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Trade Openness and Inflation:
the Role of Real and Nominal Price Rigidities

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Highlights:

- I model the impact of trade openness and competition on price flexibility
- Trade openness increases real price rigidities
- Trade openness reduces nominal price rigidities
- The impact of trade openness on the inflation-output trade-off is ambiguous

Abstract

The paper revisits the long-standing question of the impact of trade openness on the inflation-output trade-off by accounting for the effects of product market competition on price flexibility. The study develops a New-Keynesian open-economy dynamic stochastic general equilibrium model with non-constant price elasticity of demand and Calvo price setting in which the frequency of price adjustment is endogenously determined. It demonstrates that trade openness has two opposing effects on the sensitivity of inflation to output fluctuations. On the one hand, it raises strategic complementarity in firms' pricing decisions and the degree of real price rigidities, which makes inflation less responsive to changes in real marginal cost. On the other hand, it strengthens firms' incentives to adjust their prices, thereby reducing the degree of nominal price rigidities and increasing the sensitivity of inflation to changes in marginal cost. The study explains the positive relationship between competition and the frequency of price adjustment observed in the data. It also provides new insights into the effects of global economic integration on the Phillips Curve.

JEL classification: F41; E31; E32

Keywords: Trade Openness; Inflation; Nominal Rigidities; Real Rigidities; Phillips Curve

1 Introduction

The substantial increase in global economic integration during recent decades initiated a heated debate on the impact of trade openness on inflation and the short-run inflation-output trade-off. As understanding this impact is of crucial importance for the optimal design and conduct of monetary policy, the topic has attracted significant interest not only among academics but also policy makers.¹ One of the key determinants of the sensitivity of inflation to changes in domestic economic activity is the degree of nominal price rigidities, which depends on the

¹See speeches by Kohn (2006), Bean (2006), Bernanke (2007), Fukui (2007) and Trichet (2008).

frequency with which firms change their prices. Previous studies analysing the effects of trade integration on inflation with the use of structural macroeconomic models have assumed that the frequency of price adjustment is constant and have therefore ignored the fact that changes in the openness of the economy and the resulting changes in competition may affect firms' pricing policies. This is an important omission as surveys of firms' price-setting behaviour as well as empirical studies based on disaggregated price data provide strong evidence of a positive relationship between the level of competition and the frequency of price changes.² This study fills this gap by examining, within a New-Keynesian open-economy model, the impact of trade openness and product market competition on price flexibility and their implications for inflation dynamics.

The contribution of this paper is two-fold. First, the study provides new insights into the determinants of real and nominal price rigidities and, in particular, it explains the positive relationship between competition and the frequency of price adjustment observed in the data. Second, by accounting for the impact of competition on firms' price-setting behaviour, it sheds new light on the effects of trade openness on the Phillips Curve and the inflation-output trade-off.

For the purpose of the analysis, the paper develops a New-Keynesian DSGE model which builds on the open-economy framework with staggered price setting developed by Clarida, Galí and Gertler (2002) and Galí and Monacelli (2005). In order to capture the effects of competition on firms' pricing policies, the proposed model departs from two standard assumptions used in New-Keynesian open-economy general equilibrium models. First, in place of the usual Dixit-Stiglitz consumption aggregator implying constant elasticity of substitution between differentiated goods, the model introduces an extension of the consumption aggregator suggested by Kimball (1995) to an open-economy environment with a variable number of traded goods. The consumption aggregator is characterised by non-constant price elasticity of demand, which generates strategic complementarity in firms' price-setting decisions in that a firm's optimal price depends positively on the prices charged by its competitors. It also accounts for the negative impact of trade openness on firms' steady-state mark-ups.³ Second, the frequency of price adjustment is endogenised. Firms set their prices as in Calvo (1983); however, the probability of a price change in a given period is not exogenous, as is usually assumed, but is subject to firms' optimising decisions.⁴

In the framework developed, the level of competition is defined as the total number of varieties available to domestic consumers. Trade integration, associated with an increase in the number of imported varieties, leads to a higher level of competition faced by firms.⁵ The level of competition affects the steady-state price elasticity of demand and desired mark-ups, which in

²Surveys of the literature on the link between competition and the frequency of price adjustment can be found in Carlton (1989), Asplund and Friberg (1998) and Álvarez *et al.* (2006).

³The negative effect of trade openness on mark-ups has been documented by Chen, Imbs and Scott (2009), Konings and Vandenbussche (2005), Beccarelli (1996) and Katicic and Petersen (1994). See also Tybout (2003) for further references.

⁴A similar approach has been used by Romer (1990), Devereux and Yetman (2002), Levin and Yun (2007), Kimura and Kurozumi (2010) and Senay and Sutherland (2014) to study other determinants of the frequency of price adjustment, while Devereux and Yetman (2010) have applied it to examine the determinants of exchange rate pass-through.

⁵Empirical evidence suggests that an increase in the number of traded varieties has been an important feature of recent global economic integration (Broda and Weinstein, 2006; Galstyan and Lane, 2008).

turn determine the degree of strategic complementarity in firms' price-setting decisions and firms' incentives to adjust their prices.

The analysis demonstrates that trade openness has two opposing effects on firms' optimal pricing and inflation. On the one hand, greater trade integration and competition increases strategic complementarity in firms' price-setting decisions and the degree of real price rigidities, which makes inflation less sensitive to changes in domestic economic conditions. On the other hand, stronger competitive pressure raises the opportunity cost of not adjusting prices and leads to more frequent price adjustment, reducing nominal price rigidities and making inflation more sensitive to shocks. The overall impact of these changes on the short-run trade-off between output and inflation depends on the initial level of competition and openness of the economy. This paper therefore helps explain the fact that empirical studies fail to find a robust relationship between trade openness and the inflation-output trade-off.⁶

In the presence of strategic complementarity in firms' price-setting decisions, domestic inflation depends on two factors: real marginal cost and the relative price of domestic and imported goods. The ratio of domestic to import prices influences the prices charged by domestic firms in addition to its impact through the marginal cost channel as it affects firms' price elasticity of demand and their desired mark-ups. Trade openness affects the sensitivity of inflation to both the marginal cost and the relative international prices. An increase in trade integration and in the number of varieties available in the domestic market raises firms' steady-state price elasticity of demand and lowers their desired mark-ups. It also increases the sensitivity of a firm's profit-maximising price to the prices charged by its competitors. This has two implications for firms' price setting decisions. First, in a more open economy it is costlier for firms adjusting their prices in a given period to deviate from the prices charged by firms not adjusting their prices. In consequence, following any changes in real marginal cost, they adjust prices by a lesser amount. This increase in real price rigidity results in inflation becoming less responsive to changes in domestic economic conditions and a flattening of the Phillips Curve. Second, as in a more open economy the opportunity cost of any given deviation of a firm's price from the profit-maximising price increases, firms adjust their prices more frequently. This in turn increases the responsiveness of inflation to changes in marginal cost and makes the Phillips Curve steeper. The overall effect of trade openness on the relationship between real marginal cost and inflation and the slope of the Phillips Curve is therefore ambiguous. At the same time, trade integration has a positive impact on the sensitivity of inflation to the relative price of domestic and imported goods. As the number of imported varieties in the domestic economy increases, prices charged by foreign competitors become more important in determining the optimal price of domestic firms and, in consequence, domestic inflation becomes more sensitive to changes in relative international prices.

The remainder of the paper is organised as follows. The second section discusses related literature and how this paper contributes to it. Section three sets out the baseline version of the model developed for the purpose of this analysis, in which the frequency of price adjustment is assumed to be exogenous. Section four discusses the calibration of the model parameters. Section five analyses the impact of competition on the degree of real price rigidities and the Phillips Curve. In section six, the baseline model is extended by endogenising the frequency of price adjustment. The impact of competition and other structural features of the economy on the

⁶E.g. Temple (2002) finds little evidence for a correlation between openness and the inflation-output trade-off. Daniels, Nourzad and VanHoose (2005) report a negative impact of trade openness on the relationship between output and inflation, while Bowdler (2009) demonstrates a positive effect.

optimal frequency of price adjustment is then analysed and the overall effect of trade openness on inflation is discussed. The final section concludes and suggests avenues for further research.

2 Related Literature

Since the seminal paper by Romer (1993), the question of the impact of trade openness on inflation and the inflation-output trade-off has received much attention in macroeconomic literature. The results of this research are far from conclusive.⁷ Empirical and theoretical studies identified a number of factors which affect the relationship between trade openness and the sensitivity of inflation to output fluctuations. They include goods- and labour-market structures (Daniels and VanHoose, 2006; Bowdler and Nunziata, 2010), political regime (Caporale and Caporale, 2008), exchange rate regime (Bowdler, 2009), trade costs (Cavelaars, 2009), capital mobility (Daniels and VanHoose, 2009), the importance of imported commodities in production (Pickering and Valle, 2012) and exchange rate pass-through (Daniels and VanHoose, 2013). This paper contributes to this research by accounting for the impact of trade openness and the resulting changes in product market competition on price flexibility within a micro-founded New-Keynesian open-economy DSGE model. It shows that as trade openness has opposing effects on the degree of real and nominal price rigidities, its impact on the inflation-output trade-off is theoretically ambiguous and it depends on the initial level of openness and competition in the economy.

In the New-Keynesian framework, the sensitivity of domestic inflation to changes in domestic economic activity depends on two factors: the elasticity of inflation with regard to real marginal cost and the sensitivity of real marginal cost to changes in the output gap. The elasticity of inflation with regard to real marginal cost in turn depends on the frequency of price adjustment, which reflects the degree of nominal price rigidity, and on the responsiveness of firms' profit-maximising price to changes in real marginal cost, which is determined by the degree of real price rigidity. Previous studies examining the effects of trade openness on the inflation-output trade-off based on structural macroeconomic models with staggered price setting focus either on the impact of trade integration on the sensitivity of marginal cost to the output gap (e.g. Galí and Monacelli, 2005; Binyamini and Razin, 2008; Woodford, 2010; Pickering and Valle, 2012) or on its effects on the responsiveness of firms' optimal price to changes in marginal cost and the associated real price rigidity (Sbordone, 2010; Guerrieri, Gust and López-Salido, 2010; Benigno and Faia, 2010). This study is the first to explore the influence of trade integration and the resulting changes in competition on the frequency with which firms change their prices.⁸

The first part of the paper examines the effects of trade openness and product market competition on the degree of real price rigidities. This relationship has previously been investigated by Sbordone (2010), Guerrieri, Gust and López-Salido (2010) and Benigno and Faia (2010). However, this paper is the first to analyse it within a general equilibrium framework. There are also other important differences. In both Sbordone (2010) and Guerrieri, Gust and López-Salido (2010) real rigidities are due to households' preferences implying non-constant price elasticity of demand, as is the case in this paper. However, Sbordone's analysis is based on a closed-economy rather than an open-economy model. Guerrieri, Gust and López-Salido do not allow for the impact of trade integration on firms' steady-state mark-ups and market shares,

⁷ See Daniels, Mazumder and VanHoose (2015) and Badinger (2009) for recent surveys of the literature.

⁸ Rogoff (2003) postulated that globalisation affects inflation through its impact on price flexibility; however, he did not formalise this argument in a structural macroeconomic model.

which this paper takes into account. Benigno and Faia (2010) consider a different source of real rigidity. In their analysis, variable desired mark-ups arise not on the demand side of the economy but from strategic pricing associated with oligopolistic competition.

The second part of the paper analyses the impact of trade openness and competition on the frequency of price adjustment. Despite the central role that nominal price rigidities play in macroeconomic theory, their determinants are not well understood. Existing studies investigating the determinants of the frequency of price adjustment focus on the role of trend inflation, the size of the price adjustment costs and the variance of shocks (Romer, 1990; Dotsey, King and Wolman, 1999; Kiley, 2000; Devereux and Yetman, 2002; Levin and Yun, 2007) and monetary policy preferences (Kimura and Kurozumi, 2010; Senay and Sutherland, 2014). At the same time, there is substantial empirical evidence that the frequency with which firms change their prices depends on the degree of competition. Recent surveys of firms' pricing policies conducted in a number of countries indicate that companies operating in markets with higher competitive pressure adjust their prices more frequently (Druant *et al.*, 2009; Vermeulen *et al.*, 2007; Álvarez and Hernando, 2007; Hoeberichts and Stokman, 2010; Álvarez and Hernando, 2005; Fabiani *et al.*, 2005; Aucremanne and Druant, 2005). In a study conducted by the Bank of England, UK firms named an increase in competition as the most important factor behind the rise in the frequency with which they changed their prices over the last decade (Greenslade and Parker, 2008). The positive link between the degree of competition and the frequency of price adjustment has also been confirmed by empirical studies based on disaggregated price data (Cornille and Dossche, 2006; Álvarez *et al.*, 2006; Lünemann and Matha, 2005; Encaoua and Geroski, 1986; Geroski, 1992; Carlton, 1986). Álvarez, Burriel and Hernando (2010) find that the frequency of producer price changes increases with import penetration. Despite the considerable empirical evidence, the theoretical literature investigating the relationship between competition and the speed of price adjustment is scant and the mechanism underlying it remains unclear.

Industrial organisation studies which analyse the impact of competition on the degree of nominal price rigidities in an oligopolistic environment provide conflicting results concerning the direction of this relationship.⁹ The influence of competition on the frequency of price adjustment under the assumption of monopolistic competition, which prevails in macroeconomic models, has hardly been examined. Some insights into the effects of competition on nominal rigidities in a monopolistically competitive environment can be gained from analysing the link between the price elasticity of demand and the frequency of price adjustment. Martin (1993) conducted such an analysis within a simple static setting, while Dotsey, King and Wolman (1999) use a dynamic general equilibrium model with state-dependent pricing. However, while a change in the price elasticity of demand can be an important outcome of the entry of new firms into a market and the associated increase in competition, it is not the only consequence. Changes in the number of traded varieties also affect firms' market shares, the degree of strategic complementarity in price-setting decisions and the variability of desired prices, all of which influence firms' incentives to adjust their prices. In contrast to previous studies, this paper analyses the effects of competition on the frequency of price changes in a dynamic stochastic general equilibrium model with real rigidities and a variable number of traded varieties which takes all these effects into account.

3 Model

⁹See Ginsburgh and Michel (1988) for a brief review.

The analysis is based on a New-Keynesian open-economy DSGE model. The world economy consists of two symmetric countries, Home and Foreign. Each country is populated by utility-maximising households and profit-maximising firms, owned by households, which produce differentiated goods and sell them in monopolistically competitive markets. There are two types of firms – exporters, which sell their goods in both the domestic and foreign economy, and non-exporters, which operate only in the domestic market. Firms set their prices using pricing-to-market, as in Betts and Devereux (1996), and Calvo contracts, as in Calvo (1983). In the baseline version of the model it is assumed that the probability of price adjustment in a given period is exogenous. Households consume all varieties which are sold in the domestic market. Their consumption aggregator is characterised by non-constant price elasticity of demand, which gives rise to strategic complementarity in firms' price-setting decisions – a firm's optimal relative price depends not only on its marginal cost but is also positively related to the prices charged by its competitors. In each country monetary policy is conducted by a central bank which sets the nominal interest rate following a Taylor rule. Business cycles are driven by productivity, preference and monetary policy shocks.

3.1 Firms

In each country, there is a continuum of firms indexed by $i \in [0,1]$. All firms operating in the Home economy produce differentiated final consumption goods and sell them in an environment of monopolistic competition. They use a production technology with constant returns to scale in which domestic labour is the only factor of production:

$$Y_{i,t} = A_t L_{i,t} \quad (1)$$

where $Y_{i,t}$ is the output produced by firm i at time t and $L_{i,t}$ is the labour input used in the production of that good. A_t denotes the level of technology which follows an exogenous process:

$$\ln A_t = \rho_a \ln A_{t-1} + \xi_t^a \quad \text{such that } \rho_a \in (0,1) \quad \text{and } \xi_t^a \sim N(0, \sigma_a^2).$$

In the Home and in the Foreign economy, a fraction of firms, equal to N and N^* respectively, sell their goods both in the domestic market and abroad, whereas the remaining firms sell their goods only in the domestic market. All firms set their prices in the currency of the country in which their goods are sold.¹⁰

Non-exporting firms in the Home economy, located in the interval $[N,1]$, set their prices to maximise their expected discounted profits subject to the demand function, the production technology and the Calvo contracts. When they receive a signal to update their prices at time t , they choose the price of their product in the domestic market, $P_{H,i,t}$, that maximises:

$$\sum_{k=0}^{\infty} E_t \left(\alpha^k Q_{t,t+k} C_{H,i,t+k} (P_{H,i,t} - MC_{i,t+k}) \right) \quad (2)$$

where $C_{H,i,t}$ is the Home demand for the good produced by firm i at time t , $MC_{i,t}$ denotes the firm's nominal marginal cost at time t , $Q_{t,t+1}$ is the stochastic discount factor and $\alpha \in (0,1)$ represents the fraction of firms that do not adjust their prices in a given period.

Exporting firms in the Home economy, located in the interval $[0, N]$, also maximise their expected discounted profits subject to similar constraints. However, they set two different prices – one for the Home market, $P_{H,i,t}$, and one for the Foreign market, $P_{F,i,t}^*$, so that they maximise:

¹⁰Throughout the chapter, Foreign variables are denoted by an asterisk.

$$\sum_{k=0}^{\infty} E_t \left(\alpha^k Q_{t,t+k} \left[C_{H,i,t+k} (P_{H,i,t} - MC_{i,t+k}) + C_{F,i,t+k}^* (S_{t+k} P_{F,i,t}^* - MC_{i,t+k}) \right] \right) \quad (3)$$

where $C_{F,i,t}^*$ denotes the Foreign demand for the good produced by firm i at time t ; S_t is the nominal exchange rate at time t , defined as the price of one unit of Foreign currency in terms of Home currency. The price $P_{H,i,t}$ is expressed in the Home currency, whereas $P_{F,i,t}^*$ is expressed in the currency of the Foreign economy.

The assumption that exporters are engaging in international price discrimination is consistent with the findings from substantial empirical literature on pricing-to-market which shows that the same goods are priced with different mark-ups across importing markets (see Goldberg and Knetter, 1997, for an extensive review).

3.2 Households

Each country is populated by a continuum of identical, infinitely-lived households located in the interval $[0,1]$. A representative household has a utility function which is additively separable in consumption, C_t , and labour, L_t , and given by:

$$E_t \sum_{k=0}^{\infty} \beta^k \left[\frac{C_{t+k}^{1-\sigma}}{1-\sigma} e^{u_t} - \frac{L_{t+k}^{1+\phi}}{1+\phi} \right] \quad (4)$$

where $\beta \in (0,1)$ is the intertemporal discount factor, $\sigma > 0$ is the inverse of the intertemporal elasticity of substitution in consumption, $\phi \geq 0$ is the inverse of the Frisch elasticity of labour supply, and e^{u_t} represents a shock to the marginal utility of consumption such that $u_t = \rho_u u_{t-1} + \xi_t^u$ where $\rho_u \in (0;1)$ and $\xi_t^u \sim N(0, \sigma_u^2)$.

Households maximise their expected discounted lifetime utility subject to a sequence of budget constraints:

$$P_t C_t + E_t [Q_{t,t+1} D_{t+1}] = W_t L_t + D_t + T_t \quad (5)$$

where D_{t+1} is the nominal payoff in period $t+1$ of the portfolio held at the end of period t , W_t denotes nominal wage and T_t is a lump-sum component of income including dividends from ownership of firms. It is assumed that in both countries, households have unrestricted access to a complete set of contingent claims, traded internationally.

3.3 Demand aggregator

Households in the Home economy consume all domestically produced differentiated goods and all Foreign varieties available in the domestic market. Their consumption aggregator, C_t , is implicitly defined by the condition:

$$\int_0^1 f \left(\frac{C_{H,i,t}}{C_t} \right) di + \int_1^{(1+N^*)} f \left(\frac{C_{F,i,t}}{C_t} \right) di = 1 \quad (6)$$

where $f \left(\frac{C_{X,i,t}}{C_t} \right)$ is an increasing, strictly concave function and $X = \{H, F\}$. The consumption

aggregator adopted in the analysis extends the aggregators suggested by Kimball (1995) and Sbordone (2010) to an open-economy environment with a variable number of traded varieties.

The parameter $N^* \in (0,1)$ is the fraction of Foreign goods which are exported to the Home economy and it determines the degree of trade openness. The total number of varieties available for sale in the Home market is equal to $(1 + N^*)$ and it is a measure of the level of

competition in the economy.

The functional form of $f\left(\frac{C_{X,i,t}}{C_t}\right)$ used in the analysis is given by:

$$f\left(\frac{C_{X,i,t}}{C_t}\right) = \frac{1}{(1+\eta)\gamma} \left[(1+\eta) \frac{C_{X,i,t}}{C_t} - \eta \right]^\gamma - \frac{1}{1+N^*} \left[\frac{1}{(1+\eta)\gamma} - 1 \right] \quad (7)$$

where the parameters η and γ determine the shape of the demand function.

The demand aggregator defined in this way departs from the standard assumption of constant price-elasticity of demand and introduces strategic complementarity in firms' price-setting decisions which generates variable desired mark-ups.¹¹ It is shown in *Appendix A.1* that the demand function associated with the consumption aggregator adopted can be written as:

$$\frac{C_{X,i,t}}{C_t} = \frac{1}{1+\eta} \left(\frac{P_{X,i,t}}{\tilde{P}_t} \right)^{\frac{1}{\gamma-1}} + \frac{\eta}{1+\eta} \quad (8)$$

where $\frac{C_{X,i,t}}{C_t}$ is firm i 's market share and \tilde{P}_t is an aggregate, competition-based price index which is given by:¹²

$$\tilde{P}_t = \left[\int_0^1 (P_{H,i,t})^{\frac{\gamma}{\gamma-1}} di + \int_1^{1+N^*} (P_{F,i,t})^{\frac{\gamma}{\gamma-1}} di \right]^{\frac{\gamma-1}{\gamma}} \quad (9)$$

Its derivation is shown in *Appendix A.2*.

In the framework adopted, the price elasticity of demand, $\theta_{X,i,t}$, is not constant, as is usually assumed, but is a function of firm i 's relative price and its market share:

$$\theta_{X,i,t} \left(\frac{C_{X,i,t}}{C_t} \right) = - \frac{f' \left(\frac{C_{X,i,t}}{C_t} \right)}{\frac{C_{X,i,t}}{C_t} f'' \left(\frac{C_{X,i,t}}{C_t} \right)} = - \frac{1}{\gamma-1} \frac{\left(\frac{P_{X,i,t}}{\tilde{P}_t} \right)^{\frac{1}{\gamma-1}}}{\left(\frac{P_{X,i,t}}{\tilde{P}_t} \right)^{\frac{1}{\gamma-1}} + \eta} \quad (10)$$

In consequence, firm i 's desired mark-up, $\mu_{X,i,t}$, is also a function of the firm's relative price:¹³

$$\mu_{X,i,t} \left(\frac{C_{X,i,t}}{C_t} \right) = \frac{\theta_i \left(\frac{C_{X,i,t}}{C_t} \right)}{\theta_i \left(\frac{C_{X,i,t}}{C_t} \right) - 1} = \frac{1}{\gamma + \eta(\gamma-1) \left(\frac{P_{X,i,t}}{\tilde{P}_t} \right)^{\frac{1}{1-\gamma}}} \quad (11)$$

In an equilibrium with symmetric prices, firm i 's market share is a function of the number of varieties traded in the economy, given by:

¹¹Eichenbaum and Fisher (2007) show that allowing for non-constant price elasticity of demand in Calvo-style models is important for rendering these models consistent with price duration data.

¹²This competition-based aggregate price index differs from the utility-based price index, P_t , defined as the cost of a unit of the composite good, C_t , but is also a homogenous function of degree one.

¹³Surveys conducted among firms in the Euro Area and in the UK indicate that pricing strategies based on variable mark-ups are widespread (Fabiani *et al.*, 2005; Greenslade and Parker, 2008).

$$\frac{C_{x,i}}{C} = f^{-1}\left(\frac{1}{1+N^*}\right) = \frac{1}{1+\eta} \left[\left(\frac{1}{1+N^*}\right)^{\frac{1}{\gamma}} + \eta \right] \quad (12)$$

As a result, the steady-state price elasticity of demand, θ , and mark-up, μ , are also determined by the number of varieties traded and the level of competition in the economy:

$$\theta = -\frac{1}{(\gamma-1)} \frac{1}{1+\eta(1+N^*)^{\frac{1}{\gamma}}} \quad (13)$$

$$\mu = \frac{1}{1+(\gamma-1)[1+\eta(1+N^*)^{\frac{1}{\gamma}}]} \quad (14)$$

The positive relationship between the number of varieties sold in a market and the steady-state price elasticity of demand, which is incorporated into the model through the specification of households' preferences, is in line with the theory developed by Lancaster (1979), according to which firms' entry causes 'crowding' of the varieties space. As more firms sell their differentiated products in the market, varieties become more substitutable and their own price elasticity of demand increases. The existence of a positive link between the number of varieties and the price elasticity of demand has been empirically supported by Hummels and Lugovskyy (2008).

The number of traded varieties also affects the curvature of the demand function, denoted by ϵ , which is the steady-state value of the elasticity of the price elasticity of demand with respect to the relative price, also referred to as the superelasticity of demand, and is given by:

$$\epsilon = \frac{1}{(\gamma-1)} \frac{\eta}{\eta + (1+N^*)^{-\frac{1}{\gamma}}} \quad (15)$$

The functional form of the demand aggregator adopted in the analysis has the convenient property that in the special case of $\eta = 0$ it is equivalent to a standard CES Dixit-Stiglitz consumption aggregator.

3.4 Monetary policy

Following Taylor (1993), in each country there is a central bank which sets the nominal interest rate, i_t , according to a simple rule:

$$\tilde{i}_t = \phi_\pi \tilde{\pi}_t + \phi_y \tilde{x}_t + v_t \quad (16)$$

where $\tilde{\pi}_t$ is the deviation of inflation from its target, \tilde{x}_t is the domestic output gap, defined as the difference between actual and potential output, and v_t is a monetary policy shock such that $v_t = \rho_v v_{t-1} + \xi_t^v$, where $\rho_v \in (0;1)$ and $\xi_t^v \sim N(0, \sigma_v^2)$.

Determinacy of the model solution is ensured by choosing policy parameters ϕ_π and ϕ_y such that the Taylor principle is satisfied.

The monetary policy rule in the Home and Foreign economy together with the optimality conditions of profit-maximising firms and utility-maximising households and the resource constraints in both countries determine the equilibrium in the world economy.

4 Parametrisation

The model is calibrated assuming that one period of time corresponds to one quarter. In the benchmark calibration of the model parameters, firms' probability of not receiving a price adjustment signal in a given period, denoted by α , is set to 0.75. The discount factor β is assumed

to be equal to 0.995, which implies an annual steady-state real interest rate of 2 per cent. The parameters of the monetary policy rule corresponding to the weights that the central bank places on inflation and output stabilisation, given by ϕ_π and ϕ_x , are set to 1.5 and 0.5 respectively, as in Taylor (1993). The values of the inverse of the elasticity of intertemporal substitution in consumption, σ , and the inverse of the Frisch elasticity of labor supply, φ , are set to 1.38 and 1.83 respectively, in line with Smets and Wouters' (2007) estimates. The parametrisation of the shock processes is also based on Smets and Wouters (2007). A complete set of the values of the model parameters adopted in this analysis is listed in Table 0 in *Appendix A.6*.

The parameters γ and η , which control the shape of the demand function, are calibrated based on the study by Dossche, Heylen and Poel (2010). The authors use scanner price data from a large Euro Area retailer to estimate the price elasticity and superelasticity of demand for a wide range of products. They provide empirical evidence that the price elasticity of demand rises with relative price, which supports the introduction of concave demand functions into macroeconomic models. The study shows that the degree of strategic complementarity in firms' price-setting decisions, determined by the curvature of the demand function, is quite small and that it is strongly positively correlated with the price elasticity of demand. Based on the findings of Dossche, Heylen and Poel (2010), two different parametrisations of the demand function are considered. The values of the parameters adopted in this analysis are $\eta_1 = -0.30$ and $\gamma_1 = 0.62$ in the baseline calibration and $\eta_2 = -0.28$ and $\gamma_2 = 0.67$ in an alternative calibration.

Figures 1 and 2 illustrate the properties of the demand function for the two calibrations adopted throughout the analysis. Figure 1 shows how firms' price elasticity of demand and profits alter with changes in the relative price and how they compare with those obtained for a CES demand function. The figure demonstrates that in the case of a concave demand function and the associated strategic complementarity in firms' price-setting decisions, a firm's price elasticity of demand is an increasing function of its relative price. As a result, the firm's profits are more sensitive to changes in relative prices than in the case of the Dixit-Stiglitz consumption aggregator with constant price elasticity of demand.

In the framework adopted, the price elasticity of demand varies not only with a firm's relative price but also with the degree of competition in the economy. The relationships between the level of competition, measured by $(1 + N^*)$, the steady-state mark-up, μ , the corresponding steady-state price elasticity of demand, θ , and the superelasticity of demand, ϵ , are shown in Figure 2. The figure demonstrates a negative relationship between competition and firms' desired mark-ups. As the number of foreign firms in the domestic market increases from 0 to 1, which corresponds to a 100 per cent increase in the number of all varieties traded in the economy, the steady-state mark-up declines from 36 to 3 per cent in the baseline calibration and from 31 to 8 per cent in the alternative calibration.

5 Competition and real rigidities

In the framework with non-constant price elasticity of demand and a variable number of traded varieties developed above, inflation in the sector of domestically produced goods, $\tilde{\pi}_{H,t}$, is determined according to the following Phillips Curve:¹⁴

¹⁴The equation is derived in *Appendix A.4*. The derivations of domestic and imported price indices, both utility-based and competition-based, as well as domestic and foreign demand functions, which are necessary in order to derive the Phillips Curve equations for inflation in the domestic and imported goods sectors, are presented in *Appendices A.1 – A.3*.

$$\tilde{\pi}_{H,t} = \beta E_t \tilde{\pi}_{H,t+1} + \lambda \frac{(1-\alpha)(1-\alpha\beta)}{\alpha} \left[m\tilde{c}r_t - \frac{d}{\theta-1} \varpi (\tilde{p}_{H,t} - \tilde{p}_{F,t}) \right] \quad (17)$$

where $\lambda = \frac{\theta-1}{\theta-1+d}$ is a structural parameter reflecting the degree of strategic complementarity

in firms' price-setting decisions, $\varpi = \frac{N^*}{1+N^*}$ is the share of imported goods in the consumption

basket and $d = \frac{1}{\gamma-1} + \theta$; $m\tilde{c}r_t$ is the log deviation of the domestic real marginal cost from its

steady state at time t ; $\tilde{p}_{H,t}$ and $\tilde{p}_{F,t}$ denote the log deviations of the domestic and imported price indices, derived in *Appendix A.3*, from their respective steady states at time t .

Equation (17) shows that in the presence of strategic complementarity in firms' price-setting decisions, domestic inflation depends not only on marginal cost but also on the relative price of domestic to imported goods. This is due to the fact that changes in the ratio of domestic to import prices affect the price elasticity of demand and firms' desired mark-ups. To give an example, following a decrease in the price of imports which leads to an increase in the relative price of domestic goods, domestic producers face higher price elasticity of demand which prompts them to lower their mark-ups. As a result, domestic prices decline even if marginal cost remains unchanged.

Furthermore, the coefficients of the Phillips Curve depend on the number of varieties traded and the level of competition in the economy. The level of competition determines firms' price elasticity of demand and the sensitivity of their optimal price to the prices charged by their competitors and affects both the sensitivity of domestic inflation to changes in real marginal cost and relative international prices. Firstly, an increase in competitive pressure in the Home economy, corresponding to an increase in $1+N^*$, leads to a decrease in λ and therefore also a decline in the elasticity of inflation with respect to domestic marginal cost and an increase in the degree of real rigidities in price setting. Secondly, an increase in the number of imported varieties in the domestic market, resulting in higher ϖ , raises the sensitivity of domestic inflation to changes in the ratio of domestic to import prices.¹⁵

Figure 3 shows the relationship between the level of competition and the coefficients of the Phillips Curve. For the two calibrations of the model adopted in the analysis, an increase in the number of traded varieties by 100 per cent leads to a decrease in the elasticity of inflation with respect to real marginal cost by 26 and 27 per cent. At the same time, the coefficient on relative international prices rises from 0 to about 0.02.

The considerable increase in the sensitivity of domestic inflation to changes in the relative price of domestic to imported goods may suggest that an increase in the openness of the economy and competition leads to a dramatic increase in the importance of foreign economic developments in the determination of domestic inflation. However, it should be noted that this effect is partly counterbalanced by the fact that an increase in competition and the resulting

¹⁵Guerrieri, Gust and López-Salido (2010) also find that in the presence of strategic complementarity domestic inflation depends on the relative price of domestic and imported goods. However, as their analysis does not take into account the impact of trade integration and competition on steady-state mark-ups, the elasticity of inflation with regard to marginal cost is independent of the level of competition. In contrast, Sbordone (2010) accounts for the impact of competition on the sensitivity of inflation to marginal cost but ignores the role of international relative prices in the determination of domestic inflation.

increase in the degree of strategic complementarity among firms raises the impact of the prices of domestic goods on the prices of goods which are imported. This is evident from the equation for imported goods inflation, $\tilde{\pi}_{F,t}$, given by:¹⁶

$$\tilde{\pi}_{F,t} = \beta E_t \tilde{\pi}_{F,t+1} + \lambda \frac{(1-\alpha)(1-\alpha\beta)}{\alpha} \left[m\tilde{c}r_t^* + \tilde{z}_t - \frac{d}{\theta-1} (1-\varpi)(\tilde{p}_{F,t} - \tilde{p}_{H,t}) \right] \quad (18)$$

where $\lambda = \frac{\theta-1}{\theta-1+d}$, $d = \frac{1}{\gamma-1} + \theta$ and $(1-\varpi) = \frac{1}{1+N^*}$ is the share of domestically produced goods in the consumption basket; $m\tilde{c}r_t^*$ is the log deviation of the real marginal cost of the Foreign firms from its steady state at time t ; \tilde{z}_t , given by $\tilde{z}_t = \tilde{p}_{H,t}^* - \tilde{p}_{F,t} + \tilde{s}_t$, denotes the deviation from the law of one price at time t – the discrepancy between the prices of the imported goods charged in the Foreign and Home markets and expressed in the Home currency.¹⁷

The effects of changes in the openness of the economy on inflation dynamics are illustrated by examining the impact of a positive one-standard-deviation productivity shock in the Home economy on inflation and its components in both the Home and Foreign economies, which is shown in Figure 4.¹⁸ The figure compares the responses of inflation to the shock in models with constant and non-constant price elasticity of demand.¹⁹ As would be expected, in the more open economy, the responses of Home price indices to a Home shock are relatively weaker and the responses of Foreign variables to such a shock are relatively stronger than in the less open economy. However, the effects of changes in openness on inflation are more pronounced in the presence of non-constant price elasticity of demand and strategic complementarity in firms' price-setting behaviour due to the additional competitive effects of trade integration discussed above.

6 Endogenous frequency of price adjustment

In the analysis, it has so far been assumed that the fraction of firms which adjust their prices in each period, given by $(1-\alpha)$, is exogenously determined and does not depend on the level of competition in the economy. However, surveys of firms' price-setting behaviour as well as empirical studies based on micro price data strongly suggest that the intensity of competitive pressures faced by firms affects the frequency with which they change their prices. In order to take this effect into account, in what follows the frequency of price adjustment is endogenised. It is still assumed that firms set their prices in a time-dependent manner; however, it is now posited that for a given set of structural features of the economy, including the level of competition, they are able to choose the frequency of price adjustment optimally.

¹⁶For derivation see *Appendix A.4*.

¹⁷ $\hat{p}_{H,t}^*$ is the log deviation of the price of the Foreign good in the Foreign market expressed in the Foreign currency from its steady state, $\hat{p}_{F,t}$ denotes the log deviation of the price of the Foreign good in the Home market expressed in the Home currency from its steady state and \hat{s}_t is the log deviation of the nominal exchange rate from its steady state level.

¹⁸Two levels of openness are considered, one in which foreign goods constitute 20 per cent of all goods sold in the domestic economy and one in which the share of foreign goods in the consumption basket is equal to 43 per cent, which correspond to $N = 0.25$ and $N = 0.75$ respectively. The difference in trade openness in these two parametrisations is similar to the increase in openness in Germany between 1993 and 2012.

¹⁹In the model with constant price elasticity of demand, firms' steady-state desired mark-ups are set to 19 per cent, which corresponds to the desired mark-ups obtained for $N^* = 0.5$ in the non-constant price elasticity model.

As in Eichenbaum and Fisher (2007), the assumption that firms use time-dependent rather than state-dependent pricing policies is motivated by the presence of re-optimization costs such as the costs associated with information-gathering, decision-making, negotiation and communication, which do not make it optimal for firms to review their prices in each period. Using microeconomic data, Zbaracki *et al.* (2004) show that these costs are substantially more important than menu costs.²⁰

6.1 Firms' price setting decisions

In this framework, firms' pricing decisions can be thought of as being taken in two stages. In the first stage, firms decide on their pricing policy – they choose a frequency of price adjustment which, for a given structure of the economy and a given cost of price adjustment, maximises the expected discounted value of their lifetime profits. In the second stage, firms set their prices optimally in line with their chosen pricing policy. In other words, once the frequency of price adjustment has been chosen, firms take it as given in subsequent periods and adjust their prices accordingly as long as the structure of the economy remains unchanged.

Following Rotemberg (1982) and Romer (1990), firm i 's problem of profit maximisation associated with its choice of the frequency of price adjustment is equivalent to the problem of minimisation of the unconditional expected value of the following loss function:²¹

$$L_t(\alpha_i, \alpha) = G + \min_{P_{i,t}^o} E_t \sum_{k=0}^{\infty} (\beta \alpha_i)^k \left[\Pi_{t+k} \left(\frac{P_{i,t+k}^f}{P_{t+k}} \right) - \Pi_{t+k} \left(\frac{P_{i,t}^o}{P_{t+k}} \right) \right] \quad (19)$$

$$+ \beta(1 - \alpha_i) \sum_{k=1}^{\infty} (\beta \alpha_i)^{k-1} E_t L_{t+k}(\alpha_i, \alpha)$$

with respect to α_i , where α_i is the probability that firm i keeps its price unchanged in a given period; α is the fraction of all firms which do not adjust their prices in a given period; G is the cost of price adjustment; $\frac{P_{i,t}^f}{P_t}$ is the optimal relative price in period t if prices were adjusted

without cost in each period; $\frac{P_{i,t}^o}{P_t}$ is the optimal relative price in period t in the presence of

nominal rigidities and price adjustment costs. $\Pi_{t+k} \left(\frac{P_{i,t+k}^f}{P_{t+k}} \right)$ denotes firm i 's profit at time $t+k$ if

its price is equal to $\frac{P_{i,t+k}^f}{P_{t+k}}$, and $\Pi_{t+k} \left(\frac{P_{i,t}^o}{P_{t+k}} \right)$ is firm i 's profit at time $t+k$ if its price is equal to

$$\frac{P_{i,t}^o}{P_{t+k}}.$$

²⁰The assumption of time-dependent price setting policies is also consistent with survey evidence. Firms' surveys indicate that in the Euro Area 34 per cent of firms use purely time-dependent pricing policies, whereas about 46 per cent of them use a combination of time- and state-dependent strategies (Fabiani *et al.*, 2005). In the US the fraction of firms reviewing their prices on a periodic basis is even higher and equals 40 per cent (Blinder *et al.*, 1998).

²¹For tractability, it is assumed that firms choose the frequency with which they change their prices in the domestic market optimally and that exporters adopt the same frequency of price adjustment for exports. In consequence, the frequency of price adjustment of all goods sold in the economy, whether they are domestically produced or imported, is the same.

The loss function represents the difference in the expected present value of firm i 's profits in the case in which it adjusts its price in a given period with probability $(1 - \alpha_i)$ and incurs a fixed cost of price adjustment and the case in which it adjusts its price in each period without any costs. The first term on the right hand side of the equation reflects the cost of setting a new price in period t , the second term denotes a loss in profit resulting from keeping this price unchanged in subsequent periods, whereas the last term represents the sum of losses in profit from setting a new price in some future period and keeping it unchanged thereafter.

Using the law of iterated expectations, $E_0[E_t L_{t+k}(\alpha_i, \alpha)] = E_0[L_t(\alpha_i, \alpha)]$, the unconditional expected value of the loss function (19), given by $L_E(\alpha_i, \alpha) = E_0[L_t(\alpha_i, \alpha)]$, can be expressed as follows:

$$L_E(\alpha_i, \alpha) = \frac{1 - \alpha_i \beta}{1 - \beta} \left[G + E_0 \sum_{k=0}^{\infty} (\alpha_i \beta)^k \left(\Pi_{t+k} \left(\frac{P_{i,t+k}^f}{P_{t+k}} \right) - \Pi_{t+k} \left(\frac{P_{i,t}^o}{P_{t+k}} \right) \right) \right] \quad (20)$$

Minimisation of (20) with respect to α_i gives rise to the following first order condition, which in equilibrium must hold for all firms:

$$G + E_0 \sum_{k=0}^{\infty} (\alpha_i \beta)^{k-1} [\alpha_i \beta - k(1 - \alpha_i \beta)] \left[\Pi_{t+k} \left(\frac{P_{i,t+k}^f}{P_{t+k}} \right) - \Pi_{t+k} \left(\frac{P_{i,t}^o}{P_{t+k}} \right) \right] = 0 \quad (21)$$

When choosing their frequency of price adjustment $(1 - \alpha_i)$, firms take as given the frequency of price adjustment of other firms. The condition for the economy-wide frequency of price adjustment $(1 - \alpha)$ to be a symmetric Nash equilibrium is that the optimality condition (21) holds at α_i equal to α for all firms. Therefore, the frequency of price adjustment $(1 - \alpha_i)$ which satisfies (21) with $\alpha_i = \alpha$ for all firms is the optimal frequency of price adjustment.

6.2 Forces driving the optimal frequency of price adjustment

The first order condition (21) shows that the optimal frequency of price adjustment equalises the cost of price adjustment with the opportunity cost of not adjusting prices. This opportunity cost depends on the expected discounted sum of the differences between profits obtained at the optimal flexible price and the actual price in a given period. The greater the differences, the greater incentive firms have to adjust their prices. In order to understand the determinants of the frequency of price adjustment, it is therefore crucial to identify the factors determining the difference between profits obtained at a price which would be optimal for a given period if firms were able to adjust their prices in each period without cost and profits obtained at the prevailing price in that period. This difference will henceforth be referred to as the 'period loss function'.

After a second-order approximation of firm i 's profits, $\Pi_{t+k} \left(\frac{P_{i,t}^o}{P_{t+k}} \right)$, around the optimal flexible price, $\frac{P_{i,t+k}^f}{P_{t+k}}$, the period loss function can be expressed as follows:

$$\Pi_{t+k} \left(\frac{P_{i,t+k}^f}{P_{t+k}} \right) - \Pi_{t+k} \left(\frac{P_{i,t}^o}{P_{t+k}} \right) \approx -\frac{1}{2} \Pi_{t+k}'' \left(\frac{P_{i,t+k}^f}{P_{t+k}} \right) \left(\frac{P_{i,t+k}^f}{P_{t+k}} - \frac{P_{i,t}^o}{P_{t+k}} \right)^2 \quad (22)$$

The approximation (22) reveals that the loss in profits in a given period depends on two factors: the deviation of the optimal relative price from the actual price in that period,

$\left(\frac{P_{i,t+k}^f}{P_{t+k}} - \frac{P_{i,t}^o}{P_{t+k}}\right)$, and the curvature of the profit function, $\Pi_{t+k}''\left(\frac{P_{i,t+k}^f}{P_{t+k}}\right)$, which determines the

opportunity cost of a given deviation of the actual price from the optimal flexible price. The period loss function can be further approximated and rewritten as a function of the steady-state values of the model variables and the log deviations of the optimal flexible price and the actual price from their steady states:²²

$$\Pi_{t+k}\left(\frac{P_{i,t+k}^f}{P_{t+k}}\right) - \Pi_{t+k}\left(\frac{P_{i,t}^o}{P_{t+k}}\right) \approx \frac{1}{2}\left(\frac{P_i}{P}\right)\left(\frac{Y_i}{Y}\right)Y(\theta + \epsilon - 1)(\tilde{p}_{i,t+k}^f - \tilde{p}_{i,t}^o)^2 \quad (23)$$

where $\left(\frac{P_i}{P}\right)\left(\frac{Y_i}{Y}\right) = \frac{1}{1 + N^*}$, Y is the equilibrium level of output in a steady state with symmetric

prices, $\frac{Y_i}{Y}$ is firm i 's steady-state market share, $\frac{P_i}{P}$ is the steady-state relative price of firm i 's

product, $\tilde{p}_{i,t+k}^f$ is the log deviation of $\frac{P_{i,t+k}^f}{P_{t+k}}$ from its steady state and $\tilde{p}_{i,t}^o$ is the log deviation

of $\frac{P_{i,t}^o}{P_{t+k}}$ from its steady state.

The profit loss associated with a given deviation of the actual price from the optimal price depends on the sensitivity of demand to changes in a firm's relative price, which is determined by the price elasticity of demand and the superelasticity of demand. It also depends on the steady-state demand for the firm's product, which is determined by the firm's steady-state market share and the steady-state level of output. The deviation of the optimal relative price from the actual price depends on a number of structural features of the economy, including the degree of strategic complementarity in firms' price setting decisions, the importance of the relative price of imported to domestic goods in the determination of domestic inflation and the frequency with which firms change their prices.

6.3 Competition and nominal rigidities

Having identified the factors determining the opportunity cost of not adjusting prices, it is now possible to analyse how they are affected by the level of competition in the economy. Firstly, the level of competition affects firms' steady-state revenues and profits. There are two forces acting in opposite directions. On one hand, an increase in the number of competitors lowers firms'

steady-state market shares, $\frac{Y_i}{Y}$, and mark-ups, $\mu = \frac{\theta}{\theta - 1}$, which has a negative impact on firms'

profits and drives the opportunity cost of not adjusting prices down. On the other hand, however, an increase in competitive pressure reduces the distortion associated with imperfect competition and increases the steady-state level of output, Y , which raises firms' profits and thereby strengthens their incentives to adjust prices. Secondly, a rise in competition increases the sensitivity of firms' profits to a given deviation of the actual price from the desired price. Greater competition is associated with higher price elasticity of demand, θ , and higher superelasticity of demand, ϵ , which makes it costlier for firms to keep their prices unchanged. Furthermore, an increase in trade openness and competition increases strategic complementarity in firms' price-setting decisions and the importance of the relative price of domestic to imported goods in

²²For derivation see Appendix A.5.

the determination of domestic inflation, which influence the deviations of firms' prices from their desired prices, $\tilde{p}_{i,t+k}^f - \tilde{p}_{i,t}^o$, and thereby also the costs and benefits of price adjustment. Finally, the deviations of a firm's price from its desired price are also affected by the frequency of price adjustment by other firms in the economy, which in turn depends on the level of openness and competition.

The analysis shows that competition affects several determinants of the opportunity cost of not adjusting prices and that there are divergent forces at work. The net effect of greater competition on the degree of nominal price rigidities can be determined numerically.

Combining (21) and (23), the equilibrium condition associated with the choice of a firm's pricing policy can be written as follows:

$$G + E_0 \sum_{k=0}^{\infty} (\alpha_i \beta)^{k-1} [\alpha_i \beta - k(1 - \alpha_i \beta)] \frac{1}{2} \left(\frac{P_i}{P} \right) \left(\frac{Y_i}{Y} \right) Y (\theta + \epsilon - 1) (\tilde{p}_{i,t+k}^f - \tilde{p}_{i,t}^o)^2 = 0 \quad (24)$$

For a given level of competition, the equilibrium frequency of price adjustment can be obtained in the following way. Firstly, the model described in section two is solved for a given level of α . Secondly, the obtained solution is substituted into equation (24) and it is examined whether the condition holds with α_i equal to α . The α for which this is the case determines the equilibrium frequency of price adjustment. This strategy can be used to find the optimal frequency of price adjustment for different levels of competition.

Figures 5 and 6 illustrate the relationship between the level of competition and the price adjustment frequency, $(1 - \alpha)$, for two different calibrations of the demand function. They show that competition generally has a positive impact on the optimal frequency of price changes. A 100 per cent increase in the number of varieties available to domestic consumers, associated with a decline in mark-ups from 36 to 3 per cent in the baseline calibration and from 31 to 8 per cent in the alternative calibration, leads to an increase in the share of firms adjusting their prices in a given period from 35 per cent to 49 and 41 per cent respectively.²³

The effects of greater competition are relatively small and ambiguous when the initial levels of the openness of the economy and competition are low and they are much larger for a higher initial degree of openness and competitive pressure. This is due to the fact that when a firm enjoys high market power and its steady-state mark-up is high, an increase in competition resulting in a decline in this mark-up by one percentage point is associated with relatively small increases in the steady-state price elasticity and superelasticity of demand. While these increases raise the profit loss resulting from a given deviation of the firm's actual price from its optimal price, this effect is to some extent offset by a decrease in the average deviation of the actual price from the desired price induced by higher competition. In turn, when a firm's steady-state mark-up is low, a decrease in this mark-up by one percentage point gives rise to a substantial increase in both price elasticity and superelasticity of demand and this increase has a strong and dominating effect on firms' incentives to adjust their prices.

The analysis of the impact of trade openness and competition on the frequency with which firms change their prices demonstrates that greater competitive pressure reduces the degree of nominal price rigidities, which is consistent with empirical and survey evidence

²³When solving for the optimal frequency of price adjustment, the value of the price adjustment cost, G , is calibrated based on a study by Zbaracki *et al.* (2004), who estimate that these costs constitute 1.22 per cent of firms' revenues. Setting these costs equal to about 4 per cent of firms' revenues, an estimate obtained by Willis (2000), reduces the optimal price adjustment frequency by about 6-8 percentage points for any given level of competition as compared to the benchmark calibration.

concerning firms' price-setting behaviour.

6.4 Other determinants of the frequency of price adjustment

Competition is not the only factor affecting the optimal frequency of price adjustment. Any changes in the structural features of the economy which influence the variability of desired prices also affect the average deviation of the actual price from the optimal price and therefore the optimal price adjustment frequency. One such feature is the magnitude of shocks hitting the economy.

Figure 7 shows the optimal frequency of price adjustment for different values of the standard deviation of shocks. A 20 per cent decrease in the standard deviations of all macroeconomic shocks reduces the opportunity cost of not adjusting prices and leads to a decrease in the fraction of firms updating their prices in a given period by about 3 percentage points for any given level of competition.²⁴

For a similar reason, the optimal frequency of price adjustment also depends on the parameters of the monetary policy rule. The greater weight the central bank places on inflation stabilisation, the less variable is the desired price and the less frequent the price adjustment.²⁵ An increase in ϕ_π from 1.5 to 2.0 reduces the fraction of firms adjusting their prices in a given period by 5-7 percentage points, which is illustrated in Figure 8.

The analysis sheds new light on the results from previous studies, discussed in section 2, which identified a number of factors influencing the short-run inflation-output trade-off and its relationship with trade openness. By affecting the opportunity cost of not adjusting prices, any factors which influence the level and volatility of inflation and hence also the variability of desired prices, such as central bank independence, exchange rate pass-through and the exchange rate regime, may lead to changes in the optimal frequency of price adjustment and the sensitivity of inflation to fluctuations in domestic economic activity.

6.5 Competition and the Phillips Curve

The study has demonstrated that greater trade openness and competition leads to a higher degree of real price rigidities and a lower degree of nominal price rigidities in the economy. The overall impact of openness on the parameters of the Phillips Curve is shown in Figure 9. An increase in trade openness and competitive pressures faced by firms unambiguously leads to an increase in the elasticity of inflation with respect to the relative price of domestic and imported goods and this effect is particularly strong for highly integrated economies. The influence of greater competition on price flexibility and the sensitivity of domestic inflation to changes in domestic marginal cost depends on the initial level of openness and competitive pressure in the economy. For a relatively closed economy in which firms have high market power the effect is small and negative. For a high initial level of openness and competition, an increase in the frequency of price adjustment associated with trade integration more than offsets the increase in the degree of real price rigidities and, as a result, price flexibility and the elasticity of inflation with respect to marginal cost rise. For the two calibrations of the model parameters adopted in the analysis, greater competition results in greater sensitivity of inflation to changes in real marginal cost when steady-state mark-ups are below 22-23 per cent.

By accounting for the effects of competition on price rigidities, the study provides yet

²⁴A similar result has been obtained by Romer (1990) who also finds a positive relationship between the frequency of price changes and the variance of shocks.

²⁵This result confirms findings by Kimura and Kurozumi (2010) and Senay and Sutherland (2014) obtained in closed-economy models. They also show that the frequency of price adjustment is negatively related to the weight that the central bank places on inflation stabilisation.

another channel through which the impact of trade openness on the slope of the Phillips curve is theoretically ambiguous and which helps to explain the conflicting results concerning the direction of this relationship obtained in the empirical literature. Furthermore, the finding that the effects of trade openness on the inflation-output trade-off depend on the initial level of openness and competition is consistent with the general pattern in the empirical results obtained for different sets of countries over different time periods. As noted in Daniels, Mazumder and VanHoose (2015), earlier studies on this topic based on data up to the late 1980s tend to find no or negative impact of increased openness on the sensitivity of inflation to changes in domestic economic activity (Temple, 2002; Daniels, Nourzad and VanHoose, 2005). In contrast, studies examining more recent data consistently find evidence of a positive, statistically significant effect of trade openness on the slope of the Phillips Curve (Bowdler, 2009; Pickering and Valle, 2012; Daniels and VanHoose, 2013; Daniels, Mazumder and VanHoose, 2015). A comparison of the shares of imports in GDP, which is the standard measure of trade openness used in the literature, reveals that the average levels of openness in the cross-country data samples used by Bowdler (2009), Pickering and Valle (2012), Daniels and Van Hose (2013) and Daniels, Mazumder and VanHoose (2015) are higher than the average levels of openness in the data analysed by Temple (2002) and Daniels, Nourzad and VanHoose (2005), which may help to explain their different findings.

The results of this paper have several implications for future empirical work on the impact of trade openness on the sensitivity of inflation to output fluctuations. Firstly, as countries with different initial levels of openness may observe very different effects of trade integration on price stickiness and inflation, the study provides additional motivation for country-specific time-series analysis of this relationship along the lines of Eijffinger and Qian (2010) which does not impose the assumption of parameter constancy across countries. Secondly, the results suggest that both cross-country and country-specific studies should account for the initial level of competition and firms' market power as one of the determinants of the impact of trade openness on the short-run trade-off between output and inflation.

7 Conclusions

This paper examined the impact of trade openness and product market competition on firms' price-setting decisions and the inflation-output trade-off. It provided new insights into the determinants of real and nominal price rigidities. The analysis demonstrated that stronger competitive pressure, resulting from a higher number of varieties available in the domestic market, raises the sensitivity of firms' profit-maximising price to the prices charged by their competitors and the degree of real price rigidities. The level of competition and the associated degree of strategic complementarity affect firms' opportunity cost of not adjusting prices. There are two divergent forces at work. On one hand, greater competition and the resulting higher degree of real rigidities leads to a lower average deviation of firms' optimal price from their actual price following a change in economic conditions, which reduces firms' incentives to adjust their prices. On the other hand, higher steady-state price elasticity and superelasticity of demand associated with greater competition raises the loss of profit resulting from a given deviation of the desired price from the actual price, which makes it more profitable for firms to adjust their prices. For plausible calibration of the model parameters the latter effect dominates and, as a result, stronger competitive pressure leads to more frequent price adjustment and a lower degree of nominal rigidities in the economy. The study therefore provides a theoretical explanation of the positive link between competition and the frequency of price adjustment evident from empirical studies and surveys of firms' price-setting behaviour.

Accounting for the effects of competition on the degree of real and nominal price rigidities sheds new light on the impact of global economic integration on the Phillips Curve and inflation dynamics. In the presence of strategic complementarity in firms' price-setting decisions, domestic inflation depends not only on domestic real marginal cost but also on the ratio of the prices of imported goods to the prices of domestically produced goods. The level of competition affects both the elasticity of inflation with regard to marginal cost and relative international prices. The stronger the competitive pressure, the greater the importance of the price ratio of imported to domestic goods in the determination of domestic inflation. Due to the fact that changes in competition lead to changes in real and nominal price rigidities in opposite directions, the overall impact of trade openness on the inflation-output trade-off and the slope of the Phillips Curve is ambiguous and depends on the initial level of openness and competition in the economy. For highly integrated economies the effect of trade integration on price flexibility is positive and therefore trade openness raises the sensitivity of inflation to changes in domestic economic activity, which is consistent with recent empirical evidence.

There are a number of ways in which the impact of trade openness and competition on price rigidities and its implications for the inflation-output trade-off could be explored further. Firstly, in line with extensive empirical evidence and in order to focus on the strategic interactions between firms selling their goods in a given market, this study assumes that firms set prices in the currency of the country in which goods are sold. It would be interesting to consider the effects of openness on price stickiness under alternative assumptions concerning price setting by exporters, including producer currency pricing and a combination of local currency pricing and producer currency pricing strategies. This would make it possible to analyse the impact of the degree of exchange rate pass-through on the relationship between trade openness and the inflation-output trade-off, which has been shown to play a role in the related literature.

Furthermore, one limitation of the analysis is that in the model developed the parameters of the monetary policy rule are assumed to be exogenous and independent of the parameters of the Phillips Curve. However, studies on optimal monetary policy have shown that the inflation-output trade-off affects the optimal monetary policy rule. In turn, as has been discussed in section 6.4, by affecting the variability of inflation, the parameters of the monetary policy rule affect the optimal frequency of price adjustment. It would therefore be valuable to analyse the effects of trade openness and competition on the inflation-output trade-off in a setting in which monetary policy parameters are endogenously determined and which takes the above feedback effects into account.

Finally, in order to isolate the effects of trade openness on the inflation-output trade-off resulting from changes in real and nominal price rigidities and provide a clear exposition of the underlying mechanism, the model has been kept relatively simple and does not incorporate many other channels which have been shown to affect this relationship. In future research it would be desirable to examine the impact of trade-openness on price flexibility alongside these other channels within a richer framework which would allow assessing their relative importance and providing a more comprehensive analysis of the net effect of trade openness on the slope of the Phillips Curve.

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A Appendix

A.1 Derivation of demand functions

A.1.1 Demand for individual varieties as a fraction of aggregate consumption

The consumption aggregator C_t is implicitly defined by equations (6) and (7). Therefore, households choose the levels of consumption of individual Home and Foreign varieties, $C_{H,i,t}$ and $C_{F,i,t}$, in order to minimise their expenditure D_t given by:

$$D_t = \int_0^1 P_{H,i,t} C_{H,i,t} di + \int_1^{1+N^*} P_{F,i,t} C_{F,i,t} di \quad (25)$$

subject to (6).

The Lagrangian for the optimisation problem is:

$$L = \int_0^1 P_{H,i,t} C_{H,i,t} di \quad (26)$$

$$+ \int_1^{1+N^*} P_{F,i,t} C_{F,i,t} di - \Lambda \left[\int_0^1 f\left(\frac{C_{H,i,t}}{C_t}\right) di + \int_1^{1+N^*} f\left(\frac{C_{F,i,t}}{C_t}\right) di - 1 \right]$$

The first order condition with respect to $C_{X,i,t}$, where $X = \{H, F\}$, is given by:

$$P_{X,i,t} = \frac{\Lambda}{C_t} [(1 + \eta) \frac{C_{X,i,t}}{C_t} - \eta]^{\gamma-1} \quad (27)$$

We define the competition-based aggregate price index $\tilde{P}_t = \frac{\Lambda}{C_t}$. After substitution:

$$\frac{P_{X,i,t}}{\tilde{P}_t} = [(1 + \eta) \frac{C_{X,i,t}}{C_t} - \eta]^{\gamma-1} \quad (28)$$

The demand function for an individual variety is therefore given by equation (8)

A.1.2 Demand for individual domestic varieties as a fraction of the consumption of domestic goods

The demand aggregator for the consumption of domestic goods, denoted by $C_{H,t}$, is implicitly defined by:

$$\int_0^1 f\left(\frac{C_{H,i,t}}{C_{H,t}}\right) di = 1 \quad (29)$$

$$\text{where } f\left(\frac{C_{H,i,t}}{C_{H,t}}\right) = \frac{1}{(1 + \eta)\gamma} \left[(1 + \eta) \frac{C_{H,i,t}}{C_{H,t}} - \eta \right]^\gamma - \left[\frac{1}{(1 + \eta)\gamma} - 1 \right] \quad (30)$$

Households choose the levels of consumption of individual domestic varieties, $C_{H,i,t}$, in order to minimise their expenditure:

$$D_{H,t} = \int_0^1 P_{H,i,t} C_{H,i,t} di \quad (31)$$

subject to (29).

The Lagrangian for the optimisation problem is:

$$L = \int_0^1 P_{H,i,t} C_{H,i,t} di - \Lambda_H \left[\int_0^1 f\left(\frac{C_{H,i,t}}{C_{H,t}}\right) di - 1 \right] \quad (32)$$

The first order condition with respect to $C_{H,i,t}$ is given by:

$$P_{H,i,t} = \frac{\Lambda_H}{C_{H,t}} [(1 + \eta) \frac{C_{H,i,t}}{C_{H,t}} - \eta]^{\gamma-1} \quad (33)$$

We define the competition-based domestic price index $\tilde{P}_{H,t} = \frac{\Lambda_H}{C_{H,t}}$. After substitution:

$$\frac{P_{H,i,t}}{\tilde{P}_{H,t}} = [(1 + \eta) \frac{C_{H,i,t}}{C_{H,t}} - \eta]^{\gamma-1} \quad (34)$$

The demand function for the domestic good as a fraction of the domestic consumption

aggregator is therefore given by:

$$\frac{C_{H,i,t}}{C_{H,t}} = \frac{1}{(1+\eta)} \left(\frac{P_{H,i,t}}{P_{H,t}} \right)^{\frac{1}{\gamma-1}} + \frac{\eta}{(1+\eta)} \quad (35)$$

A.1.3 Demand for individual imported varieties as a fraction of the consumption of imported goods

The demand aggregator for the consumption of imported goods, denoted by $C_{F,t}$, is implicitly defined by:

$$\int_1^{1+N^*} f\left(\frac{C_{F,i,t}}{C_{F,t}}\right) di = 1 \quad (36)$$

$$\text{where } f\left(\frac{C_{F,i,t}}{C_{F,t}}\right) = \frac{1}{(1+\eta)\gamma} \left[(1+\eta) \frac{C_{F,i,t}}{C_{F,t}} - \eta \right]^\gamma - \frac{1}{N^*} \left[\frac{1}{(1+\eta)\gamma} - 1 \right] \quad (37)$$

Households choose the levels of consumption of individual imported varieties, $C_{F,i,t}$, in order to minimise their expenditure:

$$D_{F,t} = \int_1^{1+N^*} P_{F,i,t} C_{F,i,t} di \quad (38)$$

subject to (36).

The Lagrangian for the optimisation problem is:

$$L = \int_1^{1+N^*} P_{F,i,t} C_{F,i,t} di - \Lambda_F \left[\int_1^{1+N^*} f\left(\frac{C_{F,i,t}}{C_{F,t}}\right) di - 1 \right] \quad (39)$$

The first order condition with respect to $C_{F,i,t}$ is given by:

$$P_{F,i,t} = \frac{\Lambda_F}{C_{F,t}} \left[(1+\eta) \frac{C_{F,i,t}}{C_{F,t}} - \eta \right]^{\gamma-1} \quad (40)$$

We define the competition-based imported price index $\tilde{P}_{F,t} = \frac{\Lambda_F}{C_{F,t}}$. After substitution:

$$\frac{P_{F,i,t}}{\tilde{P}_{F,t}} = \left[(1+\eta) \frac{C_{F,i,t}}{C_{F,t}} - \eta \right]^{\gamma-1} \quad (41)$$

The demand function for the imported good as a fraction of domestic consumption aggregator is:

$$\frac{C_{F,i,t}}{C_{F,t}} = \frac{1}{(1+\eta)} \left(\frac{P_{F,i,t}}{\tilde{P}_{F,t}} \right)^{\frac{1}{\gamma-1}} + \frac{\eta}{(1+\eta)} \quad (42)$$

A.2 Derivation of competition-based price indices

A.2.1 Aggregate competition-based price index

After substituting the demand function (8) into (6) we obtain:

$$\int_0^1 \left[\frac{1}{(1+\eta)\gamma} \left(\frac{P_{H,i,t}}{\tilde{P}_t} \right)^{\frac{\gamma}{\gamma-1}} - \frac{1}{1+N^*} \left(\frac{1}{(1+\eta)\gamma} - 1 \right) \right] di \quad (43)$$

$$+ \int_1^{1+N^*} \left[\frac{1}{(1+\eta)\gamma} \left(\frac{P_{F,i,t}}{P_t} \right)^{\frac{\gamma}{\gamma-1}} - \frac{1}{1+N^*} \left(\frac{1}{(1+\eta)\gamma} - 1 \right) \right] di = 1$$

The competition-based aggregate price index can then be expressed as (9).

A.2.2 Domestic competition-based price index

After substituting the demand function (35) into (29) we obtain:

$$\int_0^1 \left[\frac{1}{(1+\eta)\gamma} \left(\frac{P_{H,i,t}}{P_{H,t}} \right)^{\frac{\gamma}{\gamma-1}} - \left(\frac{1}{(1+\eta)\gamma} - 1 \right) \right] di = 1 \quad (44)$$

The competition-based domestic price index can then be written as:

$$\tilde{P}_{H,t} = \left[\int_0^1 (P_{H,i,t})^{\frac{\gamma}{\gamma-1}} di \right]^{\frac{\gamma-1}{\gamma}} \quad (45)$$

A.2.3 Imported competition-based price index

After substituting the demand function (42) into (36) we obtain:

$$\int_1^{1+N^*} \left[\frac{1}{(1+\eta)\gamma} \left(\frac{P_{F,i,t}}{P_{F,t}} \right)^{\frac{\gamma}{\gamma-1}} - \frac{1}{N^*} \left(\frac{1}{(1+\eta)\gamma} - 1 \right) \right] di = 1 \quad (46)$$

The competition-based imported price index can then be written as:

$$\tilde{P}_{F,t} = \left[\int_1^{1+N^*} (P_{F,i,t})^{\frac{\gamma}{\gamma-1}} di \right]^{\frac{\gamma-1}{\gamma}} \quad (47)$$

A.3 Derivation of utility-based price indices

A.3.1 Aggregate utility-based price index

The aggregate utility-based consumption index, P_t , defined as the minimum expenditure necessary to obtain a unit level of aggregate consumption C_t , satisfies the following condition:

$$P_t C_t = \int_0^1 P_{H,i,t} C_{H,i,t} di + \int_1^{1+N^*} P_{F,i,t} C_{F,i,t} di = \int_0^{1+N^*} P_{i,t} C_{i,t} di \quad (48)$$

Substituting the demand function (8) into (48) we have:

$$P_t = \frac{1}{C_t} \int_0^{1+N^*} P_{i,t} \left[\frac{1}{1+\eta} \left(\frac{P_{i,t}}{P_t} \right)^{\frac{1}{\gamma-1}} + \frac{\eta}{1+\eta} \right] C_t di \quad (49)$$

After using (9) we obtain:

$$P_t = \frac{1}{(1+\eta)} \left[\tilde{P}_t + \eta \int_0^{1+N^*} P_{i,t} di \right] = \frac{1}{(1+\eta)} \left[\left(\int_0^{1+N^*} P_{i,t}^{\frac{\gamma}{\gamma-1}} di \right)^{\frac{\gamma-1}{\gamma}} + \eta \int_0^{1+N^*} P_{i,t} di \right] \quad (50)$$

A.3.2 Domestic utility-based price index

The domestic utility-based consumption index, $P_{H,t}$, defined as the minimum expenditure necessary to obtain a unit level of domestic consumption $C_{H,t}$, satisfies the following condition:

$$P_{H,t} C_{H,t} = \int_0^1 P_{H,i,t} C_{H,i,t} di \quad (51)$$

Substituting the demand function (35) into (51) we have:

$$P_{H,t} = \frac{1}{C_{H,t}} \int_0^1 P_{H,i,t} \left[\frac{1}{1+\eta} \left(\frac{P_{H,i,t}}{P_{H,t}} \right)^{\frac{1}{\gamma-1}} + \frac{\eta}{1+\eta} \right] C_{H,i,t} di \quad (52)$$

After using (45) we obtain:

$$P_{H,t} = \frac{1}{(1+\eta)} \left[\tilde{P}_{H,t} + \eta \int_0^1 P_{H,i,t} di \right] \quad (53)$$

A.3.3 Imported utility-based price index

The imported utility-based consumption index, $P_{F,t}$, defined as the minimum expenditure necessary to obtain a unit level of imported consumption $C_{F,t}$, satisfies the following condition:

$$P_{F,t} C_{F,t} = \int_1^{1+N^*} P_{F,i,t} C_{F,i,t} di \quad (54)$$

Substituting the demand function (42) into (54) we have:

$$P_{F,t} = \frac{1}{C_{F,t}} \int_1^{1+N^*} P_{F,i,t} \left[\frac{1}{1+\eta} \left(\frac{P_{F,i,t}}{P_{F,t}} \right)^{\frac{1}{\gamma-1}} + \frac{\eta}{1+\eta} \right] C_{F,i,t} di \quad (55)$$

After using (47) we obtain:

$$P_{F,t} = \frac{1}{(1+\eta)} \left[\tilde{P}_{F,t} + \eta \int_1^{1+N^*} P_{F,i,t} di \right] \quad (56)$$

A.4 Derivation of the Phillips Curve equations

A.4.1 Domestic price inflation

In order to derive the Phillips Curve for domestic inflation, it is necessary to solve the optimisation problem of a domestic firm setting the price of its good in the domestic market, $P_{H,i,t}$. When receiving a signal to update its price, a domestic non-exporter chooses a price of its good in the domestic market to maximise (2) subject to (8), whereas a domestic exporter chooses a price of its good in the domestic market such that it maximises (3) subject to (8).

The first order condition with respect to $P_{H,i,t}$ is the same for both the exporter and the non-exporter and is given by:

$$E_t \sum_{k=0}^{\infty} \alpha^k Q_{k,t+k} [C_{H,i,t+k} - C_{H,i,t+k} \theta_{H,i,t+k} + MC_{t+k} \theta_{H,i,t+k} \frac{C_{H,i,t+k}}{P_{H,i,t}^o}] = 0 \quad (57)$$

The equation can be rewritten as:

$$E_t \sum_{k=0}^{\infty} \alpha^k Q_{k,t+k} C_{H,i,t+k} \left[\frac{P_{H,i,t}^o}{P_{H,t}} (1 - \theta_{D,i,t+k}) + \frac{MC_{t+k}}{P_{H,t+k}} \frac{P_{H,t+k}}{P_{H,t-1}} \frac{P_{H,t-1}}{P_{H,t}} \theta_{H,i,t+k} \right] = 0 \quad (58)$$

We will now define the relative optimal domestic price $R_{H,i,t} = \frac{P_{H,i,t}^o}{P_{H,t}}$, real domestic marginal

cost $MCR_{t+k} = \frac{MC_{t+k}}{P_{H,t+k}}$ and domestic inflation $\Pi_{H,t} = \frac{P_{H,t}}{P_{H,t-1}}$. After substitution, (58) can be expressed as:

$$E_t \sum_{k=0}^{\infty} \alpha^k Q_{k,t+k} C_{H,i,t+k} [R_{H,i,t} (1 - \theta_{H,i,t+k}) + MCR_{t+k} \frac{\prod_{s=0}^k \Pi_{H,t+s}}{\Pi_{H,t}} \theta_{H,i,t+k}] = 0 \quad (59)$$

Using the fact that $Q_{k,t+k} = \beta^k \left(\frac{C_{t+k}}{C_t} \right)^{-\sigma} \frac{P_t}{P_{t+k}} e^{u_{t+k} - u_t}$ and after log-linearizing (59) around a symmetric steady state we have:

$$\tilde{r}_{H,i,t} = (1 - \alpha\beta) E_t \sum_{k=0}^{\infty} (\alpha\beta)^k (m\tilde{c}r_{t+k} + \sum_{s=0}^k \tilde{\pi}_{H,t+s} - \tilde{\pi}_{H,t} - \frac{1}{\theta-1} \tilde{\theta}_{H,i,t+k}) \quad (60)$$

The log deviation of the price elasticity of demand from its steady state is given by:

$$\tilde{\theta}_{H,i,t+k} = \left(\frac{1}{\gamma-1} + \theta \right) \left[\tilde{r}_{H,i,t} + \tilde{\pi}_{H,t} - \sum_{s=0}^k \tilde{\pi}_{H,t+s} + \frac{N^*}{1+N^*} (\tilde{p}_{H,t} - \tilde{p}_{F,t}) \right] \quad (61)$$

Therefore, after substitution, (60) can be expressed as follows:

$$\begin{aligned} \tilde{r}_{H,i,t} &= -\tilde{\pi}_{H,t} + (1 - \alpha\beta) E_t \sum_{k=0}^{\infty} (\alpha\beta)^k \sum_{s=0}^k \tilde{\pi}_{H,t+s} \\ &+ \frac{1}{1+b} (1 - \alpha\beta) E_t \sum_{k=0}^{\infty} (\alpha\beta)^k [m\tilde{c}r_{t+k} - b\varpi (\tilde{p}_{H,t} - \tilde{p}_{F,t})] \end{aligned} \quad (62)$$

where $b = \frac{1}{\theta-1} \left(\frac{1}{\gamma-1} + \theta \right)$ and $\varpi = \frac{N^*}{1+N^*}$.

It therefore follows that:

$$\begin{aligned} \tilde{r}_{H,i,t} - \alpha\beta E_t \tilde{r}_{H,i,t+1} &= \alpha\beta E_t \tilde{\pi}_{H,t+1} - \tilde{\pi}_{H,t} + (1 - \alpha\beta) E_t \sum_{k=0}^{\infty} (\alpha\beta)^k \tilde{\pi}_{H,t} \\ &+ \frac{1}{1+b} (1 - \alpha\beta) [m\tilde{c}r_t - b\varpi (\tilde{p}_{H,t} - \tilde{p}_{F,t})] \end{aligned} \quad (63)$$

Using the fact that under Calvo price setting $\tilde{r}_{H,i,t} = \frac{\alpha}{1-\alpha} \tilde{\pi}_{H,t}$ we have:

$$\frac{\alpha}{1-\alpha} (\tilde{\pi}_{H,t} - \alpha\beta E_t \tilde{\pi}_{H,t+1}) = \alpha\beta E_t \tilde{\pi}_{H,t+1} + \frac{1}{1+b} (1 - \alpha\beta) [m\tilde{c}r_t - b\varpi (\tilde{p}_{H,t} - \tilde{p}_{F,t})] \quad (64)$$

The equation can then be expressed as (17).

A.4.2 Imported price inflation

In order to derive the Phillips Curve for inflation in the imported goods sector, it is necessary to solve the optimisation problem of Foreign firms setting the price of their goods in the Home market. When receiving a signal to update its price, a Foreign exporter chooses the price of its good in the Home market $P_{F,i,t}$ to maximise:

$$\sum_{k=0}^{\infty} E_t (\alpha^k Q_{k,t+k}^* \left[C_{H,i,t+k}^* (P_{H,i,t}^* - MC_{i,t+k}^*) + C_{F,i,t+k} \left(\frac{P_{F,i,t}}{S_{t+k}} - MC_{i,t+k}^* \right) \right]) \quad (65)$$

subject to (8).

The first order condition with respect to $P_{F,i,t}$ is given by:

$$E_t \sum_{k=0}^{\infty} \alpha^k Q_{t,t+k}^* \left[\frac{1}{S_{t+k}} C_{F,i,t+k} - \frac{1}{S_{t+k}} C_{F,i,t+k} \theta_{F,i,t+k} + MC_{t+k}^* \theta_{F,i,t+k} \frac{C_{F,i,t+k}}{P_{F,i,t}^o} \right] = 0 \quad (66)$$

The equation can be rewritten as:

$$E_t \sum_{k=0}^{\infty} \alpha^k Q_{t,t+k}^* C_{F,i,t+k} \left[\frac{1}{S_{t+k}} \frac{P_{F,i,t}^o}{P_{F,t}} (1 - \theta_{F,i,t+k}) + \frac{MC_{t+k}^*}{P_{H,t+k}^*} \frac{P_{H,t+k}^*}{P_{F,t}} \theta_{F,i,t+k} \right] = 0 \quad (67)$$

We will now define the relative optimal imported price $R_{F,i,t} = \frac{P_{F,i,t}^o}{P_{F,t}}$, real foreign marginal

cost $MCR_{t+k}^* = \frac{MC_{t+k}^*}{P_{H,t+k}^*}$, imported inflation $\Pi_{F,t} = \frac{P_{F,t}}{P_{F,t-1}}$ and the deviation from the law of one

price $Z_{t+k} = \frac{P_{H,t+k}^*}{P_{F,t}} S_{t+k}$. After substitution, (67) can be expressed as:

$$E_t \sum_{k=0}^{\infty} \alpha^k Q_{t,t+k}^* C_{F,i,t+k} \left[\frac{1}{S_{t+k}} R_{F,i,t} (1 - \theta_{F,i,t+k}) + MCR_{t+k}^* \frac{Z_{t+k}}{S_{t+k}} \frac{P_{F,t+k}}{P_{F,t}} \theta_{F,i,t+k} \right] = 0 \quad (68)$$

Using the fact that $Q_{k,t+k}^* = \beta^k \left(\frac{C_{t+k}^*}{C_t^*} \right)^{-\sigma} \frac{P_t^*}{P_{t+k}^*} e^{u_{t+k}^* - u_t^*}$ and after log-linearizing (68) around a symmetric steady state we have:

$$\tilde{r}_{F,i,t} = (1 - \alpha\beta) E_t \sum_{k=0}^{\infty} (\alpha\beta)^k (m\tilde{c}r_{t+k}^* + \tilde{z}_{t+k} + \sum_{s=0}^k \tilde{\pi}_{F,t+s} - \tilde{\pi}_{F,t} - \frac{1}{\theta-1} \tilde{\theta}_{F,i,t+k}) \quad (69)$$

The log deviation of the price elasticity of demand from its steady state is given by:

$$\tilde{\theta}_{F,i,t+k} = \left(\frac{1}{\gamma-1} + \theta \right) \left[\tilde{r}_{F,i,t} + \tilde{\pi}_{F,t} - \sum_{s=0}^k \tilde{\pi}_{F,t+s} + \frac{1}{1+N^*} (\tilde{p}_{F,t} - \tilde{p}_{H,t}) \right] \quad (70)$$

Therefore, after substitution, (69) can be expressed as follows:

$$\begin{aligned} \tilde{r}_{F,i,t} &= -\tilde{\pi}_{F,t} + (1 - \alpha\beta) E_t \sum_{k=0}^{\infty} (\alpha\beta)^k \sum_{s=0}^k \tilde{\pi}_{F,t+s} \\ &+ \frac{1}{1+b} (1 - \alpha\beta) E_t \sum_{k=0}^{\infty} (\alpha\beta)^k \left[m\tilde{c}r_{t+k}^* + \tilde{z}_{t+k} - b(1 - \varpi)(\tilde{p}_{F,t} - \tilde{p}_{H,t}) \right] \end{aligned} \quad (71)$$

where $b = \frac{1}{\theta-1} \left(\frac{1}{\gamma-1} + \theta \right)$ and $(1 - \varpi) = \frac{1}{1+N^*}$.

It therefore follows that:

$$\begin{aligned} \tilde{r}_{F,i,t} - \alpha\beta E_t \tilde{r}_{F,i,t+1} &= \alpha\beta E_t \tilde{\pi}_{F,t+1} - \tilde{\pi}_{F,t} + (1 - \alpha\beta) E_t \sum_{k=0}^{\infty} (\alpha\beta)^k \tilde{\pi}_{F,t} \\ &+ \frac{1}{1+b} (1 - \alpha\beta) \left[m\tilde{c}r_{t+k}^* + \tilde{z}_{t+k} - b(1 - \varpi)(\tilde{p}_{F,t} - \tilde{p}_{H,t}) \right] \end{aligned} \quad (72)$$

Using the fact that under Calvo price setting $\tilde{r}_{F,i,t} = \frac{\alpha}{1-\alpha} \tilde{\pi}_{F,t}$ we have:

$$\begin{aligned} \frac{\alpha}{1-\alpha}(\tilde{\pi}_{F,t} - \alpha\beta E_t \tilde{\pi}_{F,t+1}) &= \alpha\beta E_t \tilde{\pi}_{F,t+1} \\ &+ \frac{1}{1+b}(1-\alpha\beta)[m\tilde{c}r_{t+k}^* + \tilde{z}_{t+k} - b(1-\varpi)(\tilde{p}_{F,t} - \tilde{p}_{H,t})] \end{aligned} \quad (73)$$

The equation can then be expressed as (18).

A.5 Approximation of a firm's profit loss function

Using Taylor series expansion, the quadratic approximation of firm i 's profits $\Pi_{t+k} \left(\frac{P_{i,t}^o}{P_{t+k}} \right)$ around $\frac{P_{i,t+k}^f}{P_{t+k}}$, which corresponds to the price which would be optimal for firm i at time $t+k$ if the firm were able to adjust its price costlessly in each period, is given by:

$$\begin{aligned} \Pi_{t+k} \left(\frac{P_{i,t}^o}{P_{t+k}} \right) &\approx \Pi_{t+k} \left(\frac{P_{i,t+k}^f}{P_{t+k}} \right) + \Pi_{t+k}' \left(\frac{P_{i,t+k}^f}{P_{t+k}} \right) \left(\frac{P_{i,t}^o}{P_{t+k}} - \frac{P_{i,t+k}^f}{P_{t+k}} \right) \\ &+ \frac{1}{2} \Pi_{t+k}'' \left(\frac{P_{i,t+k}^f}{P_{t+k}} \right) \left(\frac{P_{i,t}^o}{P_{t+k}} - \frac{P_{i,t+k}^f}{P_{t+k}} \right)^2 \end{aligned} \quad (74)$$

From the Envelope Theorem, the first-order term is equal to zero. Therefore, the difference in profits obtained at price $\frac{P_{i,t}^o}{P_{t+k}}$ prevailing at time $t+k$ and profits obtained at the optimal flexible price in that period, $\frac{P_{i,t+k}^f}{P_{t+k}}$, is given by (22).

A firm's profit (in real terms) at time $t+k$ is equal to:

$$\Pi_{t+k} \left(\frac{P_{i,t+k}}{P_{t+k}} \right) = \left(\frac{P_{i,t+k}}{P_{t+k}} \right) Y_{i,t+k} - MCR_{t+k} Y_{i,t+k} \quad (75)$$

The second derivative of the profit function with respect to $\left(\frac{P_{i,t+k}}{P_{t+k}} \right)$, evaluated at the optimal

flexible price $\frac{P_{i,t+k}^f}{P_{t+k}} = \frac{\theta_{t+k}}{\theta_{t+k}-1} MCR_{t+k}$, is equal to:

$$\Pi_{t+k}'' \left(\frac{P_{i,t+k}^f}{P_{t+k}} \right) = -[\theta_{i,t+k} + \varepsilon_{i,t+k} - 1] Y_{i,t+k} \left(\frac{P_{i,t+k}^f}{P_{t+k}} \right)^{-1} \quad (76)$$

The first-order approximation of (76) around a symmetric steady state is given by:

$$\begin{aligned} \Pi_{t+k}'' \left(\frac{P_{i,t+k}^f}{P_{t+k}} \right) &\approx -(\theta + \varepsilon - 1)(1 - \tilde{y}_{i,t+k} + \tilde{p}_{i,t+k}^f) Y_i \left(\frac{P_i}{P} \right)^{-1} \\ &+ (\theta + \varepsilon)(\tilde{\theta}_{i,t+k} + \tilde{\varepsilon}_{i,t+k}) Y_i \left(\frac{P_i}{P} \right)^{-1} \end{aligned} \quad (77)$$

Using (77), the difference in profits obtained at the optimal flexible price $\frac{P_{i,t+k}^f}{P_{t+k}}$ and the price

$\frac{P_{i,t}^o}{P_{t+k}}$, which prevails at time $t+k$, can be written as:

$$\begin{aligned} & \Pi_{t+k} \left(\frac{P_{i,t+k}^f}{P_{t+k}} \right) - \Pi_{t+k} \left(\frac{P_{i,t}^o}{P_{t+k}} \right) \approx \\ & \approx \frac{1}{2} \left[(\theta + \varepsilon - 1) (1 - \tilde{y}_{i,t+k} + \tilde{p}_{i,t+k}^f) - (\theta + \varepsilon) (\tilde{\theta}_{i,t+k} + \tilde{\varepsilon}_{i,t+k}) \right] \left(\frac{P_i}{P} \right) Y_i (\tilde{p}_{i,t+k}^f - \tilde{p}_{i,t}^o)^2 \end{aligned} \quad (78)$$

Therefore, up to the second order, the period loss function can be approximated as in (23).

A.6 Structural parameters

Table 1: Structural parameters

| Parameter | Description | Value |
|---------------|--|-------|
| σ | Inverse of the intertemporal elasticity of substitution in consumption | 1.38 |
| ϕ | Inverse of the Frisch elasticity of labour supply | 1.83 |
| β | Discount factor | 0.995 |
| α | Probability of not receiving a signal to update prices in a given period | 0.75 |
| η_1 | Shape parameter of the demand function – baseline calibration | -0.30 |
| η_2 | Shape parameter of the demand function – alternative calibration | -0.28 |
| γ_1 | Shape parameter of the demand function – baseline calibration | 0.62 |
| γ_2 | Shape parameter of the demand function – alternative calibration | 0.67 |
| φ_π | Monetary policy rule – weight on inflation stabilisation | 1.5 |
| φ_y | Monetary policy rule – weight on output stabilisation | 0.5 |
| ρ_a | Persistence of productivity shocks | 0.95 |
| σ_a | Standard deviation of productivity shocks | 0.45 |
| ρ_u | Persistence of demand shocks | 0.97 |
| σ_u | Standard deviation of demand shocks | 0.53 |
| ρ_v | Persistence of monetary policy shocks | 0.15 |
| σ_v | Standard deviation of monetary policy shocks | 0.24 |

Figure 1: Price elasticity of demand and profits as functions of relative price

Note: red line: $\eta = -0.30$, $\gamma = 0.62$; blue line: $\eta = -0.28$, $\gamma = 0.67$; dotted line: CES demand function; solid line: non-CES demand function

Figure 2: Desired mark-up, price elasticity of demand and superelasticity of demand as functions of the number of varieties traded

Note: red line: $\eta = -0.30$, $\gamma = 0.62$; blue line: $\eta = -0.28$, $\gamma = 0.67$

Figure 3: Coefficients of the Phillips Curve as functions of the number of varieties traded

Note: red line: $\eta = -0.30$, $\gamma = 0.62$; blue line: $\eta = -0.28$, $\gamma = 0.67$

Figure 4: Impulse responses to a positive, one-standard-deviation productivity shock in the Home economy

Note: red line: non-CES (with $\eta = -0.30$ and $\gamma = 0.62$); blue line: CES; dotted line: relatively closed economy ($N^* = 0.25$) ; solid line: relatively open economy ($N^* = 0.75$)

Figure 5: Optimal frequency of price adjustment as a function of the number of varieties traded

Note: red line: $\eta = -0.30$, $\gamma = 0.62$; blue line: $\eta = -0.28$, $\gamma = 0.67$

Figure 6: Optimal frequency of price adjustment as a function of the mark-up

Note: red line: $\eta = -0.30$, $\gamma = 0.62$; blue line: $\eta = -0.28$, $\gamma = 0.67$

Figure 7: Optimal frequency of price adjustment as a function of the mark-up and the number of varieties traded for different parametrisations of the shock processes

Note: solid line: $\sigma_{1,a} = 0.45$; $\sigma_{1,u} = 0.53$; $\sigma_{1,v} = 0.24$; dotted line: $\sigma_{2,a} = 0.8 \sigma_{1,a}$; $\sigma_{2,u} = 0.8 \sigma_{1,u}$; $\sigma_{2,v} = 0.8 \sigma_{1,v}$; the demand function parameters are: $\eta = -0.30$, $\gamma = 0.62$

Figure 8: Optimal frequency of price adjustment as a function of the mark-up and the number of varieties traded for different parametrisations of the monetary policy rule

Note: solid line: $\varphi_\pi = 1.5$; dotted line: $\varphi_\pi = 2.0$; the demand function parameters are: $\eta = -0.30$, $\gamma = 0.62$

Figure 9: Coefficients of the Phillips Curve as functions of the number of varieties traded in the case of endogenous frequency of price adjustment

Note: red line: $\eta = -0.30$, $\gamma = 0.62$; blue line: $\eta = -0.28$, $\gamma = 0.67$