z_i + e_i \tag{6}$$

Where the coefficient θ_m captures the non-exclusive partial effects of make; θ_b is the non-exclusive returns of buy; θ_{bm} tells the returns of adopting make and buy together; θ_0 is constant. If we inset (5) into (6), we will go back to equation (3). Equation (6) is preferable since the coefficient θ_{bm} is exactly the complementarity coefficient we are trying to test. Hence, the condition for the production function (5) in a supermodular form can be simplified as:

$$\theta_{bm} = \theta_{11} + \theta_{00} - \theta_{10} - \theta_{01} > 0 \tag{7}$$

One important point need to be highlighted here is that the objective function (6) is the same as expressed in equation (3) but with some transformation, the complementarity now can be reflected by the positive sign of coefficient θ_{bm} in (6), which enable us we to skip the test of inequality (4a) and (4b). Considering this simplicity, we will adopt equation (6) in our empirical analysis in section 5. Furthermore, it also worth to note here that function (6) clearly shows that the marginal returns to either make or buy will not be constant anymore if synergy effect is present (showed as $\theta_{bm} \neq 0$). Henceforth, the complementarity coefficient should also be included in the estimation of partial effects of each of the strategy. The marginal returns to BUY and MAKE can be expressed respectively as

$$\begin{aligned}
\frac{\partial f}{\partial y_b} &= \theta_b + \theta_{bm} \\
\frac{\partial f}{\partial y_0} &= \theta_m + \theta_{bm}
\end{aligned}$$

Athey and Stern (1998) considerably explained that simply run OLS on the above function will deliver us inconsistent results. They argued that the existence of firms' unobserved heterogeneity may have substantial influence on the association between strategies even though complementarily may not exist at all which is the famous endogenous problem. Consequently, PROD approach might deliver bias if there are unobserved factors in the error term that are correlated with the adoption of firms' technological MAKE and BUY strategies.

In order to correct this bias, a structural model should be developed, either using instruments in the cross sectional data or dynamic panel method if panel dataset is available (Wooldridge, 2002). Cassiman and Veugelers (2006) have tried to adopt instrumental variables (correlated with adoption decision without affecting innovation output). However, the results can be refined only if the instrumental variables are properly identified. Here in the current case, even the input prices that each firm faces in adopting innovation practise are observed by econometrician, factors affects the return to those practises are mostly unobserved. In all, the PROD approach will somehow possibly suffers biases because it ignores the existence of unobserved elements or simply assumed that there is no existence of unobserved heterogeneity among firms.

3.3 Adoption approach (ADOPT)

In the following part, we are trying to develop an alternative approach to investigate complementarity between practices which follows the intuition of Miravete and Pernias (2006).

If the presence of one practice is likely to raise the marginal effect on other practices, then the joint adoption of two practices together should be encouraged. It in the meantime implies that, if there is a co-movement phenomenon of two practices, it can be interpreted as the first evidence in favour of existing complementarity. This co-movement can be indexed by the positive correlation (negative if substitutes) between pair wise practices. Empirical realization usually can be fulfilled by using Pearson correlation coefficient and correlation coefficient generated from adoption functions. This approach is defined as *Adoption approach* or *Correlation approach*. A number of empirical studies referenced on complementarity use this approach as auxiliary evidence². This approach is adopted for the reason of testing what we have defined as *behaviour complementarity*.

Several drawbacks should be drew our attention here. First, using Pearson correlation can only provide very preliminary results with regard to the fact that heterogeneity always produces noise in the practice adoption process. Without control firm specifics and characteristics, it is very unlikely that the pair-wise correlation coefficient can generate consistent results. Second, in order the control for firm characteristics, bivariate probit or multinomial logit model has been implemented to test the complementarity by looking at the correlation between residuals (...).

² For example: Arora and Gambardella (1990) introduce a formal analysis of (CORR) as a test for complementarity. Brickley (1995) explicitly uses (CORR) as a test for the comparative static predictions of Holmstrom and Milgrom (1994) in the context of franchising contract provisions.

This method may successfully investigate factors which cause the correlation, for example, if the correlation coefficient depressed by adding some factors, then one would argue that these factors are the causes of complementarity; however, it still fails to provide consistent results due to a fundamental error that it simply use the correlation between residuals to index complementarity.

Here we consider that firms make decision to maximize the total utility of innovation strategies y_{mi} and y_{bj} ($m, b \in j$), where the assumption is that the adoption of y_{ji} is a rational choice of firms which means that firms always make the right decision to make sure to maximize the utility of their choice. In light of the dichotomous nature of variables, the utility function of the adopting strategy MAKE or BUY can be written as

$$u_{bi}^* = \delta_{bm} y_{mi} + \gamma_{bi} W_b + \varepsilon_{bi}, [y_{bi} = 1 \text{ if } u_{bi}^* > 0; y_{bi} = 0 \text{ if } u_{bi}^* < 0] \quad (8a)$$

$$u_{mi}^* = \delta_{bm} y_{bi} + \gamma_{mi} W_m + \varepsilon_{mi}, [y_{mi} = 1 \text{ if } u_{mi}^* > 0; y_{mi} = 0 \text{ if } u_{mi}^* < 0] \quad (8b)$$

Firm i chooses strategy j if $u_{ji}^* > 0$, and y_{ji} will take value 1. In the equation, parameters δ_{ji} are inserted to explicitly indicate the possibility of synergy effects. W represent observed firms' characteristics is a set of exogenous variables which affect the decision of adoption; additionally, ε_{ji} on the right side of the equations denote the unobserved characteristics of firms. To accomplish the identification problem, here we assume that $\text{Var}(\varepsilon_b) = 1$, $\text{Var}(\varepsilon_m) = 1$;

Several interpretations need to be emphasized here. First, the complementarity here is behaviour complementarity. It is not embedded in a specific objective function but only exhibited by utility function for each innovation strategy. Without objective function, the complementarity measure by correlation between error terms is merely the implication of behaviour association. It did not indicate the synergy effects of two strategies with respect to a specific outcome, such as productivity, profit or innovation output. It is a general sense of synergy effect which is described to achieve the optimal utility. Attempting to maximize the utility function, we assume that these utility functions represent firms' optimal decision rules to maximize firms' economic need.

Second, on the presence of the synergy effect, we expect to see the existence of complementarity in the adoption function, which will exhibit in the function as $\delta_{bm} > 0$. δ_{bm} is theoretically consistent with the intuition that if activities complement each other mutually, then there will present the reinforcement of the utility of adopting these practices. In the current case,

if there is complementarity between in-house R&D and external sourcing strategy, there should appear that adoption of one strategy will have positive significant effect on the adoption of another strategy. Theoretically, complementarity between MAKE and BUY is in line with the absorptive capacity theory, firms' in-house knowledge stocks would be expected to have benefited from the previous R&D spending and consequently reduce the adopting cost or stimulus higher return of external technologies. Simultaneously, introducing external technological sourcing facilitates firms to improve their R&D capability to accommodate the maximum utility.

Third, both observed and unobserved characteristics of firms affect the utility of different choices. We denote W_{ji} as the firm specific factors which can be observed by economists but ϵ_{ji} is unobserved heterogeneity. The unobservable can be the institutional or managerial factors which cannot be observed. Such as appropriation regime, manager's experiences, factors that cannot be quantitatively or qualitatively identified. Even though the maximization problem is analogous for all firms, the heterogeneity across firms substantially influences the utility and hence the strategy adoption, ultimately leads firms to make different choices. Accordingly, the existence of complementarity can only be concluded under the condition of controlling both observed and unobserved characteristic. Only controlling observed factors (production approach) will lead to inconsistent estimation.

Forth, complementarity between MAKE and BUY in terms of maximizing utility is identified by coefficient δ_{bm} . Positive sign of δ_{bm} indicates that, in the general setting, adoption of MAKE and BUY is supermodular - the adoption of "make" and "buy" strategies simultaneously will generate maximum utility than adopt them separately. On the other hand, the estimation results will also present us the correlation between error terms which might be induced by the correlation between unobserved factors. The significant correlation coefficient can only provide the evidence that some factors undetected quantitatively by economist do exist and, moreover, they are correlated with each other in the practice adoption process. It can possibly be because of the complementarity effect if the y_{ji} is absent on the right side of the equation system, such as the traditional way of using bivariate or multinomial equation system. Clearly, by using parameter δ_{bm} to capture the mutual effects of y_{ji} in the utility equation system, our approach enable us distinguish the fundamental difference between complementarity and correlation between unobservables.

Last, in order to avoid the identification problem, we assume that the unobserved error terms $(\varepsilon_{bi}, \varepsilon_{mi})$, are normal distributed with zero mean and that the standard deviation can be written as (ρ_b, ρ_m) . The correlation matrix is given as

$$\begin{bmatrix} 1 & \\ \rho_{bm} & 1 \end{bmatrix} \quad (10)$$

It is always argued that synergy effects could be attributed to the association between ε_{bi} and ε_{mi} , it appears as $\rho_{bm} > 0$. Most of empirical studies of testing complementarity are ignored this correlation. For instance, the simple OLS regression in ‘productivity approach’ is a typical example which based on the assumption that there is no unobserved heterogeneity across firms.

Attempting to estimate the maximum utility equation, we need to derive the likelihood function. Before proceeding, we define $\lambda_{bi} = \gamma_{bi}W$; $\lambda_{mi} = \gamma_{mi}W$. Firms have two strategies needed to be chosen, and the utility of choosing these strategies are denoted as $U(y_{bi}, y_{mi})$. Thus, four choice combinations are presented, $U(y_{bi}, y_{mi}) = \{U(1,1), U(1,0), U(0,1), U(0,0)\}$. The intuitive criteria here is that the combination which maximizes the utility will be chosen by firm. For example, in the case of $U(1,1)$ - adopting both MAKE and BUY simultaneously, three inequality restrictions are needed to be satisfied,

$$U(1,1) > U(1,0) \Rightarrow (\lambda_{bi} + \delta_{bm} + \varepsilon_{bi}) + (\lambda_{mi} + \delta_{bm} + \varepsilon_{mi}) > (\lambda_{bi} + \varepsilon_{bi}) \Rightarrow \varepsilon_{mi} > -\lambda_{mi} - 2\delta_{bm} \quad (11a)$$

$$U(1,1) > U(0,1) \Rightarrow (\lambda_{bi} + \delta_{bm} + \varepsilon_{bi}) + (\lambda_{mi} + \delta_{bm} + \varepsilon_{mi}) > (\lambda_{mi} + \varepsilon_{mi}) \Rightarrow \varepsilon_{bi} > -\lambda_{bi} - 2\delta_{bm} \quad (11b)$$

$$U(1,1) > U(0,0) \Rightarrow (\lambda_{bi} + \delta_{bm} + \varepsilon_{bi}) + (\lambda_{mi} + \delta_{bm} + \varepsilon_{mi}) > 0 \Rightarrow \varepsilon_{mi} > -\lambda_{bi} - \lambda_{mi} - 2\delta_{bm} - \varepsilon_{bi} \quad (11c)$$

Interestingly, if $U(1,1)$ is the optimal choice for firm, then inequality functions (11a)-(11c) also automatically satisfy the supermodular condition in (2a). This can be proved by some simple mathematical manipulation. Firstly, the supermodular condition can be addressed from (2a) as

$$\begin{aligned} U(1,1) - U(1,0) &> U(0,1) - U(0,0) \\ \Rightarrow (\lambda_{bi} + \delta_{bm} + \varepsilon_{bi}) + (\lambda_{mi} + \delta_{bm} + \varepsilon_{mi}) - (\lambda_{bi} + \varepsilon_{bi}) &> (\lambda_{mi} + \varepsilon_{mi}) - 0 \Rightarrow 2\delta_{bm} > 0 \end{aligned} \quad (12)$$

Secondly, by adding (11a) and (11b) together, we will have

$$\varepsilon_{bi} + \varepsilon_{mi} + \lambda_{bi} + \lambda_{mi} + 4\delta_{bm} > 0 \quad (13a)$$

then rearrange (11c), put the left sequence to the right,

$$\varepsilon_{bi} + \varepsilon_{mi} + \lambda_{bi} + \lambda_{mi} + 2\delta_{bm} > 0 \quad (13b)$$

last, we subtract (13b) from (13a), it will consequently generate the supermodular condition as expressed in(12),

$$(\varepsilon_{bi} + \varepsilon_{mi} + \lambda_{bi} + \lambda_{mi} + 4\delta_{bm}) - (\varepsilon_{bi} + \varepsilon_{mi} + \lambda_{bi} + \lambda_{mi} + 2\delta_{bm}) > 0 \Rightarrow 2\delta_{bm} > 0 \quad (14)$$

The same criteria can be applied in the other cases - U(1,0), U(0,1) or U(0,0). For each of these choices we will get a corresponding inequality equation as follow

$$\begin{aligned} U_{(1,1)} &\Rightarrow \left\{ \begin{array}{l} f(1,1) > f(0,1) \\ f(1,1) > f(1,0) \\ f(1,1) > f(0,0) \end{array} \right\} = \left\{ \begin{array}{l} \varepsilon_{bi} > -\lambda_{bi} - 2\delta_{bm} \\ \varepsilon_{mi} > -\lambda_{mi} - 2\delta_{bm} \\ \varepsilon_{mi} > -\lambda_{bi} - \lambda_{mi} - 2\delta_{bm} - \varepsilon_{bi}^* \end{array} \right\} \\ U_{(1,0)} &\Rightarrow \left\{ \begin{array}{l} f(1,0) > f(1,1) \\ f(1,0) > f(0,1) \\ f(1,0) > f(0,0) \end{array} \right\} = \left\{ \begin{array}{l} \varepsilon_{mi} < -\lambda_{mi} - 2\delta_{bm} \\ \varepsilon_{mi} < \lambda_{bi} - \lambda_{mi} + \varepsilon_{bi}^* \\ \varepsilon_{bi} > -\lambda_{bi} \end{array} \right\} \\ U_{(0,1)} &\Rightarrow \left\{ \begin{array}{l} f(0,1) > f(1,1) \\ f(0,1) > f(1,0) \\ f(0,1) > f(0,0) \end{array} \right\} = \left\{ \begin{array}{l} \varepsilon_{bi} < -\lambda_{bi} - 2\delta_{bm} \\ \varepsilon_{mi} > \lambda_{bi} - \lambda_{mi} + \varepsilon_{bi}^* \\ \varepsilon_{mi} > -\lambda_{mi} \end{array} \right\} \\ U_{(0,0)} &\Rightarrow \left\{ \begin{array}{l} f(0,0) > f(1,1) \\ f(0,0) > f(1,0) \\ f(0,0) > f(0,1) \end{array} \right\} = \left\{ \begin{array}{l} \varepsilon_{mi} < -\lambda_{bi} - \lambda_{mi} - 2\delta_{bm} - \varepsilon_{bi}^* \\ \varepsilon_{bi} < -\lambda_{bi} \\ \varepsilon_{mi} < -\lambda_{mi} \end{array} \right\} \end{aligned} \quad (15)$$

In order to write the likelihood function, three situations that should be separately considered here. First, under the condition of $\delta_{bm} = 0$, which tells that there is no interaction between “make” and “buy” at all, the utility function (8a) and (8b) will be transformed into a standard bivariate probit model. Second, if $\delta_{bm} > 0$, inequalities with asterisk of U(1,1) and U(0,0) in (15) are not binding. The probability distribution graph will no longer be rectangular as the case of bivariate probit distribution. Last, if $\delta_{bm} < 0$, inequalities with asterisk of U(1,0) and U(1,0) in (15) are not binding. The probability distribution graph created by Miravete and Pernias (2006) give us a clear distribution picture. The likelihood function will be generated based on two dichotomous variables, y_{bi} and y_{mi} , at the same time suffered inequality restrictions in (15).

$$L_i(y_{bi}, y_{mi}; Z_i) = P(y_{bi}, y_{mi}) = \iint_{S(y_{bi}, y_{mi})} g(\varepsilon_{bi}, \varepsilon_{mi}) d\varepsilon_{mi} d\varepsilon_{bi} \quad (16)$$

$g(\cdot)$ is the joint density function. More details of Likelihood function are explained in appendix A. In addition to the parameters in the production function (9), the parameters of the

correlation coefficients, ρ_{bm} will also be tested. The estimation of truncated bivariate probit with upper and lower bounds is achieved by adopting simulated maximum likelihood with GHK simulator (see appendix B).

Although the way that ADOPT approach addresses unobserved heterogeneity is intuitively appealing, building up a perfect structural model turns out to be a very difficult task. The genuine difficulty arises because under the framework of this approach, testing for complementarity relies on measuring the correlations among error terms of equations representing the optimal decision rules of firms. These simplified representations of the optimal decision rules may also include the effect of misspecification and/or missing variables

3.4 Quantile regression

The drawback of the ADOPTION approach is that estimates of the δ_{bm} rely on restrictive assumption of the standard normal distribution of error term - ϵ_{bi} and ϵ_{mi} - in the adoption function. Arias and Hallock (2001) introduced the “quantile treatment” effects that uses quantile regression for different quantiles yield estimates of the whole family of returns to explanatory variable A reflecting the distribution of unobserved variable B across individuals. When coefficient of A differ systematically across different quantiles τ 's, suggesting that the marginal effect of A is not homogeneous of the conditional distribution of dependent variable. Their study exhibited that the interaction between education and unobserved ability can be explored by comparing the education coefficient at different quantiles (τ_0 to τ_1). “Quantile treatment” has been widely adopted in investigating heterogeneous returns based on estimation of quantile wage equations (Buchinsky, 1994; Fizenberger and Kurz,1998; Machado and Mata, 2000).

In our case, quantile regression provides a more flexible approach to characterizing the effect of innovation strategy on different percentiles of the conditional labor productivity distribution. We adopt it as a robustness test to investigate the existence of unobserved heterogeneity. If so, it will induce the variation in the distribution of interaction variable coefficient (δ_{bm}) across different quantiles ($0 < \tau < 1$) in productivity distribution. This variation implies the evidence of unobserved heterogeneity. Testing of the hypothesis of variation ($\delta_{bm, \tau} \neq \delta_{bm}$ for different τ) can be based on Wald test or an alternative formal test - location shift test introduced by Koenker and Xiao (2001).

4. Data and variables

4.1 Data

The data used in our empirical analysis are from the World Bank Investment Climate Surveys (ICS)³. The survey conducts mostly in developing or least developed countries (LDCs) and provides us a wide range of information about the economic environment and economic activities of firms. Several aspects regarding firms' innovation activity are also covered in the survey. Such as the general information referring to firms' innovative input strategies, innovation outputs, and R&D activity.

Table 1 Innovativeness of firms in developing countries

Country	Year	Observation (firms)	Income	Percentage of innovation	Output per worker (log, 1000 USD/person)	Capital per worker (log, 1000 USD/person)	Labor (log, person)
Brazil	2003	1463	Lower-Middle income	85.99%	2.58	2.03	4.00
Chile	2004	306	Higher-Middle income	51.31%	3.70	3.69	3.90
Costa Rica	2005	88	Higher-Middle income	78.41%	3.01	2.74	3.47
Ecuador	2003	273	Lower-Middle income	75.46%	2.92	2.71	3.67
Egypt	2004	582	Lower-Middle income	11.51%	1.47	1.46	3.37
El Salvador	2003	280	Lower-Middle income	80.71%	2.69	2.60	3.79
Ethiopia	2002	243	Low income	missing	1.51	2.16	3.64
Guatemala	2003	371	Lower-Middle income	72.78%	2.41	2.19	3.58
Guyana	2004	97	Lower-Middle income	54.64%	2.52	2.73	3.09
Honduras	2003	323	Lower-Middle income	66.25%	2.19	1.98	3.28
Indonesia	2003	466	Lower-Middle income	46.35%	1.86	1.76	5.23
Lithuania	2004	74	Higher-Middle income	39.19%	2.18	0.94	3.79
Madagascar	2005	79	Low income	60.76%	1.50	1.65	4.11
Malawi	2005	84	Low income	64.29%	2.34	2.03	4.15
Mauritius	2005	98	Higher-Middle income	72.45%	2.70	2.40	4.12
Nicaragua	2003	308	Low income	75.00%	1.77	1.73	2.95
Pakistan	2002	845	Low income	missing	2.31	2.29	3.30
Philippines	2003	582	Lower-Middle income	59.79%	1.97	1.57	4.16
South Africa	2003	513	Lower-Middle income	82.85%	3.47	2.85	4.69
Syria	2003	75	Lower-Middle income	36.00%	1.83	2.70	2.23
Tanzania	2003	73	Low income	49.32%	2.09	2.21	3.51
Thailand	2004	1336	Lower-Middle income	64.97%	2.85	2.49	4.96
Turkey	2005	454	Higher-Middle income	69.16%	3.54	3.32	4.20
Zambia	2002	73	Low income	72.60%	2.54	2.24	4.07
Total		9086		57.67%	2.50	2.26	4.02

³ For more information and the methodology of the survey, please see <http://www.worldbank.org>

After cleaning out missing values, 24 countries and 9,086 firms in manufacturing sector are included in the pooled cross-sectional dataset from the period 2002-2005. Only countries with more than 50 observations are included. We also drop firms with its permanent employee less than 5. Table 1 gives simple descriptive statistics about countries and their innovativeness. Innovativeness is measured by two binary variables: product innovation and process innovation.

Due to the different levels of economic development and size of the economies, the number of firms in the samples varies considerably across countries. Innovation of firms across countries is quite dynamic with approximate 57 percent of them claimed to be innovative during the last three production years. It should be noted that the new technologies or products from innovation activities in developing countries are not conventionally defined as the one new to the market; they might be only new to the firm. This again reminds us that innovation in developing countries and LDCs is a learning and adopting process.

The survey contains two main questions with respect to firms innovation acquisition strategies. On one hand, firms were asked to choose three important methods of innovation sourcing strategy out of total twelve options. If firms chose at least one of the three technological sources: hiring key personnel, licensing from abroad or domestic, and trade fair/study tour; the dummy variable “buy” will be marked as 1. Almost 45 percent firms were answering using import machinery and equipment as one of their important innovation input. Considering the difficulty of clearly defining the use of machinery and equipment, we decided to drop this choice. It is very possible that firms might confuse buying machinery as innovation sourcing or simply for the purpose of production. On the other hand, the survey addresses question related to firms’ R&D spending in the last year as well. The definition of R&D spending in ICS refers to the relevant capital and labor cost which used in firms’ research and development. It also includes the cost on contractual and cooperative R&D activities with other firms, research institutes and universities. We give the binary variable MAKE value of 1 if firms have a positive R&D expenditure, 0 otherwise. Table 2 shows the count statistics of the appearance of each strategy and their interactions.

Table 2 “make” and “buy” strategies in developing countries

Income levels	makeonly	buyonly	makebuy	nonmakebuy
Low income	11.44%	37.30%	24.40%	26.86%
Middle income	17.25%	23.13%	20.11%	39.52%
All sample	16.16%	25.79%	20.91%	37.15%

This statistic exhibits us that the main technological strategy in developing countries is from external sources. Particularly in least developed countries, the percentage of firms that rely exclusively on “buy” is three times higher than in-house make. External technological sourcing is also the main strategy of firms in middle-income economies even the proportion of “buyonly” drops by one third compared to lower-income economies. This trend of changing strategy choosing is because that in-house R&D is severely constrained in low-income countries. Due to the low levels of financial and human resources, they seek innovation sources from external channels. In a relatively higher level of development (middle-income countries), firms have probably already achieved some knowledge stocks and innovation experiences which makes them capable of doing R&D internally. As showed from table 2, there is about 6% increase in “makeonly” strategy. One should be noted that there might be other sourcing strategies adopted internally or externally by firms. Such as transferring from mother companies, learning from international conference or study trip and cooperating with suppliers or customers. We will not address those points here due to the shortage of information.

4.2 Variables in production function

Table 3 gives the definition and summaries of variables used in our empirical analysis.

Insert Table 3 here

The dependent variable in the objective function of PORD approach is PRODUCTIVITY, measured by sales per employee, in natural logarithmic terms. The standard explanatory variables (K, L in equation 6) used in the production function are: CAPITAL (capital/labor in logs, capital is the end of year total capital stock); SIZE (log permanent workers at end of the year).

Besides the standard explanatory variables, we also control several exogenous variables to capture firms’ competitiveness and technological capability. CAPACITY indicating the differences in capacity utilization (in percentage) between firms is also controlled in our analysis because of the idea that firms are able to produce more with the same amount of inputs when their production operates in a relatively high level. Variable FOREIGN is the percentage of ownership controlled by foreign companies. Most of foreign firms in developing countries are productive compare to domestic firms. However, empirical evidences have showed that core

technologies mostly remain controlled by the foreign partners in joint ventures or by company headquarters abroad (OECD, 2007). So, in general, foreign-invested companies are expected to be less R&D-intensive than domestic firms. Variable EXPORT tells if firms have positive exports sales during the last year. Here, we use EXPORT to indicate levels of openness of the economy. Openness has generally led to greater competition in product markets and increasingly in markets for services. More vigorous competition exerts discipline on firms in developing countries, helping to lower prices and ensure better quality and variety of goods. It therefore tends to strengthen incentives for innovation in their economy. So we expect the positive relation between export activities and productivity. Two variables affect the efficiency of production will also be contained. The quality of labor force directly influences the utilization of capital. So we include EDUWORKER that measured by the percentage of permanent workers who have at least a university education background. Another indicator we use is dummy variable IT which indicates if firms use Internet in daily work.

The ICS survey contains a series of information about the business environment firms operate. Business environment consists of government regulations, institutional background, social conventions that might have substantial impact on firms' production decision and performance (Coase, 1998; North, 1991). The question which asks of lost sales (in percentage) due to power outages during last operation year constructs the variable INFRA to indicate the quality of business infrastructure. REGULATION measures the average time of a manager dealing with government regulations. It measures the extent to which regulation is a burden in firms' operation. Dummy variable FINANCE takes value 1 if accessing to finance or costs of finance is a major obstacle to firms. The dummy variable Low-tech dummy⁴ and Region dummy⁵ are used to capture the heterogeneity across industry and region. At last, constant capturing the average level of revenue and cost will be also included.

4.3 Variables in utility function

The remaining variables need to be identified are the sets of exogenous variables W_{ji} in equation (8a) and (8b). Even some of them are overlapped with the exogenous variable defined in the production function, but the interpretation will be different here as they are used for explaining the effects on the utility of acquisition strategies. In general, three categories of adoption specific

⁴ Low Tech industries are defined based the definition of OECD

⁵ Four regions are included: European, African, Asian and Latin American countries.

variables are expected to affect firms' innovation strategy decision. The first category is firm specific. We use OUTPUT, SIZE and OWNERSHIP to capture the firms' production characteristics. The better the firm's production performance is; the more dynamics are expected for firm to involve in innovation activities, both in-house and externally. The second category entails the competition specific variables. Firms that face fierce competitions in their market are generally more innovation dynamic compared to those that have fewer competitors. EXPORT will be the only variable included and expect to have positive correlation with innovation strategies. The third category of variables stands for characteristic of technological capability that affects marginal utilities of firms' innovation strategy decisions. Because information technology is commonly recognized as an important technological infrastructure to improve communication and logistic efficiency, IT is included in the both internal and external strategies utility function. The same for ASSOCIATION because it indexes the network of firms which will subsequently benefit firm's new technology information acquisition. Dummy variable ISO with value 1 indicates that the firm has received international certificates, such as ISO9000, 9002 or 14,000. It is based on the idea that the achievement of international certificates reflects to some extent the R&D capability level of firms. Hence, it will only appears in the "make" function. Moreover, EDUWORKER will be also exclusively included in the "make" function since human capital is a essential part of firms' R&D activity. EDUMANAGER dummy variable has a value 1 if the average education level of senior managers is above university level. It will only be used in the "buy" function.

Figure 1 Technological capability and institutional condition in low-income and middle-income countries

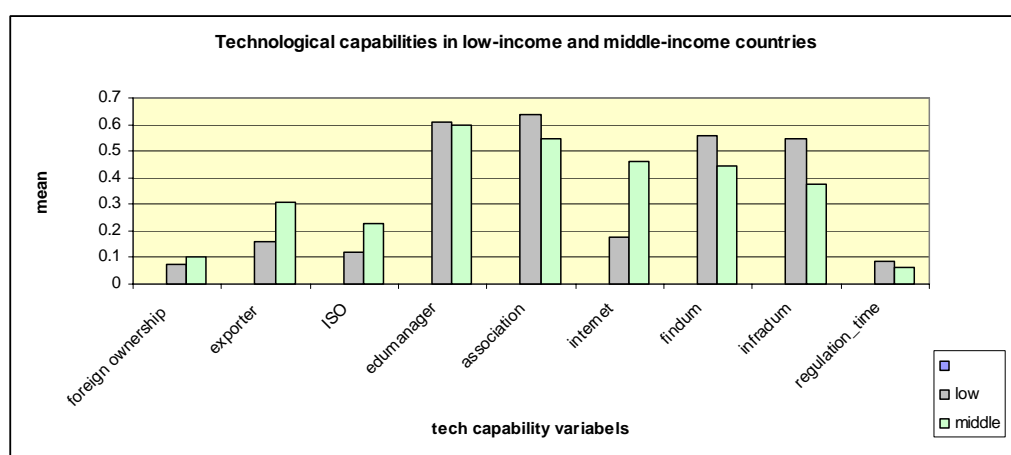


Figure 1 is a statistics of firms' technological variables. It presents us the differences in technological infrastructure and absorptive capacity between low-income and middle-income countries. Clearly, technological capability and institutional environment of firms are

heterogeneous across levels of development. The pattern exhibits that the mean of technological-related variables is generally higher in middle-income developing countries than in the low-income group.

With low levels of development, firms might be constrained by general low levels of technological capability. Hence, firms in low-income groups mainly rely on external technological acquisitions. In this circumstance, the synergy effect of MAKE and BUY on productivity performance will be depressed by factors such as low absorptive capacity, low financial source, etc. Consequently, even having adopted the same external technological strategies, firms with a low level of human capital will use these external sources less effectively.

The increase of internal technological capability will catalyze the effective absorbs external know-how, so the complementarity between in-house and external strategies is expected to appear as the development level increases. The last three columns in figure 1 show the environmental obstacles to firms. Apparently, comparing to middle-income countries, the obstacles faced by firm are more severe in low-income countries.

5. Empirical results

In this section we present the result of empirical analysis of how innovation strategies affect firms' performance. Importantly, we would like to see whether there is complementarity between innovation technological strategies across developing countries.

5.1 Unconditional correlation

Before regressing firms' production function, we did a preliminary test which is estimating the pair-wise association of MAKE and BUY strategies. Statistical association of any two-decision variables requires that all real valued nondecreasing functions of these two variables be statistically correlated. Here we first measure the association of MAKE and BUY regardless of any other differences in firms' characteristics. Table 4 gives the results from Pearson's correlation.

Table 4 Unconditional correlation between innovation strategies and scale of investment

	Low income		middle income	
	MAKE	BUY	MAKE	BUY
MAKE	1		1	
BUY	0.0981***	1	0.1651***	1

***indicates the results is significant at 0.01.

In both low-income and middle-income cases, MAKE and BUY are positively related with a significant difference in magnitude. It implies the possible existence of complementarity between MAKE and BUY strategies across countries with different levels of development. In the middle-income group, the correlation is significantly stronger compared to the low-income group. This is our first evidence of association between innovation strategies, despite it might be the result of heterogeneity across firms. Nevertheless, it is not sufficient to conclude that MAKE and BUY are complementary.

5.2 PROD approach

Based on equation 6, we regress our dependent variable (productivity) on the innovation strategy MAKE and BUY, together with firm characteristics, country and industry dummies that may affect the productivity performance. The results are presented in table 5.

Table 5 OLS regression results. Dependent variable: Labor productivity

	PROD approach	
	Low income	Middle income
	Coef.(Std. Err.)	Coef.(Std. Err.)
PROD		
LABOR	0.01(0.02)	0.08(0.01)***
CAPITAL	0.46(0.02)***	0.42(0.01)***
MAKE	0.04(0.09)	0.01(0.03)
BUY	0.12(0.06)**	-0.01(0.03)
MAKEBUY	0.02(0.11)	0.07(0.04)**
EDUWORKER	0.67(0.24)***	0.28(0.00)***
INTERNET	0.18(0.07)***	0.14(0.00)***
FOREIOWNER	0.14(0.11)	0.33(0.04)***
EXPORT	0.44(0.07)***	0.16(0.03)***
CAPACITY	0.53(0.14)***	0.36(0.05)***
FIN_DUM	-0.14(0.05)***	-0.05(0.02)***
INFRA_DUM	-0.06(0.05)	-0.04(0.02)**
REGU_TIME	-0.13(0.18)	-0.08(0.09)
Constant	0.42(0.19)***	0.04(0.11)
Number of obs	1705	7381
Adj R-squared	0.3914	0.5858

Note: nonmakebuy is the base category. Industry, country and year dummies are included.

*** Significant level 1%, ** at 5%, * at 10%.

Table 5 not only presents us the complementarity test results of innovation strategies; it also generates several important ideas about innovation activities of firms in developing world. The finding suggests that the elasticity of capital stock (CAPITAL) to productivity does not differ considerably between both groups but we find there are no increasing returns to scale (SIZE) in

low-income countries. Export-oriented firms (EXPORT) are more efficient in term of productivity as elaborated in the previous session. Productivity increases with capacity utilization (CAPACITY) and coefficients are highly significant. Firms that share ownership with foreign (FOREIGN) companies are also showing to be more productive but this is only significant in middle-income countries.

Not surprisingly, when firms are faced with more obstacles in their production process, their productivity performance is reduced. Financial constrains (FINANCE) depress productivity of firms in low-income countries more severely compared to middle-income countries. INFRA also shows negative significantly but only in middle-income countries. Estimate coefficient of REGULATION is not significant but negative in both groups. Here, the implication is that treat innovation as a system is necessary since institutional factors are important to ensure the good performance of firms.

Table 5 also presents us the marginal contribution of MAKE, BUY and the interaction term MAKEBUY to the productivity in least-developed and developing countries. The coefficient of external technological sourcing variable is positive and significant only in the case of low-income group. This result confirms our **assumption** that with low levels of technological capability, firms in low-income countries rely more on external sourcing strategies. However, Contrary to developed countries, the traditional innovation variable R&D (MAKE) does not play an important role as it does in developed countries. The coefficient of MAKE positively appears in both groups but not statistically significant.

Now, turning to the hypothesis of complementarity, in middle-income countries, consistent with the Pearson correlation, the coefficient on MAKEBUY in OLS is statistically significant at 95 percent. This evidence indicates the existence of complementarity between MAKE and BUY strategies. However, the synergy effect does not hold in low-income countries. With regard to these findings, assuming there are no unobserved factors across firms, we can conclude at this stage that there is complementarity in adopting MAKE and BUY jointed. But this synergic effect only appears in firms in middle-income countries where they have higher technological capability and less institutional constraints.

Practically, it is very difficult for economists to identify all the heterogeneity across firms. So far, our estimations with respect to complementarity (or substitutability) are reported under the assumption of no unobserved heterogeneity. Despite the fact that the unobserved still can not be identified, the ADOPT approach presented in the next section will somehow enable us to

distinguish the complementarity and association of unobserved heterogeneity.

5.3 ADOPTION approach

In this part, we present the corresponding results generated by the ADOPT approach introduced in section 3.3. The first two columns of Table 6 present the maximum likelihood estimation results under the assumption that no unobserved factors affect firms' innovation strategy choosing, which is formed in the function as $\rho_{bm} = 0$ in equation (8a) and (8b). Consistent with the PROD approach, complementarity coefficients, δ_{bm} is only positive and significant in middle-income countries but not in low-income countries.

Table 6 ADOPT approach Estimation results

ADOP approach	Without Unobserved heterogeneity		With Unobserved heterogeneity	
	Low income	Middle income	Low income	Middle income
“buy”				
OUTPUT	0.02 (0.25)	-0.05(0.01)***	0.03(0.27)	-0.06(0.01)***
SIZE	0.02(0.04)	0.07(0.01)***	0.02(0.04)	0.09(0.02)***
FOREIOWNER	-0.32(0.14)***	0.05(0.06)	-0.31(0.14)***	0.03(0.06)
EXPORT	0.11(0.10)	-0.11(0.04)***	0.09(0.09)	-0.13(0.04)***
EDUMANAGER	0.17(0.07)***	0.20(0.03)***	0.18(0.07)***	0.18(0.03)***
ASSOCIATION	0.05(0.07)	0.29(0.03)***	0.04(0.07)	0.30(0.04)***
IT	0.15(0.09)*	0.10(0.03)***	0.12(0.09)*	0.10(0.04)***
Low_Tech	-0.08(0.07)	0.10(0.03)***	-0.08(0.06)	0.09(0.03)***
Constant	-0.27(0.11)***	0.06(0.06)	-0.26(0.12)***	0.04(0.06)
“make”				
OUTPUT	0.60(0.28)***	0.02(0.01)*	0.69(0.28)***	0.02(0.01)*
SIZE	0.02(0.02)	0.08(0.01)***	0.03(0.04)	0.14(0.02)***
FOREIOWNER	0.07(0.14)	-0.21(0.06)***	0.08(0.15)	-0.21(0.06)***
EDUWORKER	-0.17(0.20)	0.51(0.08)***	-0.19(0.28)	0.59(0.08)***
EXPORT	-0.08(0.10)	0.04(0.04)	-0.09(0.10)	0.01(0.04)
ISO	-0.11(0.11)	0.05(0.04)	-0.12(0.11)	0.03(0.04)
ASSOCIATION	0.17(0.07)***	0.24(0.03)***	0.19(0.07)***	0.28(0.03)***
IT	0.06(0.09)	0.30(0.04)***	0.07(0.09)	0.31(0.04)***
Low_Tech	0.03(0.07)	0.02(0.03)	0.03(0.07)	0.02(0.03)
Constant	-1.40(0.13)***	-1.21(0.07)***	-1.42(0.13)***	-1.21(0.07)***
δ_{bm} (complementarity)	0.06(0.04)	0.17(0.02)***	0.10 (0.18)	0.01(0.01)
ρ_{bm} (correlation)			-0.04(0.21)	0.20(0.02)***
Log likelihood	-2127.54	-9156.16	-2129.34	-9125.47

Note: Industry dummies and country dummies are included.

*** Significant level 1%, ** at 5%, * at 10%.

The last two columns of Table 6 report the results based on the model which includes both complementarity and unobserved heterogeneity. In the presence of complementarity and induced correlation due to unobserved heterogeneity, the estimates of exogenous variables are

qualitatively consistent with the models without unobserved heterogeneity but slightly different in magnitudes.

The firm specific factors seem to have significant influence in firms' innovation sourcing strategy choosing. Firms with big scale in production seem to be encouraged of doing in-house research. It might attribute to the fact that big scale firms are likely to dedicate more financial resources to carry on R&D. The SIZE effect appears only in middle-income group. Firms with bigger scale of human capital are likely to engage in both internal and external innovation activities. Because technologies mostly remain controlled by the foreign partners in joint ventures or by company headquarters abroad, foreign-invested companies are reluctant to engage in innovation activities by themselves. Coefficients of FOREIOWNER are significantly negative in the BUY for low-income group and in MAKE for middle-income group. EXPORTER is also negatively significant on BUY across middle-income countries.....

Firms with better technological capability are more profitable in adopting either of the innovation strategies. This effect is found in the significant effects of technological variables. In the case of middle-income countries, IT, EDUMANAGER and ASSOCIATION are positively correlated with BUY while, IT, ASSOCIATION and EDUWORKER are positively correlation with MAKE. In the low-income country case, ASSOCIATION used as an indicator for the opportunity to gain information stimulates firms' R&D decision only. EUDUMANGER is significantly positive correlated with BUY.....

We did not include region dummies⁶ coefficients in the results but regional differences are significant across out sample. It suggests that geographic constraints may limit firms' technological opportunities and innovation information. The coefficients presented in table 6 are not interpreted as the marginal effects since a further calculation is need to complete in this process. The estimated coefficients here only imply the positive/negative effects on the adoption of MAEK and BUY.

After controlling for the correlation between residuals, the complementarity coefficients are no longer significant as it showed in δ_{bm} . However, we can still find the highly significant correlation of unobserved factors between MAKE and BUY in middle-income countries, but only at the significance level of 90 in low-income countries. These findings suggest that the positive association between innovation in-house make and external sourcing is attributed to the correlation of unobserved characteristics of firms. The correlation between unobservable creates

⁶ Region dummy are classified in four groups by the continent: Asia, Europe, South America, Africa.

the source of co-movement in firms' strategic decision making. And it might be the same reason which leads to appear as the synergic effect in the production function.

5.4 Robustness estimation: Quantile regression

Figure (2.1) and (2.2) presents the results for the quantile regression. The labor productivity is regressed in different quantiles ($\tau = 0.05, 0.15, \dots, 0.95$) based on equation (5). The complementarity coefficient δ_{bm} for the 5th to 95th quantiles are plotted in increments of 0.1 and the results are given in both low-income and middle-income groups. Graphically, homogeneity in returns would imply that the figures are flat and cursory examination of the figures suggests the presence of unobservable in the returns to joint-effects of internal and external sourcing strategies. The “make&buy” coefficients are depicted by the third graph in both (2.1) and (2.2). In low-income countries (2.1.3), returns are negative and remain essentially constant from 20th quantile to 50th quantile, after which has a striking increase up to 0.2. The return of complementarity coefficient in middle-income countries (2.2.3) remains to be positive all the time which indicate the existence of synergy effects between MAKE and BUY. It is increasing for higher quantiles of the conditional distribution of labor productivity. Especially, there is a clearly increase in the return from 0.02 at the 30th quantile to 0.09 at the 70th quantile. Accordingly, for this specification, we can confirm that there exists the evidence of complementarity in middle-income countries. However, the complementarity coefficients do not appear to be homogenous in both groups.

In line with previous findings, external technological sourcing is more effective across the low-income countries. This can be observed from the second graph in figure 2.1. It is plotted in the positive region and, in general, bigger in magnitude than the first graph in figure 2.1 which indicates the returns of in-house R&D. On contrary, in-house R&D seem to be more encouraging for the growth of labor productivity in middle-income countries since it constantly greater than returns of external sourcing strategy, even the magnitude is observed to be positive only before the medium quantile. This find can be seen from figure 2.2.1 and 2.2.2.

Figure 2.1, Return to MAKE and BUY in Quantile regression: Low-income countries

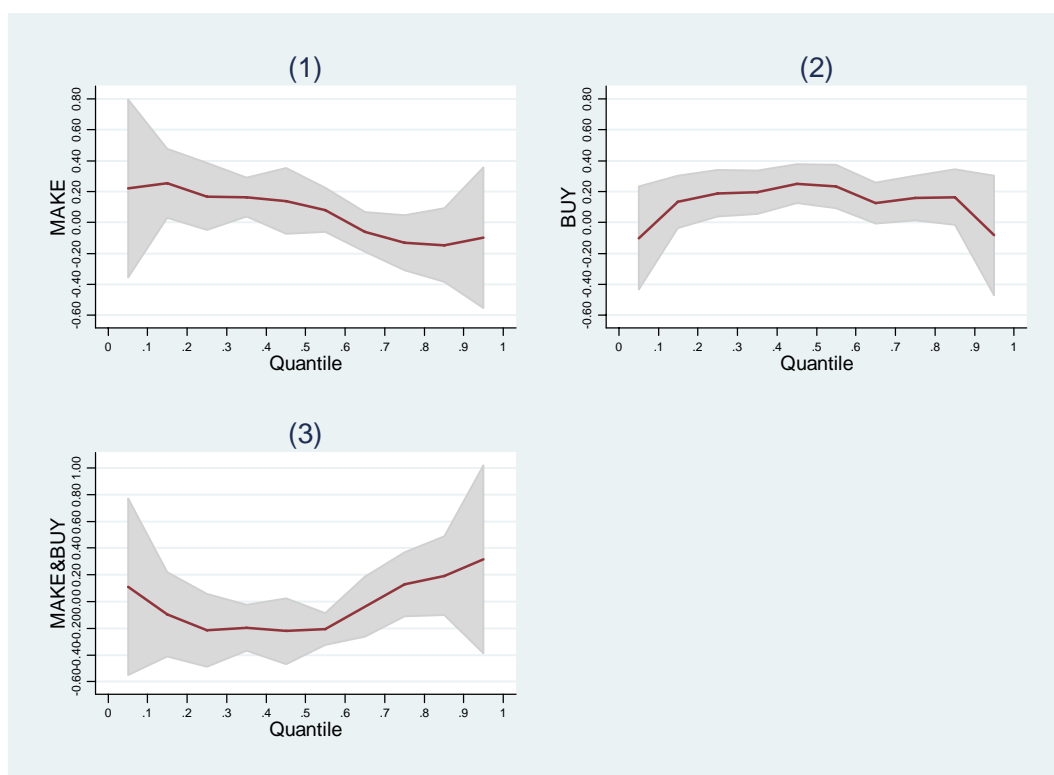
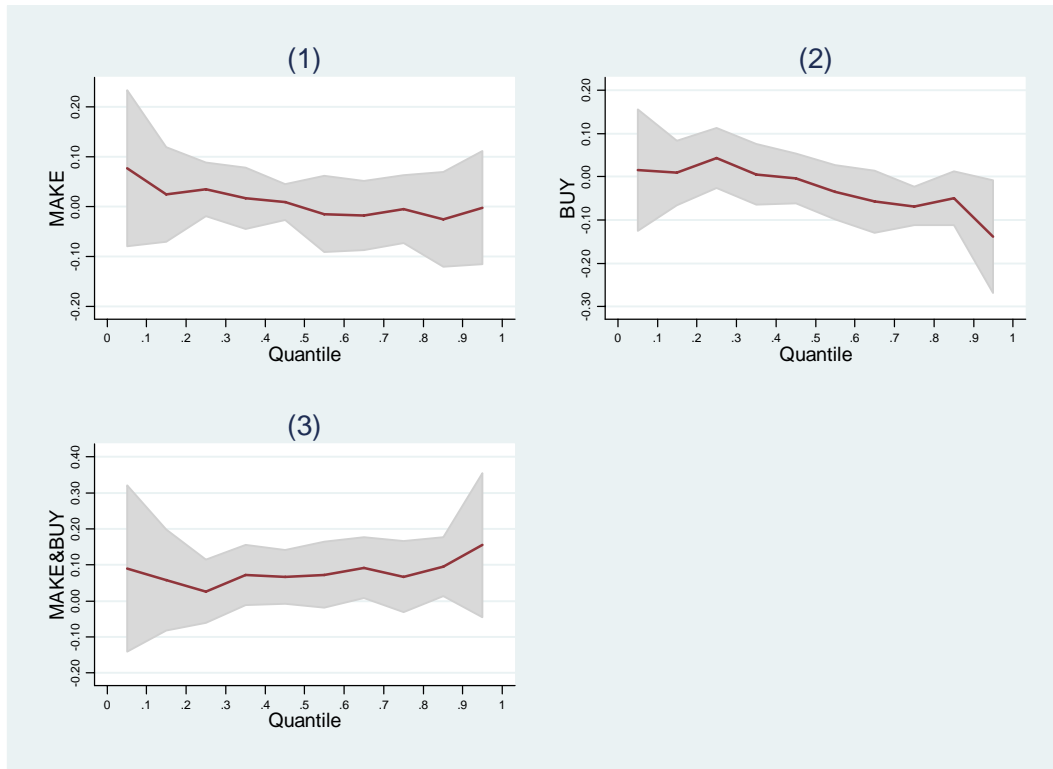


Figure 2.2, Return to MAKE and BUY in Quantile regression: Middle-income countries



Note: estimation performed in STATA 10. P-value is based on the bootstrap method.

Table 7 Test of location shift hypothesis

	Low-income		Middle-income	
trim	0.1	0.3	0.1	0.3
δ_{bm}	2.108**	1.713***	0.478***	0.318***
Joint effect	45.273	26.3	46.4	32.691
1% critical value	2.64	2.32	2.64	2.32
5% critical value	2.102	1.894	2.102	1.894

Note: Estimation performed by adopting “quantreg” package in R. *** Significant level 1%, ** at 5%

We employ the location shift test (Koenker and Xiao, 2001) to estimate whether the observed differences are statistically significant across quantiles and report the results in Table 7⁷. In this case, we focus on the equality of δ_{bm} across quantiles and also the joint effects of all coefficients are presented. In low-income countries, the value takes 2.108 and 1.713 respectively with 0.1 and 0.3 trimming⁸. With critical value 2.64 and 2.32 at 1 percent level, it suggests the acceptance of the null hypothesis that complementarity effect is different across different quantiles. The Corresponding test for middle-income countries also leads to accept at 99 percent level. These findings are remarkable consistent with the ADOPTION approach with respect to the unobserved heterogeneity. Hence we can conclude the presence of unobserved heterogeneity

⁷ See Koenker and Xiao (2001) for critical value table and further details on the proposed test.

⁸ trim is the range indicator we applied in the test. See Koenker and Xiao (2001)

and it is the cause of complementarity.

6. Conclusion

The lack of advanced technological competencies in developing and least developed countries requires innovation to occur through the adoption and learning process of already existing technologies. In order to catch up with the technological frontier, firms have been striving hard to promote technological advancement through internal R&D effort (MAKE) as well as through external sourcing (BUY). The low levels of technological capability severely constrain firms to conduct in-house R&D. For this reason, firms rely more on external knowledge acquisitions such as licensing, embedding skilled labor etc. Our results highlight the significant contribution of external sourcing strategies to firm's productivity growth, particularly in least developed countries. However, firms that combine internal R&D with external innovation activities simultaneously are having a better performance in middle-income countries. These findings indicate that different levels of development require a government to constitute different policies in order to catalyze effective innovation performance. In the context of low level of development, external sourcing strategies are essential for local firms to be integrated in the domestic and global market. Government should Developing and implementing policies to encourage external sourcing exclusively, such as provision of technological information and financial support on technology import. While in the context of middle-income countries, local firms have built up some technological capabilities and experiences. Government policy should start to encourage both internal and external sourcing strategies jointly because there is a potential better in adopting MAKE and BUY simultaneously despite the complementarity is most due to the unobserved heterogeneity.

Complementarity is a conceptual appealing approach, attempting to search for evidence of complementarity between in-house and external strategies, we applied the CORR approach first and the results showed a strong correlation between residuals of the two strategies. This unreliable finding is used as a suggestive. Then under the assumption of absence of unobserved factors across firms, we applied PROD approach to estimate the combination of MAKE and BUY and their partial returns to productivity performance. Findings are consistent with the existence of complementarity but the synergy effect only appears in middle-income countries. However, these findings do not take into account the unobserved heterogeneity across firms that could deliver bias and it has been a significant constraint in empirical studies. We adopted

the methodology introduced by Miravete and Pernias since it practically enables us to distinguish complementarity and correlation due to unobserved heterogeneity. After controlling for the unobserved characteristic of firms, the association between MAKE and BUY vanished. This result proves that the complementarity between in-house and external technological sourcing is attributed to the association of unobserved characteristics across firms in developing countries. Quantile regression and location shift test have showed us the consistent results in the robustness estimation. Further studies can proceed to identify the exact complementarily source by adopting powerful instruments in the adoption function. Moreover, in order to contemplate the dynamic change of complementarily in developing countries, panel data are desired.

7. Literature references

- Aghion, P. and P. Howitt, (1998). *Endogenous Growth Theory*, Cambridge.
- ARIAS, O., K. F. HALLOCK, AND W. SOSA-ESCUADERO (2001). "Individual Heterogeneity in the Returns to Schooling: Instrumental Variables Quantile Regression using Twins Data," *Empirical Economics*, 26, 7–40.
- Arora, Ashish and Alfonso Gambardella, (1990). Complementarity and External Linkages: The Strategies of the Large Firms in Biotechnology, *Journal of Industrial Economics*, 38, 361–379.
- Arora, Ashish and Alfonso Gambardella, (1994). Evaluating technological information and utilizing it: Scientific knowledge, technological capability and external linkages in biotechnology, *Journal of Economic Behavior and Organisation*, 91-114.
- Arrow K J. (1962.) The Economic Implications of Learning by Doing, *The Review of Economic Studies*, Vol. 29, No. 3. (1962), pp. 155-173.
- Athey, Susan, and Armin Schmutzler (1995). 'Product and Process Flexibility in An Innovative Environment', *RAND Journal of Economics*, 26(4), 557–574.
- Athey, S., Stern, S., (1998). An empirical framework for testing theories about complementarity in organizational design. NBER Working Paper No. W6600. NBER, Cambridge.
- Baldwin, J., Lin, X., 2002. Impediments to advanced technology adoption for Canadian manufacturers. *Research Policy* 31, 1–18.
- Basant R., Fikkert B. (1996). The Effects of R&D, Foreign Technology Purchase, Domestic and International Spillovers on Productivity in Indian Firms. *Review of Economics and Statistics*, 78, 187-99.
- Belderbos R., Lokshin B., Carree M. (2006). Complementarity in R&D Cooperation Strategies. *Review of Industrial Organization*, 28, 401-26.
- Benavente, J.M. (2006). The Role of Research and Innovation in Promoting Productivity in Chile. *Economics of Innovation and New Technology*, 15(4/5).

- Buchinsky M (1994). Changes in the U.S. wage structure 1963-1987: An application of quantile regression. *Econometrica* 62(2): 405-58
- Cassiman, B., Veugelers, R., (2002). Complementarity in the innovation strategy: Internal R&D, external technology acquisition, and cooperation in R&D. Mimeo.
- Cassiman B., Veugelers R. (2006). In search of Complementarity in the Innovation Strategy: Internal R&D and External Knowledge Acquisition. *Management Science*, 52, 68-82.
- CGP, 1999. Recherche et Innovation: la France dans la Compétition Mondiale, Rapport du groupe de travail présidé par Bernard Majoie. Commissariat Général du Plan, La Documentation Française, Paris.
- Chesbrough, (2003). *Open innovation, The new imperative for creating and profiting from technology*. Harvard Business School Press.
- Freeman, Christopher (1989). *The Economics of industrial Innovation*, 2nd edn, Francis Pinter, London.
- Coase, R., (1998). The New Institutional Economics, *American Economic Review*, 88, 72-74.
- Cockburn, I. and R. Henderson, 1998, Absorptive capacity, coauthoring behaviour and the organization of research in drug discovery, *Journal of Industrial Economics*, 46: 157-182.
- Coe, David T., E Helpman and A W. Hoffmaister (1997) North-South R&D Spillovers, *Economic Journal*, 107, 134-149.
- Cohen, W. and D. Levinthal, (1989) Innovation and Learning: The two Faces of R&D, *Economic Journal* 99, 569-596.
- Cooper, C. (1989). Technology and Innovation in International Economy. United Nation University Press, The Netherlands.
- Dahlman C., Ross-Larson B., Westphal L.E. (1987), Managing Technological Development: Lessons from Newly Industrializing Countries, *World Development*, 15, 6: 759-75.
- Das, T. K., and Bing-Sheng Teng (2000) 'A Resource-based Theory of Strategic Alliances', *Journal of Management*, 26(1), 31-60.
- Fernandez-Bagües M. (2004): Complementarity in Innovation Strategies: Evidence from Pharmaceutical Dynamic Panel Data. *Paper presented at the 30th E.A.R.I.E. Conference* in Helsinki.
- Fransman, M. and King, K (1984) Technological capability in the third world. The Macmillan Press LTD. London
- Fitzerberger B, Kurz C (1998) New insights on earnings trends across skill groups and industries in West Germany. Working paper.
- Galia, F. and Legros D, (2004), complementarity between obstacles to innovation: evidence from France, *research policy*, 33: 1158-1199.
- Granstrand, O., E. Bohlin, C. Oskarsson and N. Sjöberg, (1992), External Technology Acquisition in Large Multitechnology Corporations, *R&D Management*, 22: 111-133.
- Griliches, Zvi, (1994). "Productivity, R&D, and the Data Constraint," *American Economic Review*, *American Economic Association*, vol. 84(1), pages 1-23, March.
- Griliches, Z. (1979), Issues in assessing the contribution of research and development to productivity growth, *Bell Journal of Economics*, Vol. 10 pp.92-116.
- Grossman, G.M., Helpman, E., (1991). Innovation and Growth in the Global Economy, MIT press, Cambridge, MA.
- Hagedoorn, John (1993) 'Understanding the Rational of Strategic Technology Partnering: Inter-organizational Modes of Cooperation and Sectoral Differences', *Strategic Management Journal*, 14(5), 371-385.
- Ichniowski, C., Shaw, K., Prennushi, G., (1997). The effects of human resource management practices on productivity: a study of steel finishing lines. *American Economic Review* 87, 291- 313.
- Kaiser, Ulrich, (2003)> Strategy complementarities between different types of ICT-expenditures. ZEW discuss paper, Center for European Economic Research.
- Kleinknecht, A. and Mohnen, P. (Eds.), (2002). Innovation and Firm Performance. *Econometric Explorations of Survey Data*. Palgrave, New York.
- Koenker, R. and K. F. Hallock (2001): "Quantile Regression," *Journal of Economic Perspectives*, 15, 143-156.
- Koenker, R. and Z. Xiao (2002): "Inference on the Quantile Regression Process," *Econometrica*, 70, 1583-1612.
- Lokshin B., Carree M., Belderbos R. (2004): Testing for Complementarity and Substitutability in Case of Multiple Practices. *METEOR memorandum RM04002*, University of Maastricht, Maastricht.
- Machado JAF, Mata J (2000) Sources of increased wage inequality. Mimeo
- Milgrom, P., Roberts, J., (1990). The economics of modern manufacturing: technology, strategy, and organization. *American Economic Review* 80, 511-528.

Miravete E., Pernias C. (2006): innovation complementarity and scale of production. *The Journal of Industrial Economics*. No.1 0022-1821(2006).

Mohnen, P., Roller, L.-H., (2002). Complementarities in innovation policy. *CEPR Discussion Paper No. 2712*. CEPR,

Dependent variable

London.North, D., 1991, Institutions, *Journal of Economic Perspectives*, 5, 97-112.

OECD , (2007) *OECD reviews of innovation policy-China*. OECD Publishing

Parisi M.L., Schiantarelli F., Sembenelli A. (2006): Productivity, Innovation and R&D: Micro Evidence for Italy. *European Economic Review*, 50, 2037-2061.

Rosenberg N. (1976), *Perspectives on Technology*, Cambridge University Press, Cambridge.

Rothwell, R (1991), "External networking and innovation in small and medium-sized manufacturing firms in Europe", *Technovation*, Vol. 11 No.2, pp.93-112.

Solow R. (1960): Investment and Technological Progress. In Arrow, K., Karlin, S., Suppes, P. (eds.): *Mathematical Methods in the Social Sciences*, Stanford University Press, Stanford, 89-104.

Topkis, D.M., 1978. Minimizing a submodular function on a lattice. *Operations Research* 26, 305–321.

Von Hippel (1988) *The Sources of Innovation*. New York: Oxford University Press.

Vives, X. (1990), Nash Equilibrium with strategic complementarities, *Journal of Mathematical Economics*, 19, 2, 205-21

World Bank (2008), *Global Economic Prospects 2008*, Technology diffusion in the developing world, the World Bank, Washington D.C., 201P.

World Bank, (2008) <http://web.worldbank.org/WBSITE/EXTERNAL/DATASTATISTICS>

Table3 Definition of variables. Currency unit: 1000 USD

PRODUCTIVITY	Total sales /Number of long term permanent workers, in logs
Explanatory Variables	
CAPITAL	Total assets of firms (including Property, Plant and Equipment)/Number of long term permanent workers, in logs
SIZE	Number of long term permanent workers
CAPACITY	Actual output produced (1000 USD)/ Maximum output that could be produced with existing machinery and equipment and regular shifts (value between 0-1)
Innovation strategy variable	
MAKE	Dummy variable equal to 1 if firms have own R&D activities and have a positive R&D budget
BUY	Dummy variable equal to 1 if firms acquire technology through at least one of the following external technology acquisition methods: hiring key personnel; licensing; trade fair/study tour
Control variables	
FOREIGN	Dummy variable equal to 1 if a firm has foreign ownership
EXPORT	Dummy variable equal to 1 if firm's sales are exported

EDUMANAGER	Dummy variable if manager have university or above education
EDUWORKER	Dummy variable if worker have university education
IT	Dummy variable if firms use internet or have own website
ASSOCIATION	Dummy variable equal to 1 for firms being member of a business association
ISO	Dummy variable equal to 1 if a firm has ISO (international certification)
FINANCE	Dummy variable with the value 1 if accessing to finance or costs of finance is a major obstacle to firm
INFRA	Lost value of sales due to power outages during last operation year, in percentage
REGULATION	The average time of managers dealing with government regulations
Low-tech dummy	Definition of industrial categories and Low-tech industries from OECD ⁹
Country dummy	Countries included in our study

Appendix A Likelihood function

$$(A.1) l_i(y_{bi}, y_{mi}) = \int_{S(y_{bi}, y_{mi})} \phi\left(\frac{\varepsilon_{bi}}{\sigma_b}, \frac{\varepsilon_{mi}}{\sigma_m}; R\right) d\frac{\varepsilon_{mi}}{\sigma_m} d\frac{\varepsilon_{bi}}{\sigma_b}$$

We normalize the standard deviations of y_{bi} and y_{mi} equal to 1, $\sigma_b = \sigma_m = 1$. Hence, the likelihood function can be written as follows

when $\delta=0$, the likelihood function will be converted into a standard bivariate normal distribution:

$$(A.2) l_i(y_{bi} = 1, y_{mi} = 1) = \int_{\frac{-\lambda_{bi}}{\sigma_b}}^{+\infty} \int_{\frac{-\lambda_{mi}}{\sigma_m}}^{+\infty} \phi_2\left(\frac{\varepsilon_{bi}}{\sigma_b}, \frac{\varepsilon_{mi}}{\sigma_m}; R\right) d\frac{\varepsilon_{mi}}{\sigma_m} d\frac{\varepsilon_{bi}}{\sigma_b}$$

$$= \Phi_2\left(\frac{\lambda_{bi}}{\sigma_b}, \frac{\lambda_{mi}}{\sigma_m}; \rho_{bm}\right)$$

$$(A.3) l_i(y_{bi} = 0, y_{mi} = 0) = \int_{\frac{\lambda_{bi}}{\sigma_b}}^{+\infty} \int_{\frac{\lambda_{mi}}{\sigma_m}}^{+\infty} \phi_2\left(\frac{\varepsilon_{bi}}{\sigma_b}, \frac{\varepsilon_{mi}}{\sigma_m}; R\right) d\frac{\varepsilon_{mi}}{\sigma_m} d\frac{\varepsilon_{bi}}{\sigma_b}$$

$$= \Phi_2\left(\frac{-\lambda_{bi}}{\sigma_b}, \frac{-\lambda_{mi}}{\sigma_m}; \rho_{bm}\right)$$

$$(A.4) l_i(y_{bi} = 1, y_{mi} = 0) = \int_{\frac{-\lambda_{bi}}{\sigma_b}}^{+\infty} \int_{\frac{\lambda_{mi}}{\sigma_m}}^{+\infty} \phi_2\left(\frac{\varepsilon_{bi}}{\sigma_b}, \frac{\varepsilon_{mi}}{\sigma_m}; R\right) d\frac{\varepsilon_{mi}}{\sigma_m} d\frac{\varepsilon_{bi}}{\sigma_b}$$

⁹ See <http://www.oecd.org>

$$= \Phi_2\left(\frac{\lambda_{bi}}{\sigma_b}, \frac{-\lambda_{mi}}{\sigma_m}; -\rho_{bm}\right)$$

$$(A.5) \quad l_i(y_{bi} = 0, y_{mi} = 1) = \int_{\frac{\lambda_{bi}}{\sigma_b}}^{+\infty} \int_{\frac{-\lambda_{mi}}{\sigma_m}}^{+\infty} \phi_2\left(\frac{\varepsilon_{bi}}{\sigma_b}, \frac{\varepsilon_{mi}}{\sigma_m}; R\right) d\frac{\varepsilon_{mi}}{\sigma_m} d\frac{\varepsilon_{bi}}{\sigma_b}$$

$$= \Phi_2\left(\frac{-\lambda_{bi}}{\sigma_b}, \frac{\lambda_{mi}}{\sigma_m}; -\rho_{bm}\right)$$

when $\delta < 0$, inequalities with astray of $D(1,0)$ and $D(0,1)$ in (8) are not binding. The probability distribution will no longer be rectangular as the case of bivariate probit distribution.

$$(A.6) \quad l_i(y_{bi} = 1, y_{mi} = 1) = \int_{\frac{-\lambda_{bi}-\delta}{\sigma_b}}^{+\infty} \int_{\frac{-\lambda_{mi}-\delta}{\sigma_m}}^{+\infty} \phi_2\left(\frac{\varepsilon_{bi}}{\sigma_b}, \frac{\varepsilon_{mi}}{\sigma_m}; R\right) d\frac{\varepsilon_{mi}}{\sigma_m} d\frac{\varepsilon_{bi}}{\sigma_b}$$

$$= \Phi_2\left(\frac{\lambda_{bi} + \delta}{\sigma_b}, \frac{\lambda_{mi} + \delta}{\sigma_m}; \rho_{bm}\right)$$

$$(A.7) \quad l_i(y_{bi} = 0, y_{mi} = 0) = \int_{\frac{\lambda_{bi}}{\sigma_b}}^{+\infty} \int_{\frac{\lambda_{mi}}{\sigma_m}}^{+\infty} \phi_2\left(\frac{\varepsilon_{bi}}{\sigma_b}, \frac{\varepsilon_{mi}}{\sigma_m}; R\right) d\frac{\varepsilon_{mi}}{\sigma_m} d\frac{\varepsilon_{bi}}{\sigma_b}$$

$$= \Phi_2\left(\frac{-\lambda_{bi}}{\sigma_b}, \frac{-\lambda_{mi}}{\sigma_m}; \rho_{bm}\right)$$

(A.8)

$$l_i(y_{bi} = 1, y_{mi} = 0) = \int_{\frac{-\lambda_{bi}}{\sigma_b}}^{+\infty} \int_{\frac{\lambda_{mi} + \delta}{\sigma_m}}^{+\infty} \phi_2\left(\frac{\varepsilon_{bi}}{\sigma_b}, \frac{\varepsilon_{mi}}{\sigma_m}; R\right) d\frac{\varepsilon_{mi}}{\sigma_m} d\frac{\varepsilon_{bi}}{\sigma_b} - \int_{\frac{-\lambda_{bi}}{\sigma_b}}^{+\infty} \int_{\frac{\lambda_{mi} - \lambda_{mi} - \varepsilon_{bi}}{\sigma_m}}^{\frac{\lambda_{bi} - \lambda_{mi} - \varepsilon_{bi}}{\sigma_m}} \phi_2\left(\frac{\varepsilon_{bi}}{\sigma_b}, \frac{\varepsilon_{mi}}{\sigma_m}; R\right) d\frac{\varepsilon_{mi}}{\sigma_m} d\frac{\varepsilon_{bi}}{\sigma_b}$$

$$= \Phi_2\left(\frac{\lambda_{bi}}{\sigma_b}, \frac{-\lambda_{mi} - \delta}{\sigma_m}; -\rho_{bm}\right) - \int_{\frac{-\lambda_{bi}}{\sigma_b}}^{+\infty} \Phi\left(\frac{\varepsilon_{bi}}{\sigma_b}\right) \left[\Phi\left(\frac{\lambda_{bi} - \lambda_{mi} - \varepsilon_{bi}}{\sigma_m}\right) - \Phi\left(\frac{-\lambda_{mi} - \delta}{\sigma_m}\right) \right] d\frac{\varepsilon_{bi}}{\sigma_b}$$

(A.9)

$$l_i(y_{bi} = 0, y_{mi} = 1) = \int_{\frac{\lambda_{bi} + \delta}{\sigma_b}}^{+\infty} \int_{\frac{-\lambda_{mi}}{\sigma_m}}^{+\infty} \phi_2\left(\frac{\varepsilon_{bi}}{\sigma_b}, \frac{\varepsilon_{mi}}{\sigma_m}; R\right) d\frac{\varepsilon_{mi}}{\sigma_m} d\frac{\varepsilon_{bi}}{\sigma_b} + \int_{\frac{-\lambda_{bi}}{\sigma_b}}^{\frac{\lambda_{bi} - \lambda_{mi} - \varepsilon_{bi}}{\sigma_m}} \int_{\frac{-\lambda_{mi}}{\sigma_m}}^{\frac{\lambda_{bi} - \lambda_{mi} - \varepsilon_{bi}}{\sigma_m}} \phi_2\left(\frac{\varepsilon_{bi}}{\sigma_b}, \frac{\varepsilon_{mi}}{\sigma_m}; R\right) d\frac{\varepsilon_{mi}}{\sigma_m} d\frac{\varepsilon_{bi}}{\sigma_b}$$

$$= \Phi_2\left(\frac{-\lambda_{bi} - \delta}{\sigma_b}, \frac{\lambda_{mi}}{\sigma_m}; -\rho_{bm}\right) - \int_{\frac{-\lambda_{bi}}{\sigma_b}}^{\frac{\lambda_{bi} - \lambda_{mi} - \varepsilon_{bi}}{\sigma_m}} \Phi\left(\frac{\varepsilon_{bi}}{\sigma_b}\right) \left[\Phi\left(\frac{\lambda_{bi} - \lambda_{mi} - \varepsilon_{bi}}{\sigma_m}\right) - \Phi\left(\frac{-\lambda_{mi}}{\sigma_m}\right) \right] d\frac{\varepsilon_{bi}}{\sigma_b}$$

when $\delta > 0$, inequalities with astray of $D(1,1)$ and $D(0,0)$ in (8) are not binding.

(A.10)

$$l_i(y_{bi} = 1, y_{mi} = 1) = \int_{\frac{-\lambda_{bi}-\delta}{\sigma_b}}^{+\infty} \int_{\frac{-\lambda_{mi}-\delta}{\sigma_m}}^{+\infty} \phi_2\left(\frac{\varepsilon_{bi}}{\sigma_b}, \frac{\varepsilon_{mi}}{\sigma_m}; R\right) d\frac{\varepsilon_{mi}}{\sigma_m} d\frac{\varepsilon_{bi}}{\sigma_b} - \int_{\frac{-\lambda_{bi}}{\sigma_b}}^{\frac{\lambda_{bi} - \lambda_{mi} - \delta - \varepsilon_{bi}}{\sigma_m}} \int_{\frac{-\lambda_{mi}}{\sigma_m}}^{\frac{\lambda_{bi} - \lambda_{mi} - \delta - \varepsilon_{bi}}{\sigma_m}} \phi_2\left(\frac{\varepsilon_{bi}}{\sigma_b}, \frac{\varepsilon_{mi}}{\sigma_m}; R\right) d\frac{\varepsilon_{mi}}{\sigma_m} d\frac{\varepsilon_{bi}}{\sigma_b}$$

$$= \Phi_2\left(\frac{\lambda_{bi} + \delta}{\sigma_b}, \frac{\lambda_{mi} + \delta}{\sigma_m}; \rho_{bm}\right) - \int_{\frac{-\lambda_{bi}}{\sigma_b}}^{\frac{\lambda_{bi} - \lambda_{mi} - \delta - \varepsilon_{bi}}{\sigma_m}} \Phi\left(\frac{\varepsilon_{bi}}{\sigma_b}\right) \left[\Phi\left(\frac{\lambda_{bi} - \lambda_{mi} - \delta - \varepsilon_{bi}}{\sigma_m}\right) - \Phi\left(\frac{-\lambda_{mi} - \delta}{\sigma_m}\right) \right] d\frac{\varepsilon_{bi}}{\sigma_b}$$

(A.11)

$$\begin{aligned}
l_i(y_{bi} = 0, y_{mi} = 0) &= \int_{\frac{\lambda_{bi}}{\sigma_b}}^{+\infty} \int_{\frac{\lambda_{mi}}{\sigma_m}}^{+\infty} \phi_2\left(\frac{\varepsilon_{bi}}{\sigma_b}, \frac{\varepsilon_{mi}}{\sigma_m}; R\right) d\frac{\varepsilon_{mi}}{\sigma_m} d\frac{\varepsilon_{bi}}{\sigma_b} + \int_{\frac{\sigma_b}{-\lambda_{bi}-\delta}}^{\frac{-\lambda_{bi}}{\sigma_b}} \int_{\frac{-\lambda_{mi}}{\sigma_m}}^{\frac{-\lambda_{bi}-\lambda_{mi}-\delta-\varepsilon_{bi}}{\sigma_m}} \phi_2\left(\frac{\varepsilon_{bi}}{\sigma_b}, \frac{\varepsilon_{mi}}{\sigma_m}; R\right) d\frac{\varepsilon_{mi}}{\sigma_m} d\frac{\varepsilon_{bi}}{\sigma_b} \\
&= \Phi_2\left(\frac{-\lambda_{bi}}{\sigma_b}, \frac{-\lambda_{mi}}{\sigma_m}; \rho_{bm}\right) - \int_{\frac{\sigma_b}{-\lambda_{bi}-\delta}}^{\frac{-\lambda_{bi}}{\sigma_b}} \Phi\left(\frac{\varepsilon_{bi}}{\sigma_b}\right) \left[\Phi\left(\frac{-\lambda_{bi}-\lambda_{mi}-\delta-\varepsilon_{bi}}{\sigma_m}\right) - \Phi\left(\frac{-\lambda_{mi}}{\sigma_m}\right)\right] d\frac{\varepsilon_{bi}}{\sigma_b}
\end{aligned}$$

$$\begin{aligned}
\text{(A.12)} \quad l_i(y_{bi} = 1, y_{mi} = 0) &= \int_{\frac{-\lambda_{bi}}{\sigma_b}}^{+\infty} \int_{\frac{\lambda_{mi}+\delta}{\sigma_m}}^{+\infty} \phi_2\left(\frac{\varepsilon_{bi}}{\sigma_b}, \frac{\varepsilon_{mi}}{\sigma_m}; R\right) d\frac{\varepsilon_{mi}}{\sigma_m} d\frac{\varepsilon_{bi}}{\sigma_b} \\
&= \Phi_2\left(\frac{\lambda_{bi}}{\sigma_b}, \frac{-\lambda_{mi}-\delta}{\sigma_m}; -\rho_{bm}\right)
\end{aligned}$$

$$\begin{aligned}
\text{(A.13)} \quad \Gamma^i(\lambda^{pi} = 0, \lambda^{mi} = 1) &= \int_{+\infty}^{\frac{\alpha^p}{\varepsilon^{pi} + \alpha^q}} \int_{+\infty}^{\frac{\alpha^m}{-\varepsilon^{mi}}} \phi^j\left(\frac{\alpha^p}{\varepsilon^{pi}}, \frac{\alpha^m}{\varepsilon^{mi}}; \mathcal{B}\right) \mathcal{Q} \frac{\alpha^m}{\varepsilon^{mi}} \mathcal{Q} \frac{\alpha^p}{\varepsilon^{pi}} \\
&= \Phi_2\left(\frac{-\lambda_{bi}-\delta}{\sigma_b}, \frac{\lambda_{mi}}{\sigma_m}; -\rho_{bm}\right)
\end{aligned}$$

Appendix B Truncated bivariate probit with upper and lower bounds and the GHK simulator

$$\text{(B.1)} \quad \begin{pmatrix} \varepsilon_1 \\ \varepsilon_2 \end{pmatrix} \sim TN(\mu, \Sigma; a, b) \equiv N(\mu, \Sigma) \text{ s.t. } a < \varepsilon < b$$

Cholesky factorization of Σ with elements

$$\begin{pmatrix} l_{11} & 0 \\ l_{21} & l_{22} \end{pmatrix}$$

Then we can derive (B.1) as:

$$\text{(B.2)} \quad \begin{cases} \frac{a_1 - \mu_1}{l_{11}} < v_1 < \frac{b_1 - \mu_1}{l_{11}} \\ \frac{a_2 - \mu_2 - l_{21}v_1}{l_{22}} < v_1 < \frac{b_2 - \mu_2 - l_{21}v_1}{l_{22}} \end{cases}$$

The above suggests that we can draw (V_1, V_2) recursively.

$$\text{(B.3)} \quad z_1 = \Phi_i\left(\frac{b_1}{l_{11}}\right) - \Phi_i\left(\frac{a_1}{l_{11}}\right)$$

$$v_1 = \Phi_i^{-1}(z_1 * u_1)$$

$$\text{(B.4)} \quad z_2 = \Phi_i^{-1}\left(\frac{b_2 - l_{21}v_1}{l_{22}}\right) - \Phi_i^{-1}\left(\frac{a_2 - l_{21}v_1}{l_{22}}\right)$$

(B.5)

$$\text{Prob}(a_1 < \varepsilon_1 < b_1) \text{Prob}(a_2 < \varepsilon_2 < b_2 \mid a_1 < \varepsilon_1 < b_1)$$

$$= \text{Prob}\left(\frac{a_{11}}{l_{11}} < v_1 < \frac{b_{11}}{l_{11}}\right) \text{Prob}\left(\frac{a_2 - l_{21}v_1}{l_{22}} < v_2 < \frac{b_2 - l_{21}v_1}{l_{22}}\right)$$

$$\text{Prob}_{GHK} = \frac{1}{D} \left[\Phi\left(\frac{b_1}{l_{11}}\right) - \Phi\left(\frac{a_1}{l_{11}}\right) \right] * \left[\Phi\left(\frac{b_2 - l_{21} * [\Phi_i^{-1}(z_1 * u_1)]}{l_{22}}\right) - \Phi\left(\frac{a_2 - l_{21} * [\Phi_i^{-1}(z_1 * u_1)]}{l_{22}}\right) \right]$$