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Do firms maintain their chosen market serving mode over time if they are confronted with dynamic processes such as uncertain productivity? What are the determinants for switching between market serving modes over time? Within a partial equilibrium model which combines the proximity-concentration trade-off with a stochastic productivity evolution, we analyze the transition dynamics between domestic market serving, exporting and FDI. We find that a stochastic productivity development generates hysteresis, and thereby confirm a general real option result. Market serving mode switching is driven by country specific competition, irreversible fixed costs, productivity growth and volatility. Higher fixed costs and volatility increase the likeliness of serving mode continuity whereas a higher degree of competition and productivity growth raise the probability of serving mode switching.

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Key Words: Export, FDI, Market Serving Strategy, Real Option

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1. Motivation

The importance of Foreign Direct Investment (FDI) and International Trade has risen over the last two decades (Worldbank 2008). Domestic companies have steadily increased their exports to foreign markets and expanded their foreign plant shares as a means of foreign market access (UNCTAD 2008). These developments have led to an increased research effort in understanding firm behavior on international markets (see Greenaway and Kneller (2007) for a recent survey). Since the seminal work of Melitz (2003) on export behavior and industry dynamics, the triad of productivity, economies of scale, and selection are considered to be the major forces behind international enterprise behavior.

Accounting for firm heterogeneity, Melitz's New New Trade Theory (2003) lays the basis to explain firms' sorting into exporter status. Helpman et al. (2004) introduce FDI into this framework where in equilibrium the most productive firms tend to serve foreign markets via FDI, less productive firms become exporters, and low-productivity firms tend to restrict their activity to the domestic market. This sorting finds vast empirical support, see for example Baldwin and Gu (2003), Helpman (2006), Wagner (2006) or Mayer and Ottaviano (2007), Oberhofer and Pfaffermayr (2008). The resulting sorting pattern in these models is rooted in the cost structure: The export activity brings about higher variable costs due to transportation and relatively low fixed costs of market entry. Differently, firms which serve the foreign market as a foreign direct investor commonly face lower variable costs, but considerably higher fixed costs arising from the replication of production facilities abroad or information cost on the institutional environment. This cost structure depicts the proximity-concentration trade-off as introduced by Brainard (1993). Helpman et al. (2004) derive in their setting a final firm distribution within an industry by combining the proximity-concentration trade-off framework with firm productivity heterogeneity.

Here, a one time lottery draw assigns the level of productivity to the firm. This framework suffices for the objective to explain the different types of foreign market serving modes in equilibrium. But it turns out to be insufficient for transition analysis.

In light of the stylized fact that productivity evolves stochastically over time, how does this dynamic risky evolution of firm productivity influence a company's market serving mode over time? Our focus is on switches between domestic activity, export or FDI. Both, market entry and serving mode switching are associated with specific fixed costs. The static general equilibrium model of Helpman et al. (2004) cannot be easily extended into a dynamic framework. According to our best knowledge, there is no theoretical model which accounts for the described foreign market serving mode switching. We present a partial equilibrium model which combines the proximity-concentration trade-off framework with continuous productivity uncertainty. In order to derive serving mode transitions driven by productivity uncertainty, we model productivity as a Geometric Brownian motion. We are able to solve the arising analytical complexity by reducing the analysis to a single firm perspective following the seminal real option theory of Dixit (1989) which is an appropriate framework to model switching behavior under uncertainty, as it combines sunk costs with a stochastic state variable. Due to the high degree of nonlinearity of the resulting equilibrium functions we apply numerical methods.

Thus, our paper complements the existent literature: We provide a theoretical model of dynamics and transitions between domestic, export and FDI. Within our model, we introduce continuous uncertainty in a firm's productivity path and trace the determinants of serving mode switching. The model predicts that a high productivity growth rate fosters market entry via FDI or a switching strategy. Sunk cost of entry or of switching can be recouped faster due to an increase in productivity. Similarly, ceteris paribus, a highly volatile productivity development encourages market entry via FDI. However, if the initial cost constellation is such that market entry takes

Firms Entering	Domestic & Export Market (Simultaneously)	Export Market	Total
1 Time	366	123	489
2 Times	45	107	152
3 Times	2	10	12
Firms Exiting			
1 Time	526	100	626
2 Times	74	160	234
3 Times	5	19	24
Permanent Domestic:			20
Permanent Exporter:			361

Table 1: Market Entry and Exit Patterns of Danish Firms, 1995 - 2003
This table depicts export market entries and exits for Danish firms between 1995 and 2003. The sample comprises the 5000 largest Danish firms by net revenue. Data Source: Denmark Statistics.

place via exporting, a volatile productivity path encourages switching from exporting to FDI.

The remainder of the paper is structured as follows: Section 2 presents stylized facts on export dynamics and productivity for a sample of Danish firms. Section 3 introduces the model. Section 4 presents the numerical results, and section 5 concludes.

2. Stylized Facts

Based on a sample of the 5000 largest Danish firms by net revenues, provided by Statistic Denmark, table 1 presents the market entry and exit pattern of 1406 manufacturing firms into and out of export markets within the period from 1995 till 2003.[1] During the considered 8 years, 489 companies started to export and 123 of these exporters existed already as domestic companies whereas 366 firms were born as exporting enterprises.

Most importantly, table 1 conveys a clear message about the switching extensity of Danish firms. During the considered time, only 20 enterprises permanently served the domestic market without any interruption in their serving mode. The remaining 1386 manufacturing firms in the sample

[1] A firm is identified as an exporter if it exhibits positive export revenues higher than 1,000,000 DKK.

have been involved into international trade whereas 361 companies permanently continued to export within the considered time span. Other companies were born within these years immediately as exporters or started after entering the domestic market to serve a foreign destination. The number of firms which entered the export market two times amounts to 152 and implicitly these firms have exited the foreign market at least once. Differently stated, about 25% of the considered exporting Danish enterprises interrupted their market serving mode within 8 years at least one time. The observed maximum amount of market entry into new foreign markets amounts to 3 times and applies to 12 companies. Similar patterns of serving mode interruptions can be observed in the exit behavior of Danish firms whereupon the total number of exits outnumbers the intensity of market entries: Denmark experienced a reduction in the number of firms between 1995 and 2003.

In a nutshell, first of all, firm market entry and exit are highly dynamic. Secondly, there are firms which exhibit a low rate of serving mode switching, whereas others are highly agile in their entry and exit behavior.[2]

Therefore, a crucial question which arises from these facts and which is not considered within the related literature is: What distinguishes firms with a low rate of market serving mode switching from companies which exhibit a high number of interruptions in their serving mode over time? Theoretically and empirically, firm productivity stands out as the driving force for a firm's serving mode selection (Melitz, 2003; Wagner, 2008). Figure 1 depicts four productivity paths for four Danish manufacturing sectors. These paths differ crucially in their growth rate and their volatility. Productivity growth is relatively large for transport equipment and the construction sectors as

[2] So far it is not possible to assess horizontal foreign direct investment involvement due to data limitations.

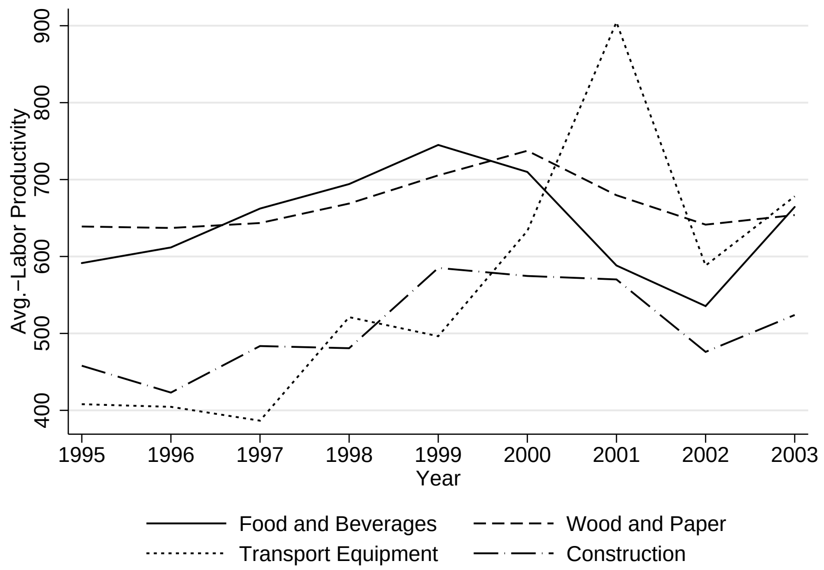


Figure 1: The Evolution of Productivity for Different Sectors
This figure presents the evolution of average firm productivity (value added over number of employees) for four different subsectors within the manufacturing sector for Danish firms. Source: Denmark Statistics.

compared to the food and beverages sector as well as wood and paper sector. On the other hand, the latter two sectors exhibit a lower volatility in their productivity paths if compared to the transportation sector. Thus, even on the sectoral level, productivity growth and volatility exhibit considerable heterogeneity.[3]

Generally spoken, productivity turns out to grow over time, whereas its growth path contains a certain degree of risk, as it deviates above its average to the bottom or to the top over time. Furthermore, there exist firms with different types of productivity evolution over time. How does this heterogeneity in productivity paths affect a company's serving mode over time?

3. The Model

Consider an investor who is initially serving only the domestic market. Confronted with an uncertain productivity evolution he may increase his sales by serving new foreign markets either

[3] Note that for data protection policies, we are not allowed to extract firm specific productivity paths.

through exports or FDI.[4] As productivity develops stochastically the investor faces a choice between three alternatives: He can either postpone his market entry decision and observe the productivity development, serve the new market through exports or through a foreign plant (FDI). Subsequently, the investor will again decide whether to remain in the chosen serving mode, switch to the alternative mode or exit the foreign market.

We define the switching between market serving modes or exiting the market as serving mode discontinuity. Here, we distinguish two different types of discontinuity in a firm's serving state over time: In the *type I* discontinuity, a firm switches from its market serving mode to inactivity on the foreign market. The *type II* discontinuity covers cases where the firm switches between the two market serving modes.[5]

Whether type I or type II discontinuity occurs, hinges on the size of switching costs, the size of export and FDI market entry costs, transport costs associated with exporting as well as on their relative sizes. First, if switching costs are at a prohibitively high level, no type II discontinuity ever arises. A firm either serves the foreign market via FDI or exporting - depending on whether the variable cost advantage of FDI outweighs the fixed cost disadvantage or not (Brainard, 1993). Whether the market serving mode is continous or discontinuous, i.e., whether a type I discontinuity occurs in a situation, where switching between modes is not attractive, hinges crucially on the absolute level of fixed costs - given a stochastic productivity evolution over time. The mechanism which drives a type I discontinuity is the same for exporting and for FDI.

In the remainder of this section, we first introduce foreign demand and a representative firm's optimization problem. Subsequently, we discuss type I and type II discontinuity.

[4] We call the decision maker investor or firm without distinguishing between the two terms.

[5] Appendix A.1 provides an overview of possible cost constellations associated with specific serving mode switching.

3.1. Demand

Consider a risk-neutral investor who intends to serve a new foreign market with his product brand X_i under monopolistic competition. The new destination market can be served either through exporting or a new foreign plant (horizontal FDI). By comparing the investment values of these two market entry modes the investor decides on whether to enter the market directly through FDI or by exporting. Preferences of the representative consumer in the destination country are given by

$$U_t(Q_t, Y_t) = Q_t^{\gamma} Y_t^{1-\gamma} \tag{1}$$
$$\text{with} \quad Q_t = \left(\sum_{i=1}^{n_t} X_{i_t}^{\rho} \right)^{\frac{1}{\rho}}, \quad 0 < \rho < 1, \quad 0 < \gamma < 1,$$

where ρ is the degree of substitutability across differentiated goods, and Y is a freely-traded homogeneous good that is produced in all countries. The income share spent on heterogeneous goods is denoted by γ. Such preferences imply the following demand function for variety i,

$$X_{i_t} = \frac{p_{i_t}^{-\eta}}{P_t^{-\eta}} \cdot \frac{\gamma \xi_t}{P_t}, \tag{2}$$
$$\text{with} \quad \eta = \frac{1}{1-\rho}, \quad P_t = \left(\sum_{j_t}^{n_t} p_{j_t}^{1-\eta} \right)^{\frac{1}{1-\eta}},$$

where ξ_t is the destination country's gross national expenditure, P_t the price index and p_{it} the price of variety i at time t. The investor assumes that the expenditure share spent on good Q and the price index P do not change over time. Consequently, equation (2) represents the investor's perceived demand function which can be summarized to

$$p_t = ZX_t^{-\frac{1}{\eta}} \tag{3}$$
$$\text{with} \quad Z = P^{\frac{\eta-1}{\eta}} (\gamma\xi)^{\frac{1}{\eta}},$$

where the subscript i is omitted, as the considered firm exports only one brand. Due to the fact that the investor is the only producer of brand i, he possesses market power which depends on the destination country's elasticity of substitution. Therefore, he will charge a price $p = w_h \frac{Z}{\nu}$, where ν is the inverse mark-up of price over marginal costs and w_h the wage rate in the home market. The wage is determined in the homogeneous-good industry. Technology in the destination country is less productive and therefore, wages w_d are lower.[6] By reformulating the demand function as

$$p = ZX^{\nu-1}, \tag{4}$$

it is possible to model the extent of market power. For ν close to 1 the market power is low since substitutability between the varieties is high ($\rho \rightarrow 1$). On the other hand for ν close to zero the investor possesses market power since the demand function becomes less elastic.

3.2. Production and a Firm's Optimization

On the technology side production is described by

$$X_t(L_t) = \vartheta_t L_t^{\theta} \tag{5}$$
$$\text{with} \quad 0 < \theta < 1 \quad \text{and} \quad \vartheta_t > 0,$$

[6] In the subsequent simulation we assume $w_d = w_h$ but still maintain higher variable costs in the export mode due to transport costs $\tau > 1$. The introduction of lower variable costs in the FDI mode amplifies the derived effects but does not act as a countervailing force.

where labor L_t is the only periodically used input and ϑ_t the firm embedded productivity level. Exporting is associated with – at least partly – irreversible fixed costs I_E^N , due to a new distribution and service-network. Besides the infrastructure costs, FDI requires a new plant and therefore its fixed costs I_F^N are strictly higher compared to exporting. In serving the destination market through exports the firm faces iceberg transport costs $\tau > 1$ which are avoided in the FDI mode. Given these cost structures the investor is confronted with a proximity-concentration trade-off where he experiences a comparative variable cost advantage in the export strategy and a comparative fixed cost advantage in the FDI mode with

$$\frac{I_E^N}{I_F^N} < 1 \quad \text{and} \quad \frac{w_d}{w_h \tau^{\frac{1}{\theta}}} < 1. \tag{6}$$

Based on the following maximization problem

$$\Pi_E = \max_L \, p \; X_E - L w_h \quad \text{s.t.} \quad X_E = \frac{X_{DE}}{\tau} \quad \text{s.t.} \quad X_{DE} = \vartheta L^{\theta} \quad \text{s.t.} \quad p = Z X_E{}^{(\nu-1)}, \tag{7}$$

with X_{DE} as the domestic output produced for the destination country, periodical export cash-flows result as

$$\Pi_E(\vartheta) = M_E \vartheta_E^{\kappa} \tag{8}$$
$$\text{with} \quad M_E = Z^{\frac{1}{1-\nu\theta}} \left(\frac{\nu\theta}{w_h \tau^{\frac{1}{\theta}}} \right)^{\frac{\nu\theta}{1-\nu\theta}} (1-\nu\theta) \quad \text{and} \quad \kappa = \frac{\nu}{1-\nu\theta}.$$

Respectively, cash-flows in the FDI mode with $\tau = 1$ result as

$$\Pi_F(\vartheta) = M_F \vartheta^{\kappa} \tag{9}$$

$$\text{with} \quad M_F = Z^{\frac{1}{1-\nu\theta}} \left(\frac{\nu\theta}{w_d}\right)^{\frac{\nu\theta}{1-\nu\theta}} (1-\nu\theta) \quad \text{and} \quad \kappa = \frac{\nu}{1-\nu\theta}.$$

With reference to recent trade models (Helpman et al. 2004; Yeaple, 2008) in the remainder we assume $\kappa \geq 1$. Periodical profits increase linearly or convexly in ϑ. Furthermore, firm embedded productivity ϑ evolves exogenously over time as a stochastic process. Specifically, we assume a Geometric Brownian motion with

$$d\vartheta_t = \alpha \vartheta_t dt + \sigma \vartheta_t dz_t, \tag{10}$$

where dz_t is an increment of the standard Wiener Process satisfying $\mathbb{E}(dz) = 0$ and $\mathbb{E}(dz^2) = dt$. The annual growth rate is given by α. The instantaneous volatility is denoted by σ. Both parameters are assumed to be time and state invariant. In $t = 0$ a firm observes its current productivity level ϑ_0 and the random productivity in t is then ϑ_t. The solution of the previous stochastic differential equation can be written as

$$\vartheta_t = \vartheta_0 \; e^{\int_0^T (\alpha - \frac{1}{2}\sigma^2)dt + \int_0^T \sigma dz_t}. \tag{11}$$

Since $\ln \vartheta_t$ is normally distributed with

$$N \sim \left(\ln \vartheta_0 + (\alpha - \frac{1}{2}\sigma^2)t, \sigma^2 t \right), \tag{12}$$

the expected periodical profit growth results as

$$\mathbb{E}\left(\frac{M_i\vartheta_t}{M_i\vartheta_0}\right) = \exp(\alpha') \quad \text{with} \quad \alpha' = \alpha\kappa + \frac{1}{2}\kappa\sigma^2(\kappa - 1) \quad \text{and} \quad i \in \{E, F\} \tag{13}$$

where α' is the trend rate of productivity growth which is adjusted for $\kappa > 1$.[7] For linear periodical profits ($\kappa = 1$) annual growth turns out to be equal to α. With reference to the capital asset pricing model (Sharpe, 1964), μ represents the appropriate return for an asset associated with the same risk pattern as represented by the Geometric Brownian motion (10). Therefore, in equilibrium the difference between the appropriate return μ and the growth rate α represents a firm's opportunity costs $\delta = \mu - \alpha$. Accounting for $\kappa > 1$ the adjusted discount rate becomes

$$\delta' = r - (r - \delta)\kappa - \frac{1}{2}\kappa(\kappa - 1)\sigma^2. \tag{14}$$

Within a Marshallian investment choice problem an investor compares the expected gross firm values $V_i(\vartheta)$ of the two entry modes with their respective entry fixed costs

$$V_i(\vartheta) - I_i^N = \int_0^\infty M_i\vartheta^\kappa e^{\alpha' t}e^{-\mu' t}dt - I_i^N \tag{15}$$

$$V_i(\vartheta) - I_i^N = \frac{M_i\vartheta^\kappa}{r - (r - \delta)\kappa - \frac{1}{2}\kappa(\kappa - 1)\sigma^2} - I_i^N \tag{16}$$

$$\text{with} \quad \vartheta = \vartheta_0 \quad \text{and} \quad i \in \{E, F\}$$

and chooses the entry strategy with the highest net investment value. However, such an approach neglects influential aspects. Given at least partly irreversible fixed costs and the possibility of postponing the investment, each investment strategy is associated with an option value which

[7] Appendix A.2 presents the derivation of α'.

needs to be accounted for. Additionally, besides the entry fixed costs I_i^N there exist furthermore by assumption abandonment benefits I_i^A which are taken into account before entering the market and which generate an option value enforcing to stay longer only in the domestic market or in the export market. We impose that $I_i^N > I_i^A$. Therefore, an appropriate framework derives the value function of all possible states, staying permanently domestic, being an exporter or foreign direct investor in a more complex way.[8] Due to numerical and analytical restrictions, in the remainder we present partial equilibrium results for relevant scenarios.

3.3. Switching between Domestic and Foreign Market

Consider first a situation where a domestic firm intends to serve a foreign market. Given the possibility to switch between the inactivity and foreign market serving, there are two state variables, productivity and the serving state. We denote the option value of the domestic firm as $V_D(\vartheta)$. Its value arises from potential future returns associated with selling abroad. Sales on the domestic market are normalized to 0. The value of a firm, which serves the foreign market is then denoted by $V_i(\vartheta)$ and includes perpetual cash-flows and an option of exiting the foreign market if productivity decreases too far. The subscript i captures the two alternative serving modes, namely exporting and FDI, such that $i \in (E, F)$. Generally, the investor will stay only in the domestic market if productivity stays between $(0, \vartheta_{hi})$ and keep on staying in the export state if productivity lies in between $(\vartheta_{li}, \vartheta_{hi})$. The market entry and exit cut-offs do not coincide. This phenomenon is depicted in figure 2 and represents a standard real option result: Due to sunk costs associated with a foreign market activity, the firm does not exit from the market as soon as its productivity level falls below the entry threshold, but remains in its current state.

[8] A formulation of all possible serving mode strategies within a single analytical framework results in a non-linear equation system which does not converge. Therefore, we split the optimization problems in subsets in order to present a partial equilibrium result.

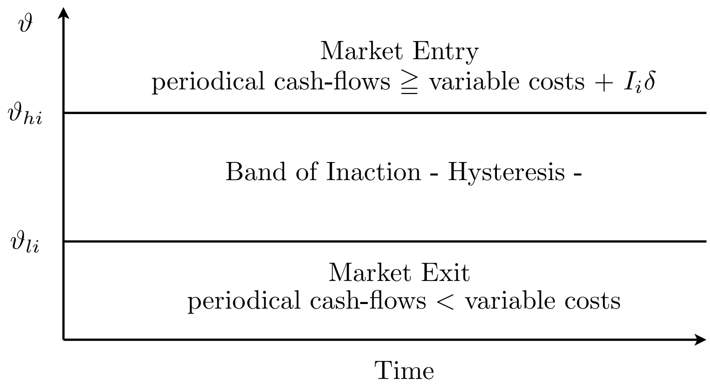


Figure 2: Hysteresis

The existence of these two critical productivity cut-offs which determine a firm's market entry and exit decision can be explained by the distinctive relevance of the accruing types of costs. According to the Marshallian investment rule an investor enters a new market if the periodical cash-flows cover both, periodical variable costs and annualized fixed costs:

$$\text{periodical cash-flows} = \text{variable costs} \; + \; I_i\delta. \tag{17}$$

As a consequence the market entry cut-off ϑ_{hi} is determined by both types of costs. On the other hand if the initial fixed costs are at least partly sunk, an investor will not exit a market if the state variable falls below the entry cut-off, since the fixed costs are sunk anyway. Due to the possibility of a future recovery of the state variable, in particular if it is assumed to develop stochastically, the exit cut-off ϑ_{li} will be therefore always lower than the entry cut-off. Implicitly, an investor is confronted with a band of inaction which lies in between these two cut-offs. This inaction is known as hysteresis and generally defined as "the failure of an effect to reverse itself as its underlying cause is reversed" (Dixit, 1989). Within the subsequent analysis, any market serving mode strategy will be influenced by the extent of this band of inaction, i.e., the range between the entry and the exit cut-off.

The derivation of critical productivity cut-offs and the value functions is achieved by applying the asset spanning method (Dixit 1994). The common differential equation for the option value $V_D(\vartheta)$ results by constructing a portfolio which contains one unit of the option to invest, and a short position of $n = \frac{\partial V_D(\vartheta)}{\partial \vartheta}$ units of output:[9]

$$\frac{1}{2}\sigma^2\vartheta^2 V_D''(\vartheta) + (r-\delta)\vartheta V_D'(\vartheta) - rV_D(\vartheta) = 0 \tag{18}$$
$$\text{with} \quad V_D''(\vartheta) = \frac{\partial^2 V_D(\vartheta)}{\partial \vartheta^2} \quad \text{and} \quad V_D'(\vartheta) = \frac{\partial V_D(\vartheta)}{\partial \vartheta}.$$

The general solution to this equation is

$$V_D(\vartheta) = A_{1i}\vartheta^{\beta_1} + A_{2i}\vartheta^{\beta_2}. \tag{19}$$

A_{1i}, A_{2i} are constants which remain to be determined, whereas β_1 and β_2 are roots of the quadratic equation under risk neutral valuation, such that[10]

$$\beta_1 = \frac{1}{2} - (r-\delta)/\sigma^2 + \sqrt{\left((r-\delta)/\sigma^2 - \frac{1}{2}\right)^2 + 2r/\sigma^2} > 1, \tag{20}$$
$$\beta_2 = \frac{1}{2} - (r-\delta)/\sigma^2 - \sqrt{\left((r-\delta)/\sigma^2 - \frac{1}{2}\right)^2 + 2r/\sigma^2} < 0. \tag{21}$$

If productivity approaches zero, the option value of market entry approaches zero. For this reason, the coefficient A_{2i} in equation (19) is equal to zero and the value of the domestic firm follows as

$$V_D = A_{1i}\vartheta^{\beta_1} \quad \forall \quad \vartheta \in (0, \vartheta_{hi}), \tag{22}$$

[9] We use Ito's lemma with $dV_D(\vartheta) = \frac{\partial V_D(\vartheta)}{\partial \vartheta} d\vartheta + \frac{1}{2}\frac{\partial^2 V_D(\vartheta)}{\partial \vartheta^2}(dx)^2$.
[10] Appendix A.3 presents the derivation of these solutions.

where ϑ_{hi} denotes the critical productivity level at which the firm switches from purely domestic activity to foreign market entry.

The value of the firm which serves the foreign market, V_i, consists of two components, namely the cash flows, $\frac{M_i \vartheta^\kappa}{\delta'}$, as derived earlier and the option value to abandon the foreign market if productivity falls too far. Thus, the value of the active firm has to suffice the differential equation

$$\frac{1}{2}\sigma^2\vartheta^2 V_i''(\vartheta) + (r-\delta)\vartheta V_i'(\vartheta) - rV_i(\vartheta) + \frac{M_i \vartheta^\kappa}{\delta'} = 0, \tag{23}$$

with the general solution

$$V_i = B_{1i}\vartheta^{\beta_1} + B_{2i}\vartheta^{\beta_2} + \frac{M_i \vartheta^\kappa}{\delta'}. \tag{24}$$

If productivity rises very strong, the option to abandon the market is far out of the money, and thus tends to zero if $\vartheta \to \infty$. Therefore, the coefficient B_{1i} has to be equal to zero, and the value of the firm results as

$$V_i = B_{2i}\vartheta^{\beta_2} + \frac{M_i \vartheta^\kappa}{\delta'} \quad \forall \quad \vartheta \in (\vartheta_{li}, \infty), \tag{25}$$

where ϑ_{li} is the critical productivity level at which an exporter stops his exporting activity.

In order to determine the market entry and exit cut-off productivity levels, ϑ_{hi} and ϑ_{li}, along with the coefficients A_{1i} and B_{2i}, we consider the value matching conditions: At the threshold ϑ_{hi}, a purely domestic firm will start to serve the foreign market and pay the fixed costs I_i^N if

$$V_D(\vartheta_{hi}) = V_i(\vartheta_{hi}) - I_i^N. \tag{26}$$

Smooth pasting requires that

$$V_D'(\vartheta_{hi}) = V_i'(\vartheta_{hi}). \tag{27}$$

An exporting firm will drop its activity and withdraw to serving solely the domestic market at the threshold ϑ_{li} if the following value-matching and smooth-pasting conditions are fulfilled:

$$\begin{aligned} V_i(\vartheta_{li}) &= V_D(\vartheta_{li}) - I_i^A && (28) \\ V_i'(\vartheta_{li}) &= V_D'(\vartheta_{li}). && (29) \end{aligned}$$

Thus, by plugging in the state-dependent firm values as given in equations (22) and (25) into equations (26) to (29), we obtain a system of four equations in four unknowns, which is highly non-linear and can be solved numerically for the productivity cut-off values, at which a firm either enters or exits the export market:

$$\begin{aligned} \frac{M_i \vartheta_{hi}^{\kappa}}{\delta'} + B_{2i}\vartheta_{hi}^{\beta_2} - A_{1i}\vartheta_{hi}^{\beta_1} &= I_i^N && (30) \\ \frac{\kappa M_i \vartheta_{hi}^{\kappa-1}}{\delta'} + \beta_2 B_{2i}\vartheta_{hi}^{\beta_2-1} - \beta_1 A_{1i}\vartheta_{hi}^{\beta_1-1} &= 0 && (31) \\ \frac{M_i \vartheta_{li}^{\kappa}}{\delta'} + B_{2i}\vartheta_{li}^{\beta_2} - A_{1i}\vartheta_{li}^{\beta_1} &= -I_i^A && (32) \\ \frac{\kappa M_i \vartheta_{li}^{\kappa-1}}{\delta'} + \beta_2 B_{2i}\vartheta_{li}^{\beta_2-1} - \beta_1 A_{1i}\vartheta_{li}^{\beta_1-1} &= 0 && (33) \end{aligned}$$

This system allows us to solve numerically for the cut-off productivity levels of type I discontinuity: For $i = E$ ($i = F$), we obtain the productivity thresholds for market entry and exit of an exporter (FDI firm).

3.4. Switching between Export and FDI

Once an investor has decided to enter the foreign market as an exporter, he might experience a strong increase in productivity. In such a case, there exists a critical productivity level above which exporting is no longer the preferable market serving mode. Instead, at this critical productivity level ϑ_S, the firm is willing to sink additional serving mode switching costs I_S in order to serve the foreign market via FDI. In this case, the value of an exporting firm V_E comprises not only the export cash-flows, but also the option value of the described serving mode discontinuity, with

$$V_E = \frac{M_E \vartheta^{\kappa}}{\delta'} + C_1 \vartheta^{\beta_1} \quad \forall \quad \vartheta \in (0, \vartheta_S). \tag{34}$$

Ruling out foreign market exit and switching back from FDI to exporting, the value of a firm which is in FDI mode is given by[11]

$$V_F = \frac{M_F \vartheta^{\kappa}}{\delta'} \quad \forall \quad \vartheta \in (\vartheta_S, \infty). \tag{35}$$

Thus, the productivity cut-off ϑ_S at which an exporting firm switches its market serving mode can be determined from the value matching and smooth pasting condition

$$V_E(\vartheta_S) = V_F(\vartheta_S) - I_S \tag{36}$$

$$V'_E(\vartheta_S) = V'_F(\vartheta_S). \tag{37}$$

[11] A switch from FDI to export is considered to be irrelevant if additional sunk switching costs arise. Since the FDI mode's variable costs are the lowest achievable ones, there is no rational behind paying irreversible switching costs in order to pay higher variable costs.

Plugging in firm values as represented in equations (34) and (35) yields

$$\frac{M_E\vartheta_S^\kappa}{\delta'} + C_1\vartheta_S^{\beta_1} - \frac{M_F\vartheta_S^\kappa}{\delta'} = -I_S \tag{38}$$

$$\frac{\kappa M_E\vartheta_S^{\kappa-1}}{\delta'} + \beta_1 C_1\vartheta_S^{\beta_1-1} - \frac{\kappa M_F\vartheta_S^{\kappa-1}}{\delta'} = 0. \tag{39}$$

From this system of equations, we determine numerically the productivity threshold at which an exporting firm stops exporting and serves the market as a foreign direct investor.

4. Numerical Results

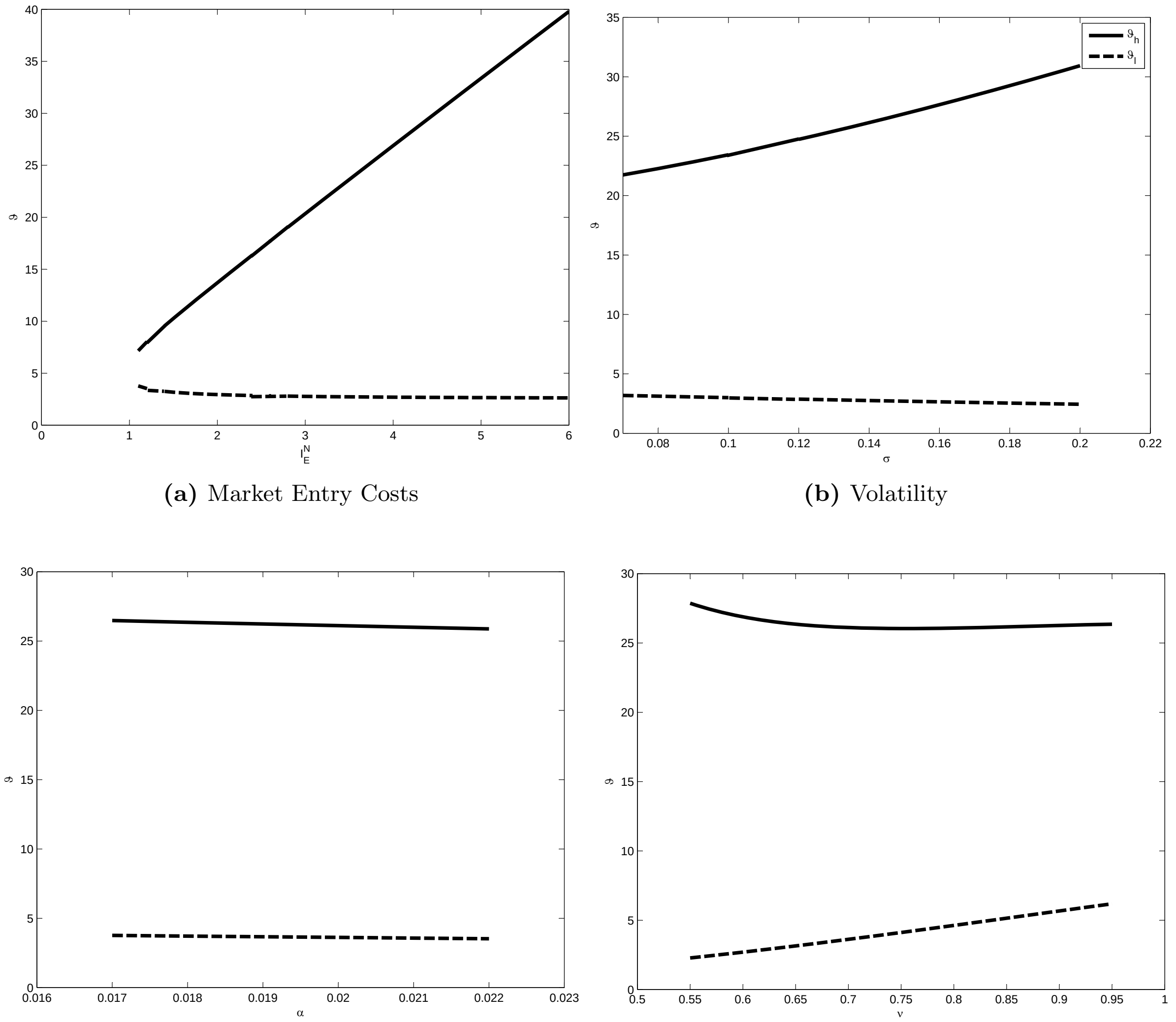
Given the stochastic motion of firm productivity, the prevalence of serving mode discontinuities hinges on the extent of hysteresis, as depicted in figure 2. The further apart the critical level of productivity which triggers market entry is from the one which triggers market exit, the less likely it is that the firm reverts its initial choice. Importantly, our conclusions rule out to determine critical parameter values for fixed entry costs, competition, growth or volatility which distinguish a discontinuous from a continuous market serving behavior. Instead, we constrain our analysis to ceteris paribus considerations, thereby tracing the directional effect of fixed entry costs, competition, growth or volatility on the propensity to switch.

The resulting subsequent figures from numerical simulations can be interpreted in two different manners. Taking the single firm perspective the presented parameter ranges can be interpreted as a) comparative statics in order to derive a firm's possible serving mode adjustments. On the other hand, the range of defined parameter values can be interpreted as b) heterogeneity in fixed costs, productivity volatility and growth rates e.g. for different firms. In the same manner competition heterogeneity in ν can be considered to capture country specific market characteristics. In the remainder we allow for both perspectives.

A serving mode discontinuity which includes all considered switches (Domestic → Export → FDI) necessarily starts with a scenario in which an investor serves a new foreign market through exports with a subsequent switch into FDI. Still, an investor initially chooses between serving a new market through exports or FDI. Therefore, we first present the results on type I discontinuities for both export and FDI specific cost structures. Notably, there are no qualitative differences between export and FDI type I discontinuities. Subsequently, we demonstrate under which conditions an exporter would switch to the FDI serving mode.

Consider a firm for which FDI is never an interesting market serving mode, because the transport costs (and therefore the variable costs) are very low, such that for a given productivity process, the variable cost advantage of exporting always outweighs the fixed cost disadvantage of the FDI mode. Under this assumption, for $I_F^N > I_E^N$, the firm would serve the foreign market as an exporter only. Whether the market serving is continuous or whether the firm switches in and out of the market depends on the level of the market entry cost, the growth rate and instantaneous volatility of productivity, as well as on the degree of competition on the foreign market.

Figure 3 depicts the productivity band of inaction for exporting. The entry (exit) cut-off levels are drawn as a solid (dashed) line. As panel a) shows, the critical productivity level of market entry ϑ_h increases in the fixed costs of market entry, whereas the market exit threshold ϑ_l stays at a similar level for the range of market entry costs. This implies that the region of hysteresis, i.e., the range between the cut-off values, increases in I_E^N. Firms which exhibit high fixed costs of exporting, are less likely to serve the export market discontinuously (still under the assumption that FDI is not an attractive alternative). In the underlying parametrical example, once the market is entered e.g. at fixed costs of $I_E^N = 5$, productivity has to fall dramatically below the initial entry cut-off in order to generate serving mode discontinuity ($\vartheta_l = 4 < \vartheta_h = 31$). The fixed cost insensibility



(a) Market Entry Costs

(b) Volatility

(c) Growth

(d) Competition

Figure 3: Export Discontinuity

This table depicts the export entry and exit cut-offs. Parameters are set to $\theta = 0.7$, $\tau = 20$, $r = 0.06$, $I_E^A = -1$, $\sigma = 0.15$, $\alpha = 0.02$, $\nu = 0.6$, $I_E^N = 4$ if not considered in the respective panel.

of the lower bound in the underlying example depends on the abandonment benefits which are at $I_E^A = -1$. In other words, one unit of the initial fixed costs can be liquidated on the foreign market (e.g. selling export specific firm entities). The lower the abandonment benefits turn out to be, the stronger does the exit threshold decrease if the entry fixed costs increase. Referring to the stylized facts from Denmark, one reason for the different extent of type I discontinuity can be found in the size of initial entry fixed costs and also in the degree of abandonment benefits.

Result 1:

The likeliness of type I discontinuity decreases in I_E^N*. The range of inaction increases further the lower the abandonment benefits* I_E^A *turn out to be. The lesser fixed costs* I_E^N *are sunk, the narrower becomes the range of hysteresis, with* $I_E^N = I_E^A \Rightarrow \vartheta_{lE} \rightarrow \vartheta_{hE}$*.*

Panel c) depicts the variation of productivity growth and its impact on the critical thresholds. Accordingly, firms with higher growth rates enter the foreign market at a relatively lower level of productivity. Simultaneously, they tolerate a fall in productivity up to a relatively lower level: Ceteris paribus, higher productivity growth will allow a firm to cover the same fixed cost starting at a lower productivity level, which explains the lower entry cut-off ϑ_{hE}. On the other hand, once in the market, the investor can bear a stronger inverse productivity development since in the medium term he can expect a deterministic positive growth. Still, different growth rates α affect the range of inactivity only mildly. Therefore, one can conclude that a heterogeneity in productivity growth in the export mode is not as strong an explanation for different extents of switching patterns over time compared to increasing fixed entry costs.

The level of productivity volatility affects the market entry and exit cut-offs more pronouncedly. The higher the productivity volatility, the higher becomes the entry cut-off ϑ_{hE}. Simultaneously, the exit threshold decreases. A firm which faces high productivity uncertainty tends to postpone the investment decision in order to gather further information on productivity development. This postponement is expressed in higher entry thresholds. Once in the market, higher volatility offers the chance to reverse an unfavorable productivity development and therefore an investor tolerates a stronger drop in productivity, which again explains the lower exit cut-offs. Similar to the fixed costs, the range of inactivity increases dramatically in σ. Firms with high productivity volatility countervail the prevailing risk by entering a market at high productivity levels. Implicitly, these firms enter markets after a longer postponement period. However, once in the market, a type I serving mode discontinuity becomes less likely, as a certain extent of uncertainty is reflected in the higher entry cut-off. Referring to the Danish evidence, the extent of type I discontinuity in the wood and paper industry should not differ dramatically between different firms due to a low productivity uncertainty, as long as the firms exhibit similar fixed costs.

Result 2:

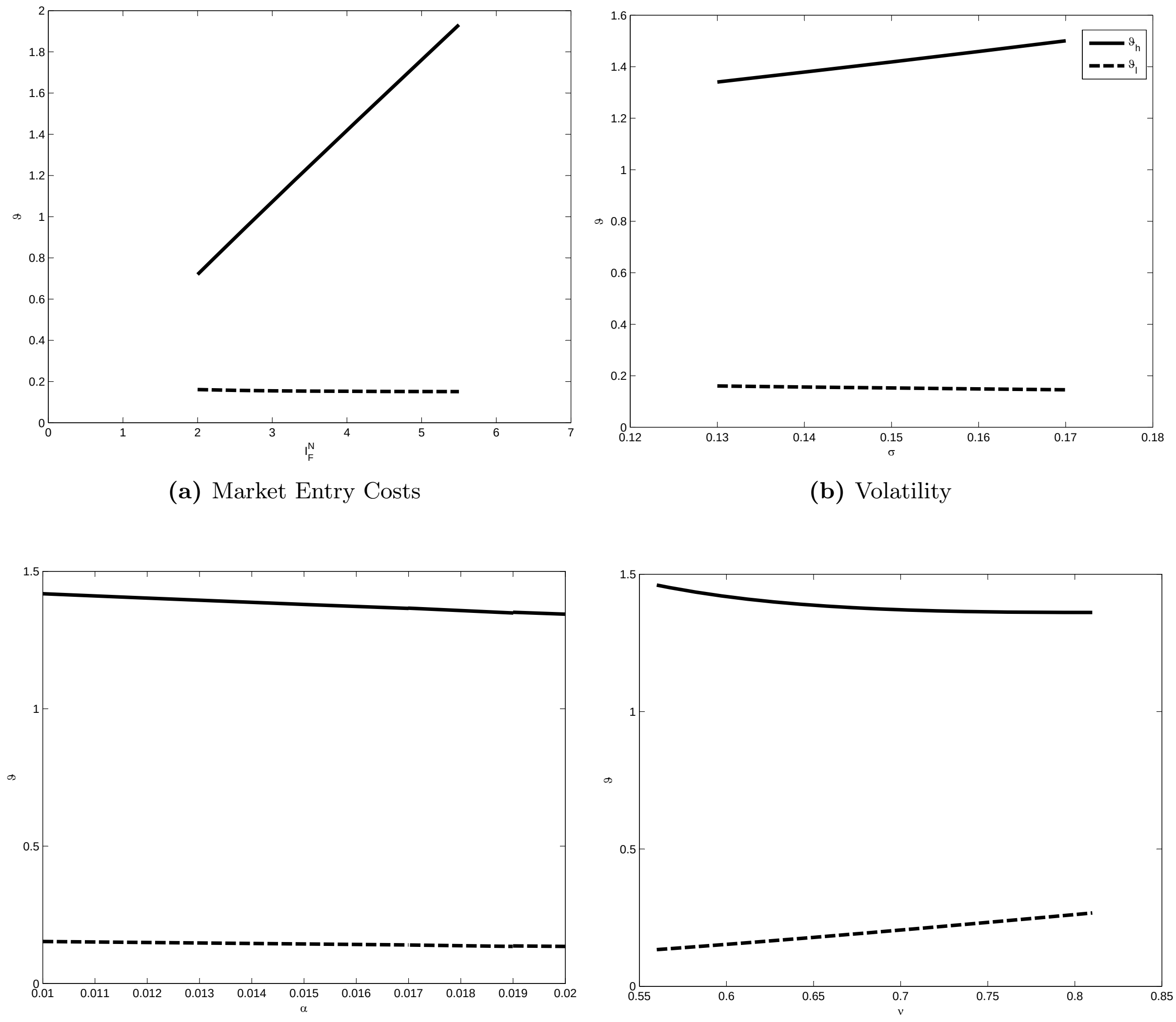
Hysteresis is mildly influenced by a change in productivity growth α, but it reacts relatively stronger if productivity uncertainty σ increases. For $\sigma \uparrow$, the entry threshold ϑ_{hi} increases, and ϑ_{li} decreases, raising the probability of serving mode continuity.

Furthermore, competition affects the serving mode continuity characteristics of exporting as depicted in panel d). Firms, which have little market power as revealed by a large inverse markup are prone to serve the market discontinuously as exporters, if confronted with volatile productivity growth - ceteris paribus. This is, because in countries with a high degree of competition, the band of inaction turns out to be relatively smaller than in countries with low competition. Therefore, in competitive markets any change in productivity over time generates a possible switch out of the serving mode in place. Importantly, the effect of competition on the region of hysteresis acts primarily through encouraging an earlier market exit.

Result 3:

Higher competition is accompanied by weaker hysteresis, since an increase in ν is followed by a mild decrease in ϑ_{hE} and a strong rise ϑ_{lE}.

Consider now a firm, for which exporting is no attractive alternative to FDI, since the export mode's variable costs are prohibitively high, such that for a given productivity evolution, the variable cost advantage of FDI always outweighs the variable cost disadvantage of exporting.



(a) Market Entry Costs

(b) Volatility

(c) Growth

(d) Competition

Figure 4: FDI Discontinuity

This table depicts the export entry and exit cut-offs. Parameters are set to $\theta = 0.7$, $\nu = 0.6$, $\alpha = 0.01$, $r = 0.06$, $\sigma = 0.15$, $\tau = 20$,$I_E^A = -1$, $I_E^N = 4$ if not considered in the respective panel.

Figure 4 depicts the cut-off productivity levels for market entry and exit as a function of fixed costs, volatility, productivity growth and market power. Note that the parameter constellation is the same as in figure 3, and that the cut-off values lie below the ones of exporting (ceteris paribus), because in the FDI mode no additional variable costs accrue. The mechanisms which incite either a continuous or a discontinuous market serving mode in FDI are the same as in exporting. The difference lies exclusively in the equilibrium levels: In a nutshell, higher fixed costs, higher volatility, a lower growth rate and less competition encourage a continuous market serving mode.

Result 4:

If FDI is the only reasonable foreign market serving mode due to $I_F^N > I_E^N$ and $\tau \geq 1$, the impact of changes in entry and exit fixed costs, productivity growth, uncertainty, and country specific competition is qualitatively the same as in the previous scenario, whereas quantitative effects differ.

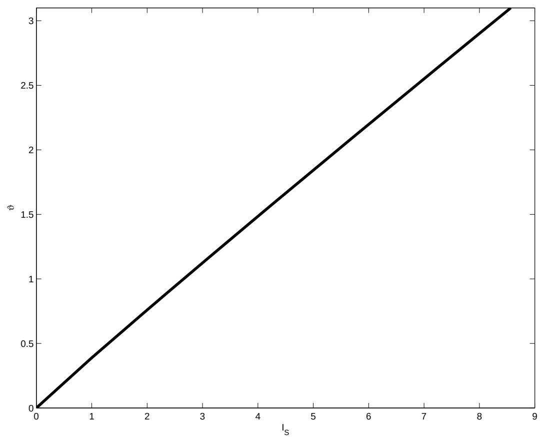
Finally, consider a firm which serves a foreign market through exports and contemplates switching into FDI. In the following, we shall address this type II discontinuity by solving the question how switching costs, volatility, productivity growth and competition do affect the continuity of a firm's market serving behavior. In principle, the investor is confronted with a mode switching problem as in the previous situation, where he had to decide on entering a new foreign market. The difference is that he is already in the foreign market and generates periodical cash-flows through exports.

Opposed to the earlier analysis, we neglect the FDI abandonment option and do not determine the exit threshold. That is, because we consider the FDI serving mode as the ultimate objective of any firm, since it exhibits the lowest achievable variable costs by paying sunk costs: in this case, incrementally first the export market entry cost I_E^N and then switching cost I_{EF}. We postulate, that within the proximity-concentration trade-off framework, once a market is served through FDI, an investor will never switch back to exporting, due to the fixed costs I_E^N and I_{EF} which are sunk. Certainly, productivity might develop in such an adverse manner forcing the firm to leave the market forever. The corresponding nominal exit cut-off lies far below the two previous ϑ_{li} since the incurred sunk costs are on the highest possible level. In the remainder we focus on the critical switching cut-off ϑ_S within this type II discontinuity and omit the calculation of ϑ_{li}. Fixed switching costs I_S for a change in serving mode from export to FDI are assumed to be higher than in a case in which firms start to serve the foreign market immediately through FDI. Although an investor might gather information as exporter and decrease e.g. marketing cost etc. still, periodical profits from the FDI serving mode need to cover the costs for a new plant $I^N_{EF} < I^N_F$ and furthermore the sunk costs of the export platform which is assumed to be shut down after the serving mode switch:

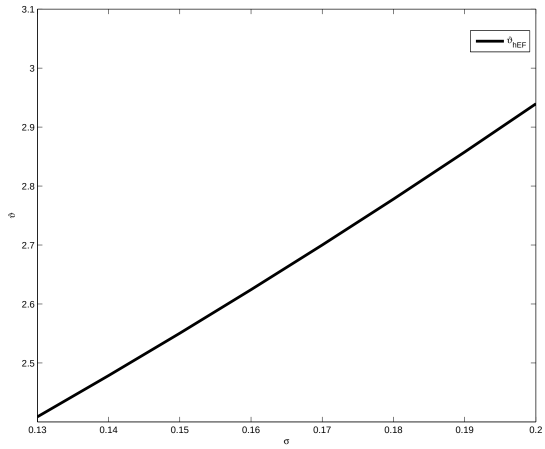
$$I_S = I^N_{EF} - I^A_E + I^N_E, \tag{40}$$

where I^N_{EF} are the fixed entry costs for FDI from an export mode. Within this setting, there is a trade-off between entering a foreign market stepwise through exporting and FDI earlier and entering directly through FDI at a later time. On the one hand, type II discontinuity reduces the inherent FDI entry costs from I^N_F to I^N_{EF} as an investor gains experience through exporting, but on the other hand the fixed cost reduction is achieved through an initial export investment which needs to be covered if it is given up later. Therefore, compared to a direct market entry through FDI, total accruing fixed costs will be higher but market entry as such will be earlier, achieved through exporting.[12] Figure 5 shows that the productivity threshold for switching from exporting to FDI increases in the respective fixed cost I_S. This type of higher costs can be explained in two ways. Either abandonment benefits for the export platform worsen or the inherent FDI entry fixed costs rise, over time or across firms. The observed rise in the entry cut-off accords with economic intuition, as the investor has to cover higher sunk costs. In contrast higher productivity growth causes a reduction in the switching threshold ϑ_S which is in line with earlier observations.

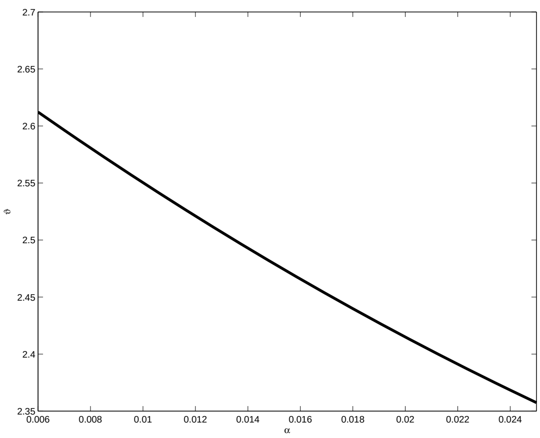
[12] There are alternative market serving modes which could appear as e.g. a simultaneous market serving through exports and FDI but this would necessitate a different frame of modelling.



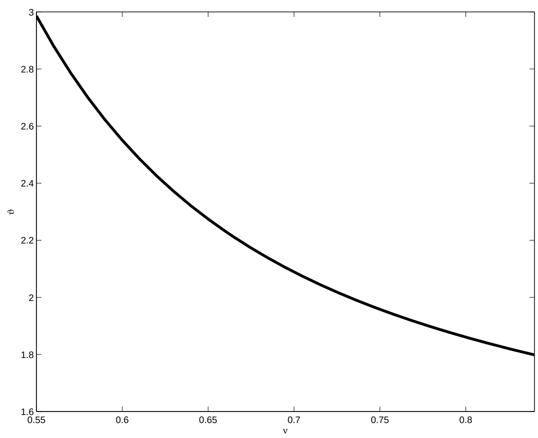
(a) Switching Costs



(b) Volatility



(c) Growth



(d) Competition

Figure 5: Type II Discontinuity: From Export to FDI
This table depicts the export entry and exit cut-offs. Parameters are set to $\theta = 0.7$, $\nu = 0.6$, $\alpha = 0.01$, $r = 0.06$, $\sigma = 0.15$, $\tau = 20$, $I_S = 7$, $I_E^N = 4$ if not considered in the respective panel.

As the investor can cover a bigger share of fixed costs at higher growth rates over time he is willed to switch into FDI earlier. Both volatility in productivity growth and a rise in competition are accompanied by a decrease in market entry thresholds as before.

Result 5:

Qualitatively a type II discontinuity is influenced through changes in α, σ, ν and fixed costs I_S in the same way as a type I discontinuity. However, an adverse productivity development does never lead to a back switching into the export mode but causes a complete market exit.

	Entry cut-off		Exit cut-off		Hysteresis	Likeliness of serving mode discontinuity
	ϑ_{hE}	ϑ_{hF}	ϑ_{lE}	ϑ_{lF}		
$\alpha \uparrow$	$\downarrow$	$\downarrow\downarrow$	$\downarrow$	$\downarrow\downarrow$	$\downarrow$	$\uparrow$
$\sigma \uparrow$	$\uparrow$	$\uparrow\uparrow$	$\downarrow$	$\downarrow$	$\uparrow$	$\downarrow$
$I_i^N \uparrow$	$\uparrow$	$\uparrow\uparrow$	$\downarrow$	$\downarrow$	$\uparrow$	$\downarrow$
$I_I^A \uparrow$	$\downarrow$	$\downarrow$	$\uparrow$	$\uparrow$	$\downarrow$	$\uparrow$
$\nu \uparrow$	$\downarrow$	$\downarrow$	$\uparrow$	$\uparrow$	$\downarrow$	$\uparrow$

Table 2: Comparative Static Results

The stronger extent of adjustment in some FDI cut-offs are due to their relative lower variable costs within the proximity-concentration trade-off framework.

In a nutshell, depending on nominal cost levels and the extent of changes in productivity growth α, volatility σ, the degree of competition ν and irreversible fixed costs I_i^j, different market serving mode strategies and discontinuity types will result. Table 2 summarizes the derived results and allows the analysis of serving mode discontinuity for different scenarios.

5. Conclusion

Whether multinational enterprises serve new foreign markets through exports or FDI, has been analyzed in recent New New Trade models on the basis of the proximity-concentration trade-off framework which constitutes a higher comparative fixed cost advantage in the export mode and a comparative variable cost advantage in the FDI serving mode (Helpman et al., 2004). These types of models derive static firm distributions in steady states distinguishing exporting firms from foreign direct investors by means of cut-off productivity levels. However, the serving mode selection of firms which are confronted with dynamic state variables over time like productivity or demand cannot be explained.

Empirically, two striking stylized facts support the introduction of dynamic elements into the mentioned static frameworks. Firstly, firm productivity which is considered to be distinctive in shaping the market serving mode of a firm, varies over time and can be modelled by a stochastic process. Exemplary, we show productivity developments for several Danish manufacturing sectors. Secondly, there is evidence that internationally acting firms exhibit a high degree of dynamics in their market entry and exit behavior, either by switching between the initially chosen serving mode, e.g. exporting and not serving (type I discontinuity), or by changing the serving mode step by step from exporting to FDI (type II discontinuity), over time. Again we can demonstrate entry and exit patterns of Danish exporters supporting this statement.

Given these empirical observations we explain theoretically two aspects: First of all, we identify how uncertain productivity influences the serving mode decision of international firms confronted with the proximity-concentration trade-off framework. We develop a basic single firm model of timing and serving mode switching, by extending the concept of real option theory following Dixit (1989). Our setting allows for interpreting the equilibrium results as heterogeneous firms. Furthermore, we are able to identify four decisive dimensions which determine the extent of serving mode discontinuity in the presence of uncertain productivity evolution. As in Dixit (1989) irreversible fixed costs generate hysteresis which represents the cause for different extents of serving mode discontinuity. Starting with a cost constellation in which a firm would choose to enter a new foreign market as an exporter we can show, that higher entry fixed costs lead to higher entry cut-offs increasing hysteresis and decreasing the likeliness of serving mode discontinuity. In the same line, higher volatility in productivity and lower competition in the destination country increase the range of hysteresis and reduce the probability of switching between serving modes. Productivity growth turns out to be less influential in the export mode compared with a type I discontinuity in the FDI mode.

After presenting numerically comparative static results we are able to analyze market serving mode discontinuity including the possibility of entering a market first as an exporter and switching afterwards into FDI. Our final results capture the effects of irreversible fixed costs, stochastic productivity and the degree of country specific competition on serving mode discontinuity. The last contribution of this model is the derivation of testable predictions on international serving mode patterns which - upon availability of appropriate firm level data - should open out into future empirical analysis.

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A. Appendix

A.1. Cost Constellations and Associated Market Serving Mode Switching

Dominance of FDI: $\mathbf{I_E > I_F}$,			$\mathbf{I_S \to \infty}$	
Variable Cost	Entry Mode	Level of Fixed Cost	Mode Discontinuity	Type
$\tau \to 1$	FDI	$I_F \to I_E$	No	
		$I_F \to 0$	Yes	Ia
$\tau \to \infty$	FDI	$I_F \to I_E$	No	
		$I_F \to 0$	Yes	Ia
Proximity-Concentration Trade-Off: $\mathbf{I_F > I_E}$,			$\mathbf{I_S \to \infty}$	
Variable Cost	Entry Mode	Level of Fixed Cost	Mode Discontinuity	Type
$\tau \to 1$	Export	$I_E \to I_F$	No	
		$I_E \to 0$	Yes	Ib
$\tau \to \bar{\tau} < \infty$	Export	$I_E \to I_F$	No	
		$I_E \to 0$	Yes	Ib
$\tau > \bar{\tau}$, $\tau \to \infty$	FDI	$I_F \to \infty$	No	
		$I_F \to I_E$	Yes	Ia
			$\mathbf{I_S < \infty}$	
Variable Cost	Entry Mode	Level of Switching Cost	Mode Discontinuity	Type
$\tau \to 1$	Export	$I_S \to \infty$	No	
		$I_S \to 0$	No	
$\tau \to \bar{\tau} < \infty$	Export	$I_S \to \infty$	No	
		$I_S \to 0$	Yes	II
$\tau > \bar{\tau}$, $\tau \to \infty$	FDI	$I_S \to \infty$	No	
		$I_S \to 0$	No	

Table 3: Limiting Cost Constellations and Market Serving Modes
This table depicts chosen market serving strategies for limiting cost constellations. I_E (I_F) are the fixed market entry cost of exporting (FDI), τ represents the transport costs associated with exporting. $\bar{\tau}$ is a critical value of τ at which for a given productivity growth and volatility, the relative fixed cost advantage of exporting outweighs the relative variable cost advantage of FDI. Considerations in this table refer exclusively to market entry cost. Thus, the superscript N is omitted for I_E and I_F.

The top part of table 3 covers cases, where the export fixed costs are strictly larger than the FDI fixed costs. For this fixed cost constellation, no matter the size of the variable export costs, FDI results as the preferred serving mode.

The intermediate part of the table covers market serving strategies for scenarios, where the entry costs for FDI exceed those for exporting firms, i.e., where $I_F > I_E$. If the variable costs tend to zero, exporting arises as the dominant strategy. Whether this mode choice is continuous or discontinuous, hinges on the size of the market entry sunk cost: If the firm has sunk very high entry cost (approaching its upper bound I_F), a firm will remain either exporter or inactive. If entry cost tend to zero, it can almost costlessly adjust to unfavorable market conditions and thus a discontinuous market serving strategy (type I) results. For transport costs τ which approach infinity from below, there exists a critical $\bar{\tau}$ for which the fixed cost advantage is turned down by the variable cost disadvantage given the uncertain productivity development. As long as the transport cost approach $\bar{\tau}$ from below, exporting is the preferable strategy.

The bottom part of the table presents a scenario, where the switching costs are no longer prohibitively high, such that *type II* discontinuities may arise. In two cases, they do not arise: If FDI is the market entry mode in light of the proximity-concentration trade-off under productivity uncertainty, the investor will not change to an export market serving mode. Since export is associated with higher variable costs as compared to foreign direct investment, there is no reason for the optimizing firm to switch from exporting to FDI if sunk costs exist. Similarly, for an exporter, there is no incentive to change his market serving mode if variable cost tend to zero, or if switching costs tend to infinity.

A.2. The Adjusted Expected Growth Rate

Given the Geometric Brownian motion

$$d\vartheta_t = \alpha\vartheta_t dt + \sigma\vartheta_t dz_t \tag{41}$$
$$\text{with} \quad dz_t = \epsilon_t\sqrt{dt} \quad \text{and} \quad \epsilon_t \sim N(0,1)$$

we define a function

$$f(\vartheta_t) = \vartheta_t^\kappa \qquad \text{and} \qquad \kappa \ln \vartheta_t = \kappa y_t \tag{42}$$

where y_t represents an arithmetic Brownian Motion. Therefore the exponential function $f(\vartheta_t)$ can be expressed as $\vartheta_t^\kappa = e^{\kappa y_t}$.

The solution of y_t is

$$y_t = y_0 + \int_0^t (\alpha - \frac{1}{2}\sigma^2)ds + \int_0^t \sigma dz_s. \tag{43}$$

Therefore, the expected value of the exponential function $f(\vartheta_t)$ can be expressed as

$$\mathbb{E}(x_t^\kappa) = e^{\kappa y_0} e^{(\alpha - \frac{1}{2}\sigma^2)t\kappa} e^{\int_0^t \sigma dz_t}. \tag{44}$$

The last term in equation (44) still includes a random variable. By defining a moment generating function it is possible to evaluate its expected value.

Moment Generating Function

Consider a normally distributed random variable Z_t with $Z_t \sim N(m, \chi^2)$.
We can write

$$\mathbb{E}(e^{\kappa Z_t}) = \int_{-\infty}^{\infty} \frac{1}{\chi\sqrt{2\pi}}\, e^{\left(-\frac{(Z_t-m)^2}{2\chi^2}\right)}\, e^{\kappa Z_t} dz_t \tag{45}$$

$$= e^{\left(m\kappa + \frac{\chi^2\kappa^2}{2}\right)}. \tag{46}$$

In the underlying case $m = 0$ and $\chi = 1$. Furthermore the random variable in the Brownian motion is related to $\sqrt{t}$ with

$$dz_t = \epsilon_t \sqrt{t} \tag{47}$$

which leads to

$$\mathbb{E}(e^{\kappa\sigma Z_t}) = e^{\frac{\kappa^2\sigma^2 t}{2}}. \tag{48}$$

Therefore, applying this result to equation (44), the expected value of the exponential function $f(\vartheta_t)$ is given by

$$\mathbb{E}(\vartheta^\kappa) = e^{\kappa y_0} e^{(\alpha - \frac{1}{2}\sigma^2)t\kappa} e^{\frac{\kappa^2\sigma^2}{2}t}. \tag{49}$$

Using equation (A.2) the expected value results as

$$\mathbb{E}(\vartheta_t^\kappa) = \vartheta_0^\kappa e^{[\alpha\kappa + \frac{1}{2}\kappa\sigma^2(\kappa-1)]t}. \tag{50}$$

Finally, the expected cash-flows result as

$$\mathbb{E}(\Pi_i(\vartheta_t)) = M_i \vartheta_0^{\kappa} e^{[\alpha\kappa + \frac{1}{2}\kappa\sigma^2(\kappa-1)]t}. \tag{51}$$

The adjusted growth rate for convex profits with $\kappa > 1$ is then given by

$$\alpha' = \alpha\kappa + \frac{1}{2}\kappa\sigma^2(\kappa - 1). \tag{52}$$

A.3. Homogeneous Differential Function

The solution of a homogeneous differential function of second order

$$\frac{1}{2}\sigma^2\vartheta^2\frac{\partial^2 F_i(\vartheta)}{\partial\vartheta^2} + (r-\delta)\vartheta\frac{\partial F_i(\vartheta)}{\partial\vartheta} - rF_i(\vartheta) = 0 \tag{53}$$

is a linear combination of any two linearly independent solutions, as

$$A_i\vartheta^{\beta}. \tag{54}$$

Substituting this guess solution into the differential equation leads to the quadratic equation

$$\frac{1}{2}\sigma^2\beta(\beta-1)A_i\vartheta^{\beta} + (r-\delta)\beta A_i\vartheta^{\beta} - rA_i\vartheta^{\beta} = 0 \tag{55}$$

$$\frac{1}{2}\sigma^2\beta(\beta-1) + (r-\delta)\beta - r = 0. \tag{56}$$

The resulting two solutions for β are

$$\beta_1 = \frac{1}{2} - \frac{r-\delta}{\sigma^2} + \sqrt{\left[\frac{r-\delta}{\sigma^2} - \frac{1}{2}\right]^2 + \frac{2r}{\sigma^2}} > 1 \tag{57}$$

$$\beta_2 = \frac{1}{2} - \frac{r-\delta}{\sigma^2} - \sqrt{\left[\frac{r-\delta}{\sigma^2} - \frac{1}{2}\right]^2 + \frac{2r}{\sigma^2}} < 0 \tag{58}$$

and the final solution for the quadratic equation is

$$F_i(\vartheta) = A_{i1}\vartheta^{\beta_1} + A_{i2}\vartheta^{\beta_2}. \tag{59}$$

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