Imperfect competition, demand uncertainty and capacity adjustment

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Abstract:

In this paper a theoretical model of the price versus quantity adjustment of the firm is developed. The model is characterized by short-run capacity constraints, uncertainty about demand and imperfect competition on the product market. The microeconomic model is complemented by aggregation. The aggregate model exemplifies the prominent role of capacity utilization as a business cycle indicator and yields a variant of an accelerator model for the capacity adjustment. The demand and cost multipliers depend on the share of capacity constrained firms, and the price adjustment is determined by unit labour costs, capacity utilization and competition.

Keywords: Imperfect competition, demand uncertainty, capacity adjustment

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1 Introduction

The analyses of market structure and macroeconomic fluctuations are related through the price-setting behaviour of firms. On the one hand, macroeconomic evidence on cyclical fluctuations and the analysis of price versus quantity adjustments of firms can reveal insights into the competitive situation on the markets.[1] On the other hand, the analysis of market structure and price adjustment can help to a better understanding of the propagation of macroeconomic shocks.[2] Classical and Keynesian models differ with respect to the underlying model of the price adjustment. In classical models, an immediate or very fast adjustment of prices and permanent market clearing is assumed. Keynesian models, in contrast, emphasize the relevance of price rigidities, market disequilibria and quantity reactions. Both models yield opposite policy implications. Therefore the analysis of price adjustment is important for macroeconomic analysis.

A convenient framework to analyse price vs. quantity adjustments is monopolistic competition. Imperfect competition provides a prerequisite for a general theory of price adjustment.[3] The theory of price adjustment is dominated by the idea that prices adjust in the presence of excess demand or supply on the market. This mechanism is essentially ad hoc and does not reflect optimizing behaviour. In addition, it requires a disequilibrium interpretation of the adjustment which is not compatible with perfect competition. Monopolistic competition, by itself, cannot explain why aggregate demand movements affect output,[4] but monopolistic competition combined with some other imperfection can explain the interrelation of real and nominal variables. The main imperfection which is analysed here is a dynamic adjustment of capacities and technology. It is assumed that capacities adjust only

[1] See Hall (1986) and Carlton (1989).

[2] See Mankiw (1985), Hall (1986), Blanchard and Kiyotaki (1987), Solow (1998) and Ellison and Scott (2000).

[3] See Barro (1972).

[4] See Blanchard and Kiyotaki (1987).

with a delay with respect to cost and demand changes, thus under uncertainty about demand.[5] The analysis of a dynamic adjustment permits the consistent introduction of capacity constraints and uncertainty into the model.

The short-run price and quantity adjustment is analysed within a model of monopolistic competition on the product market and short-run capacity constraints. An extended model introduces a delayed adjustment of prices and employment with uncertainty about demand. This medium-run model provides a framework to analyse short-run price rigidities combined with constraints on the adjustment of employment. The model can account for delivery lags and labour hoarding during recessions, i.e. it is consistent with a procyclically varying productivity of labour. The capacity adjustment is analysed within the long-run model. For the capacity decision, the optimal response of prices, output and employment with respect to demand shocks is taken into account. The model yields an accelerator mechanism for the capacity adjustment. It is shown that the inefficiency associated with a delayed adjustment of capacities and demand uncertainty exhibits the same effects on optimal capacities, capital-labour substitution and average prices as higher capital costs.

The model of the firm is complemented by aggregation. The microeconomic relations at the firm level are explicitely translated into macroeconomic relations between the aggregates. In addition, the equilibrium shares of firms with supply and demand constraints are determined. The aggregate model exemplifies the role of capacity utilization as business cycle indicator; capacity utilization determines both the adjustment of prices and employment in the medium run and capital investment in the long run. The price adjustment depends on supply and demand shocks according to a short-run Phillips curve mechanism. The extend of price vs. quantity adjustments is determined by capacity utilization. This implies an asymmetric price and quantity

[5] For the analysis of adjustment delays see Kydland and Prescott (1982) and Pacheco-de-Almeida and Zemsky (2003). The model here is basically an extended variant of the model of Hall (1986).

adjustment with respect to demand and cost shocks during the business cycle.

2 Assumptions

In the theoretical model a strong separability of the dynamic structure of the firm's decisions is assumed. In the short run, output, employment and prices are endogenous. In the long run, the firm decides on investment and the production technology, i.e. capacities and the production technology adjust only with a delay with respect to demand and cost changes, thus under uncertainty about demand.[6] As an extention, a delayed adjustment of prices and employment is discussed. In most adjustment models dynamics are analysed under the assumption of non-linear adjustment costs. However, it is difficult to find examples for adjustment costs which can account for the observed slow adjustment of many economic variables. On the other hand, changing decision variables necessarily takes time, and even a short delay between the decision to change capacities or the price and the realization of a demand shock can introduce considerable uncertainty. In addition, the analysis of the dynamic adjustment in terms of adjustment delays and uncertainty reduces the dynamic decision problem of the firm to sequential static decision models which can be solved stepwise.

The theoretical analysis is carried out within a framework of monopolistic competition on the product market.[7] Imperfect competition is firstly a prerequisite for the analysis of price change. Price adjustment with respect to excess demand and supply requires a disequilibrium interpretation which is not compatible with perfect competition. In addition, the introduction of capacity constraints and demand uncertainty implies a monopolistic adjustment of the firms operating on the market at least in the short run. Finally, fixed costs of production and increasing returns to

[6] For a discussion of adjustment delays, see Kydland and Prescott (1982) and Pacheco-de-Almeida and Zemsky (2003).

[7] See e.g. Barro (1972) and Dixit and Stiglitz (1977).

scale associated with for instance innovations or advertising provide further arguments for a monopolistic market structure.[8] Within the microeconomic analysis, a market is defined by the supply of a single firm and the demand for the firm's product. In the sequel an aggregation procedure is discussed to derive implications for macroeconomic relations. In order to distinguish demand shifts, the price elasticity of demand and demand uncertainty, a log-linear demand curve is assumed,[9]

$$\ln YD = \eta \cdot \ln p + \ln Z + \varepsilon, \qquad \eta < -1, \mathrm{E}(\varepsilon) = 0, \mathrm{Var}(\varepsilon) = \sigma_\varepsilon^2. \tag{1}$$

The time and firm indices are omitted to simplify notation. Demand YD is determined by the price p, exogenous demand shifts Z and a demand shock ε. The demand shift Z stands for aggregate demand and the market share of the firm which is determined by, for instance, the prices of other firms, consumer preferences and the quality of the firm's product. In the basic model, it is assumed that the realized value of the demand shock ε is known at the time of the output, price and employment decision, but is not known at the time of the investment decision. In the extended version, there is uncertainty about ε at the time of the price and employment decision. In addition, ε exhibits positive autocorrelation. Supply YS is determined by a short-run limitational production function with capital K and labour L as inputs,

$$YS = \min(YC, YL) = \min(\pi_k \cdot K, \pi_l \cdot L), \qquad \pi_l = \pi_l(k, \theta), \pi_k = \pi_k(k, \theta). \tag{2}$$

YC are capacities, YL is the employment constraint and π_l, π_k are the productivities of labour and capital. It is assumed that the capital stock as well as the factor productivities are predetermined in the short run; they are determined by the long-run investment decision. Adjustment delays for the capital stock arise from planning, decision, delivery and installation lags for investment, the assumption of short-run

[8]See for instance Kamien, Schwarz (1975), Scherer and Ross (1990) and Aghion and Howitt (1992).

[9]Log-linear demand curves can be derived from CES utility functions (Deaton and Muellbauer, 1980), and log-linear relations permit an easy aggregation over firms (Lewbel, 1992).

fixed production coefficients corresponds to a putty-clay technology.[10] The factor productivities are determined by the capital-labour ratio k and production efficiency θ. The factor prices are assumed to be exogenous at the firm level. These assumptions imply constant marginal costs within the capacity limit in the short run.

3 Output, prices and employment

3.1 Imperfect competition and capacity constraints

The short-run model corresponds largely to the standard framework of monopolistic competion, but is extended with capacity constraints.[11] The optimization problem of the firm is

$$\max_{\rightarrow p,Y,L} \; p \cdot Y - w \cdot L - c \cdot K \quad \text{s.t.} \quad Y \leq \{YC, YL, YD\}. \tag{3}$$

Supply and demand are determined according to eqs. (1) and (2). w are wages and c are the user costs of capital. The capital stock and the factor productivities are predetermined. The first order condition is

$$p \cdot (1 + 1/\eta) \cdot (1 - \lambda_{YC}) \cdot \pi_l - w = 0. \tag{4}$$

λ_{YC} is the shadow price of the capacity constraint; it is zero in case of sufficient capacities. For the optimal solution, two cases can be distinguished:

1. In case of sufficient capacities $\lambda_{YC} = 0$, prices, output and employment are determined as

$$p(w) = \frac{w}{\pi_l \cdot (1 + 1/\eta)}, \tag{5}$$

$$\ln Y(w) = \eta \cdot \ln p(w) + \ln Z + \varepsilon \quad \text{and} \quad L(w) = Y(w)/\pi_l. \tag{6}$$

[10]The analysis of a dynamic adjustment of capacities has a long tradition in empirical investment models (see Jorgenson, Stephenson, 1967). The assumption of a putty-clay technology became common with the work of Bischoff (1971).

[11]The model is basically an extended variant of the model of Hall (1986).

Optimal prices are determined by unit labour costs and the price elasticity of demand, output results from introducing this price into the demand function, and employment is the required labour input. The firm suffers from underutilization of capacities.

2. In case of capacity shortages $\lambda_{YC} \neq 0$, output, employment and prices result from

$$Y = YC, \quad L(YC) = YC/\pi_l, \tag{7}$$

$$\ln p(YC) = (\ln YC - \ln Z - \varepsilon)/\eta. \tag{8}$$

Optimal output is equal to the capacity constraint, employment is again given as the corresponding labour requirement, and the optimal price results from solving the demand function for p at $YD = YC$. Insufficient capacities restrain output and employment, and the firm increases the price.

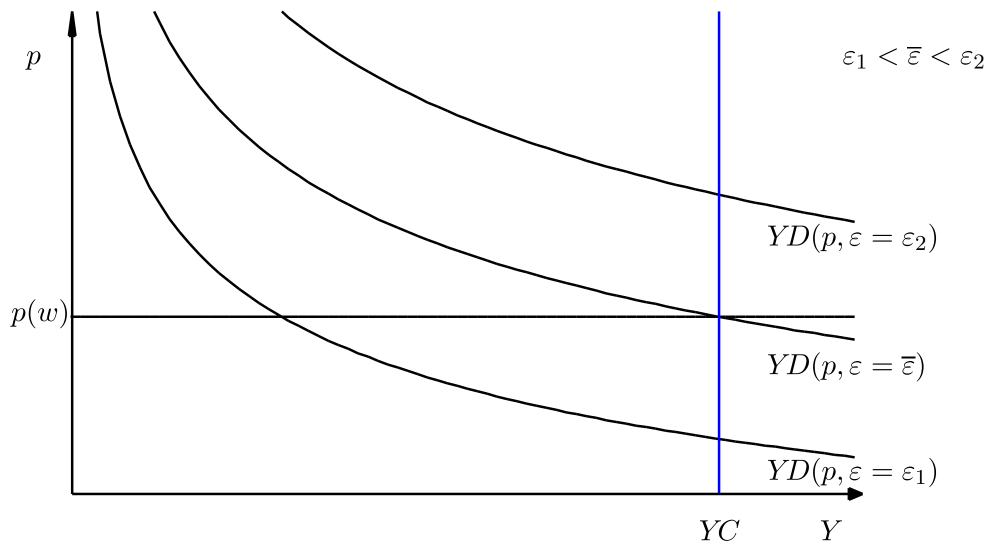
There is exactly one value of the demand shock $\varepsilon = \overline{\varepsilon}$ which distinguishes these cases,

$$\overline{\varepsilon} = \ln YC - \eta \cdot \ln p(w) - \ln Z. \tag{9}$$

The most important characteristics of the model are the minimum price $p(w)$ and the capacity limit YC. The supply curve is horizontal within the borders of capacity and vertical at the capacity limit. Optimal prices are determined either by unit labour costs and the degree of competition on the market or by the relation of the levels of demand and capacity. Optimal output and employment are determined either by unit labour costs and the level of demand or by capacities. Figure 1 gives a visual impression of the model. For a negative demand shock $\varepsilon_1 < \overline{\varepsilon}$, the price is bounded by unit labour costs and the mark-up. For a positive demand shock $\varepsilon_2 > \overline{\varepsilon}$, insufficient capacities restrain output, and the firm increases the price. $\varepsilon = \overline{\varepsilon}$ is the borderline which distinguishes these cases. Note the implied asymmetry of the price and quantity adjustment in case of positive and negative demand shocks. A similar asymmetry results for cost changes.

The microeconomic model of the firm provides a consistent basis for aggregation.

Figure 1: Immediate adjustment of output, prices and employment



If firms differ only with respect to the realization of the demand shocks ε, the microeconomic minimum condition of supply and demand at the firm level can be explicitely translated into a macroeconomic relation between the averages and the variance of demand shocks σ_ε^2. For instance, if the distribution of ε is approximated by the Normal, the aggregate relation exhibits the same functional form as the microeconomic relation, except for a change of the normalizing constant which is determined by the variance of demand shocks,[12]

$$\ln \mathrm{E}(YD) = \mathrm{E}(\ln YD) + 0.5 \cdot \sigma_\varepsilon^2 = \eta \cdot \ln p + \ln Z + 0.5 \cdot \sigma_\varepsilon^2. \tag{10}$$

E is the expectation operator, n is the number of firms and $n \cdot \mathrm{E}(YD)$ is aggregate demand. If costs, prices and demand shifts differ between firms, the normalizing constant is determined by the variance of the logarithm of demand at the micro level.[13] In addition, the aggregate counterpart of the microeconomic minimum con-

[12] See Stoker (1993) for a discussion.

[13] The variance of the logarithm of demand is determined by the variances and correlations of demand shocks ε, demand shifts Z and prices (costs).

dition can accurately be approximated by a CES-type function of aggregate output $n \cdot \mathrm{E}(Y)$ in terms of aggegate capacities $n \cdot \mathrm{E}(YC)$ and aggregate demand $n \cdot \mathrm{E}(YD)$,

$$\mathrm{E}(Y)^{1/\rho} \approx \mathrm{E}(YD)^{1/\rho} + \mathrm{E}(YC)^{1/\rho}, \qquad \rho < 0. \tag{11}$$

ρ can be interpreted as a mismatch parameter (mismatch between demand and capacities) with $\partial \mathrm{E}(Y)/\partial\rho < 0$ and $\lim_{\rho\to 0} \mathrm{E}(Y) = \min[\mathrm{E}(YD), \mathrm{E}(YC)]$. ρ is completely determined by the covariance of capacities and demand at the micro level.[14] The aggregate multipliers, i.e. the elasticities of aggregate output with respect to capacities and demand can be calculated from eq. (11) as

$$\frac{\partial \mathrm{E}(Y)}{\partial \mathrm{E}(YD)} \cdot \frac{\mathrm{E}(YD)}{\mathrm{E}(Y)} \approx \left\{ \frac{\mathrm{E}(YD)}{\mathrm{E}(Y)} \right\}^{1/\rho} \approx \mathrm{prob}(YD < YC) \tag{12}$$

and correspondingly for capacities. These elasticities approximate the shares of firms with or without capacity constraints. The aggregate model implies that the demand and cost multipliers depend on the business cycle. In boom situations with a high capacity utilization and a large share of firms with capacity constraints, prices adjust with respect to demand with only small output and employment effects and only small effects from cost changes. In recession periods with a large share of firms with sufficient capacities, quantities (output and employment) adjust with respect to demand and cost changes, and prices adjust only with respect to costs. The microeconomic case dependency of cost and demand effects corresponds to cyclical demand and cost multipliers at the macro level. For the price adjustment the aggregate model implies an augmented Phillips curve mechanism: Prices adjust with respect to unit labour cost (supply shocks) and capacity utilization (demand shocks). If aggregate demand depends on employment, the model yield the usual Keynesian multiplier but only within the borders of capacities, i.e. the model exhibits both classical and Keynesian features.

[14] ρ is determined by a nearly linear relation in terms of the standard deviation of $\ln YD - \ln YC$ within the empirically relevant range.

3.2 Uncertainty and the price and employment adjustment

The extended model introduces uncertainty into the price and employment adjustment. It is assumed that prices and employment must be chosen in advance, thus under uncertainty about demand.[15] Adjustment delays for employment can be justified with legal/contractual periods of notice and search, screening and training time.[16] The assumption that the firm sets price tags also appears plausible,[17] and even a short delay between the decision to change the price and the realization of demand can introduce considerable uncertainty. In this model, output is determined in the short run as the minimum of demand and supply,

$$Y = \min(YD, YS). \tag{13}$$

The medium-run optimization problem is

$$\max_{\rightarrow L,p} \; p \cdot \mathrm{E}(Y) - w \cdot L - c \cdot K \tag{14}$$

s.t. eqs. (1) and (2) above. Expected output is determined as

$$\mathrm{E}(Y) = \mathrm{E}[\min(YD, YS)] = \int_{-\infty}^{\overline{\varepsilon}} YD \cdot f_{\varepsilon} d\varepsilon + \int_{\overline{\varepsilon}}^{\infty} YS \cdot f_{\varepsilon} d\varepsilon \tag{15}$$

f_{ε} is the p.d.f. of the demand shock ε. For small values of the demand shock, output is determined by demand (the first integral); for large values of ε, output is determined by supply (the second integral); $\overline{\varepsilon}$ is defined as the specific value of the demand shock ε where demand equals supply,

$$\overline{\varepsilon} = \ln YS - \eta \cdot \ln p - \ln Z. \tag{16}$$

The first order conditions are given by[18]

$$\eta \cdot \int_{-\infty}^{\overline{\varepsilon}} YD \cdot f_{\varepsilon} d\varepsilon + \mathrm{E}(Y) \quad = \quad 0, \tag{17}$$

$$p \cdot \int_{\overline{\varepsilon}}^{\infty} f_{\varepsilon} d\varepsilon \cdot (1 - \lambda_{YC}) \cdot \pi_l - w \quad = \quad 0. \tag{18}$$

[15] The medium-run model is discussed in Smolny (1998a,b).

[16] See Hamermesh and Pfann (1996).

[17] See Carlton (1989) and Blinder (1991).

[18] Note that the value of the integrands in eq. (15) at $\varepsilon = \overline{\varepsilon}$ are equal.

The optimal $\overline{\varepsilon}$ depends only on the price elasticity of demand η and demand uncertainty σ_ε (see appendix A, proposition A.1),

$$\overline{\varepsilon} = \overline{\varepsilon}(\eta, \sigma_\varepsilon). \tag{19}$$

$\overline{\varepsilon}$ and σ_ε also determine the expected utilization of supply $U_l := \mathrm{E}(Y)/YS$ and the optimal probability of demand constraints $\mathrm{prob}(YD < YS)$ (see appendix A, proposition A.2). That means, utilization and the probabilities do not depend on costs, capacities and expected demand shifts Z. The economic intuition of this result is that (for given supply and costs) the elasticity of output with respect to the price is chosen equal to one: With higher prices, demand decreases with elasticity η; expected output decreases with elasticity η, times the weighted probability that demand is less than supply. The expected share of output in the demand constrained case is chosen equal to the inverse of the absolute value of the price elasticity of demand,[19]

$$\mathrm{prob}_w(YD < YS) := \frac{\int_{-\infty}^{\overline{\varepsilon}} YD \cdot f_\varepsilon d\varepsilon}{\int_{-\infty}^{\overline{\varepsilon}} YD \cdot f_\varepsilon d\varepsilon + \int_{\overline{\varepsilon}}^{\infty} YS \cdot f_\varepsilon d\varepsilon} = -\frac{1}{\eta}. \tag{20}$$

The firm chooses the price to achieve an optimal probability of supply constraints and an optimal utilization of supply. For optimal prices and employment, two cases can be distinguished:

1. In case of capacity constraints $\lambda_{YC} \neq 0$, supply and employment are determined from capacities and labour productivity,

$$Y = YL = YC \quad \text{and} \quad L(YC) = YC/\pi_l. \tag{21}$$

The optimal price results from inserting capacities and the optimal $\overline{\varepsilon}$ into eq. (16) and solving for p,

$$\ln p(YC) = \Big[\ln YC - \ln Z - \overline{\varepsilon}(\eta, \sigma_\varepsilon)\Big]/\eta. \tag{22}$$

[19] Inserting the definition of expected output, eq. (15), into the first order condition with respect to prices, eq. (17), yields eq. (20).

The price depends on capacities YC, expected demand shifts Z and the optimal $\overline{\varepsilon}$; the elasticity of the price with respect to capacities and the demand shift is $1/\eta$; the price does not depend on costs.

2. In case of sufficient capacities $\lambda_{YC} = 0$, the optimal price follows directly from the first order condition with respect to employment, eq. (18). The marginal costs of an additional unit of employment are equal to the wage rate w. Marginal returns are determined as the price, multiplied with the productivity of labour and multiplied with the probability that the additional unit of output can be sold. The mark-up of prices on unit labour costs is chosen equal to the inverse of the optimal probability of supply constraints,

$$\frac{w}{\pi_l \cdot p(w)} = \text{prob}(YL < YD). \tag{23}$$

Since the optimal probability of supply constraints is competely determined by demand uncertainty σ_ε and the price elasticity of demand η, the price does not depend on capacities and expected demand shifts. The firm adjusts quantities with respect to demand. The optimal price can also be determined from the price elasticity of demand, unit labour costs and the expected utilization of employment (see appendix A, proposition A.3),

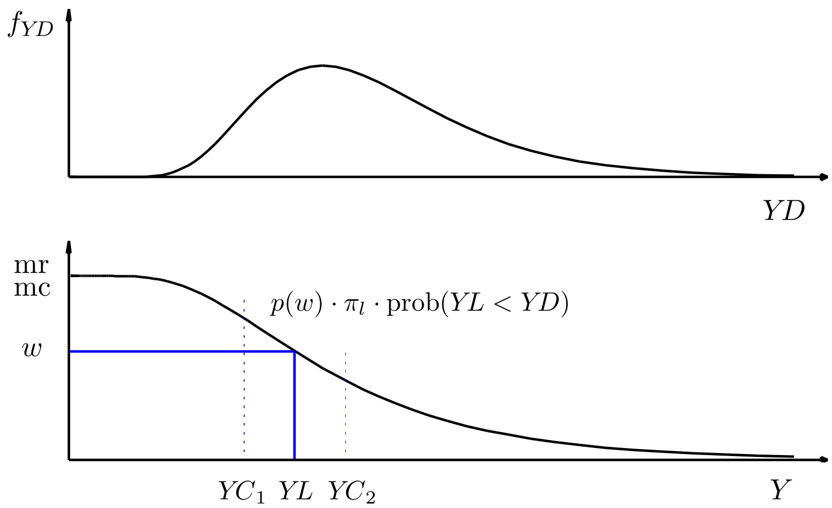
$$p(w) = \frac{w}{U_l \cdot \pi_l \cdot (1 + 1/\eta)}. \tag{24}$$

The inefficiency associated with demand uncertainty and a delayed adjustment exhibits the same effect as higher wage costs. Supply and employment result from inserting this price and the optimal $\overline{\varepsilon}$ into the definition of $\overline{\varepsilon}$ and solving for supply YL and employment L,

$$YL(w) = \eta \cdot \ln p(w) + \ln Z + \overline{\varepsilon}(\eta, \sigma_\varepsilon) \quad \text{and} \quad L(w) = YL/\pi_l. \tag{25}$$

The immediate adjustment (or the absence of uncertainty) is contained as the limiting case $\sigma_\varepsilon \to 0$. Without uncertainty $U_l \to 1$, and the firm can achieve full utilization of employment. Introducing uncertainty reduces the expected utilization of employment and exhibits the same effect on prices and employment as higher

Figure 2: Optimal employment



mr: marginal revenue mc: marginal costs

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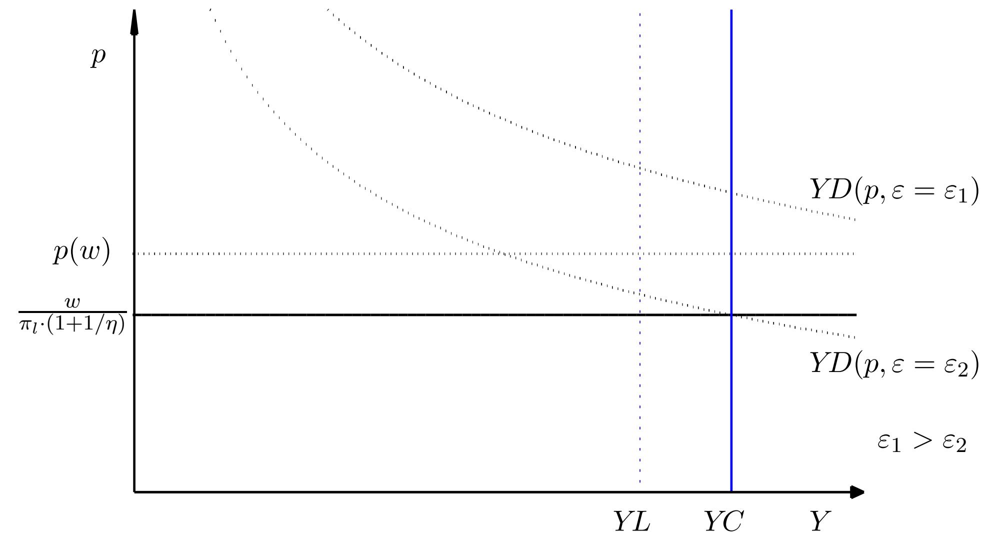
variable costs. Figure 2 gives a visual impression of the model. f_{YD} is the p.d.f. of demand. For small values of L and YL, the probability that the marginal unit of labour will be used is large; the marginal returns of labour exceed marginal costs. For higher values of YL, the probability that demand exceeds supply decreases, and the marginal return of labour decreases, a unique optimum is assured. If capacities restrain supply, the firm increases the price to achieve the optimal probability of supply constraints and the optimal utilization of supply.

The model extends the standard formulation of monopolistic competition by introducing uncertainty about demand and medium-run capacity constraints. Ex ante, the firm sets prices and employment under uncertainty about demand, i.e. the firm chooses one point in the $\{p, Y\}$-diagram (see figure 3). Uncertainty increases the optimal price and reduces employment through the costs of underutilization of employment. Relevant for the price setting is the capacity limit $YS = YL \leq YC$ and the minimum price $p(w)$. In case of sufficient capacities, there is a clear correspondence

Figure 3: Delayed adjustment of prices and employment



of income distribution shares, the price elasticity of demand and the probability of demand constraints; in case of capacity constraints, the relation of the demand shift Z and capacities YC determines the optimal price. Ex post, rationing of demand or underutilization of employment can occur. For a positive demand shock $\varepsilon = \varepsilon_1$, the firm cannot satisfy all customers (delivery lags), for a negative demand shock $\varepsilon = \varepsilon_2$, underutilization of capacities and labour hoarding occur. Short-run demand shocks can be identified from the utilization of the production factors. The short-run demand situation can be identified from the utilization of employment, the medium-run business-cycle situation can be identified from the utilization of capacities.

The extention of the model also enhances the macroeconomic interpretation of the effects of imperfect competition and capacity constraints.[20] The assumption of a delayed adjustment of prices introduces demand uncertainty, price rigidities and

[20]The aggregate counterparts of the microeconomic relations can again be derived from the aggregation procedure discussed above.

prolonged delivery lags in the short run. It also permits a discussion of wage-price patterns and a staggered price setting for the analysis of the aggregate price adjustment.[21] The assumption of a delayed adjustment of employment permits an interpretation of the procyclical development of labour productivity in terms of optimal labour hoarding during recessions. Finally, the assumption of a slow adjustment of prices and employment introduces dynamics into the multiplier process.

4 Capacities and capital-labour substitution

In the long run, the firm decides on capacities and the production technology. Since there is uncertainty about the demand shock ε, the realized future values of output, prices and employment are not known at the time of the investment decision. However, the firm knows the decision rule for those variables. They are given by the solutions of the short- and medium-run optimization problems. The capacity adjustment is firstly analyzed within the model of the short-run adjustment of output, employment and prices. The deviations caused by a delayed adjustment of prices and employment are discussed afterwards.

4.1 Demand uncertainty and capacity adjustment

The firm maximizes expected profits which depend on expected sales, expected employment, the wage rate and capital costs. The production function is characterized by constant returns to scale. The decision variables are the capital stock K and the capital-labour ratio k. The optimization problem is

$$\max_{\rightarrow K,k} \int_{-\infty}^{\overline{\varepsilon}} \left(p(w) - \frac{w}{\pi_l} \right) \cdot Y(w) \cdot f_\varepsilon d\varepsilon + \int_{\overline{\varepsilon}}^{\infty} \left(p(YC) - \frac{w}{\pi_l} \right) \cdot YC \cdot f_\varepsilon d\varepsilon - c \cdot K. \quad (26)$$

Output, prices and employment are determined from eqs. (5)-(8). Output is determined by demand in case of sufficient capacities or by capacities in case of sufficient

[21] See e.g. Blanchard (1987).

demand. Sales result from introducing the corresponding prices, and employment is given by the labour requirement. ε and f_ε refer to uncertainty about demand at the time of the investment decision. The first order condition with respect to the capital stock K is[22]

$$\int_{\overline{\varepsilon}}^{\infty} [p(YC) \cdot (1 + 1/\eta) - w/\pi_l] \cdot \pi_k \cdot f_\varepsilon d\varepsilon - c = 0. \tag{27}$$

Marginal costs are given by the user costs of capital c. Marginal returns to capital are achieved only, if capacities become the binding constraint for output, i.e. if $\varepsilon > \overline{\varepsilon}$. They are given by the price, minus the price reduction of a marginal increase in output, minus wage costs in the capacity constrained case. A unique optimum exists, $p(YC)$ is decreasing in YC and K.[23] The following properties can be derived. The optimal value of $\overline{\varepsilon}$ depends only on the price elasticity of demand, the variance of demand shocks and relative factor costs (see appendix B, proposition B.1),

$$\overline{\varepsilon} = \overline{\varepsilon}\left(\eta, \sigma_\varepsilon, \frac{c}{\pi_k}\frac{\pi_l}{w}\right). \tag{28}$$

$\overline{\varepsilon}$ and σ_ε, in turn, determine both the probability of demand constraints prob($YD < YC$) and the expected utilization of capacities $U_c := \mathrm{E}(Y)/YC$ (see appendix B, proposition B.2). Higher relative capital costs increase optimal utilization and reduce the probability of demand constraints; with high fixed costs, the firm chooses a higher probability of capacity constraints. More competition, i.e. a higher absolute value of the price elasticity of demand $|\eta|$ also increases optimal utilization and reduces the probability of demand constraints. Both, higher relative capital costs and more competition increase the ratio between marginal costs and marginal returns of capital. More uncertainty reduces optimal utilization, because it becomes more difficult to achieve a higher utilization, and the probability of demand constraints increases.[24] Both, expected capacity utilization and the probabilities of capacity constraints do not depend on expected demand shifts Z and the level of factor

[22]The value of both integrands in eq. (26) at $\varepsilon = \overline{\varepsilon}$ is equal.

[23]The integrand is equal to 0 at the lower border of the integral.

[24]σ_ε affects the relation between average $p(YC)$ and $p(w)$.

costs. The choice of capacities can be understood as the optimal choice of capacity utilization.

Expected prices $\mathrm{E}(p)$ are determined as mark-up over labour and capital costs (see appendix B, proposition B.3), the *average* price depends also on the expected utilization of capacities (see appendix B, proposition B.4),

$$\frac{\mathrm{E}(p \cdot Y)}{\mathrm{E}(Y)} = \left(\frac{w}{\pi_l} + \frac{c}{U_c \cdot \pi_k}\right) / (1 + 1/\eta). \tag{29}$$

More uncertainty reduces the expected utilization of capacities; a lower utilization of capacities, in turn, exhibits the same effect on average prices as higher capital costs c. Finally, optimal capacities are determined as[25]

$$\ln YC = \eta \cdot \ln p(w) + \ln Z + \overline{\varepsilon}. \tag{30}$$

Optimal capacities depend on expected demand shifts Z, demand shifts increase all quantities proportionally and do not affect prices or relative quantities. This implies an accelerator mechanism for the capacity adjustment. Higher relative capital costs reduce capacities through the optimal value of $\overline{\varepsilon}$. A proportional increase in c and w leaves $\overline{\varepsilon}$, the probabilities and capacity utilization unchanged, but increases the price proportionally. Capacities decrease with elasticity $|\eta|$, the model exhibits linear homogeneity both in prices and quantities. Less competition reduces capacities through higher prices and through a lower optimal utilization, and more uncertainty reduces optimal capacities through a lower utilization. Demand uncertainty exhibits the same effect on capacities and average prices as higher capital costs. The model without uncertainty is contained for $\sigma_\varepsilon \to 0$ and $U_c \to 1$. Without uncertainty the price is set as a mark-up over total costs, and the mark-up is determined by the price elasticity of demand; optimal capacities and employment are given by the equality of demand YD, capacities YC and the corresponding employment constraint YL.

The second component of the investment decision is the choice of the optimal capital-labour ratio k. The capital-labour ratio, in turn, determines the productivities of

[25] Eq. (30) results from inserting eq. (28) into eq. (9) and solving for YC.

labour and capital π_l, π_k. The optimal capital-labour ratio can be derived from differentiating eq. (26) with respect to k. The calculations are tedious but not difficult, and the result is intuitive: The optimal relation between the elasticities of the factor productivities of labour and capital with respect to the capital-labour ratio is chosen equal to the ratio of the corrected factor shares,[26]

$$-\frac{\frac{\partial \pi_k}{\partial k} \cdot \frac{k}{\pi_k}}{\frac{\partial \pi_l}{\partial k} \cdot \frac{k}{\pi_l}} = \frac{w \cdot U_c}{c} \frac{\pi_k}{\pi_l}. \tag{31}$$

Again, the inefficiency caused by uncertainty and a delayed adjustment exhibits the same effects as higher capital costs and favours substitution of labour against capital; the model without uncertainty is contained for $\sigma_\varepsilon \to 0$ and $U_c \to 1$.

The assumption of a delayed adjustment of capacities and capital-labour substitution extends the deterministic model by introducing uncertainty and permits to analyse the resulting inefficiencies. Ex ante, the firm chooses capacities and the factor productivities under uncertainty about demand. With uncertainty, optimal capacities and expected output are lower due to the costs of stochastic underutilization of capacities. Uncertainty also increases average prices and reduces the optimal capital-labour ratio through the effect on utilization. The optimal probabilities of capacity constraints, the optimal utilization of capacities and the optimal capital-labour ratio do not depend on the level of costs and the level of demand. They are determined by relative costs, demand uncertainty and the price elasticity of demand. The model exhibits linear homogeneity both in prices and in quantities. Ex post, capacity and demand constraints on the goods market are possible. The demand multiplier depends on the share of firms with capacity constraints.

[26]In case of a Cobb-Douglas production function, this relation is equal to the relative output elasticities of the factors, see appendix C. The appendix also contains the results for a CES production function

4.2 A three-step decision structure

The capacity adjustment can also be analysed in combination with uncertainty about demand for the price and employment adjustment. Let us assume uncertainty about the demand expectations at the time of the price and employment decision, i.e. uncertainty about the expected demand shift Z,

$$\ln Z = \ln \overline{Z} + z, \qquad \mathrm{E}(z) = 0, \mathrm{Var}(z) = \sigma_z^2. \tag{32}$$

z measures the difference of demand expectations at the time of the investment decision and the time of the price and employment decision. Prices and employment then depend on the realized value of z. In particular, employment and prices are determined either from eqs. (21) and (22) in the capacity constrained case or from eqs. (24) and (25) in the unconstrained case. There is exactly one value $z = \overline{z}$ which distinguishes these cases,

$$\overline{z} = \ln YC - \ln \overline{Z} - \overline{\varepsilon} - \eta \cdot \ln p(w). \tag{33}$$

Expected employment is determined as

$$\mathrm{E}(L) = \int_{-\infty}^{\overline{z}} L(w) \cdot f_z dz + \int_{\overline{z}}^{\infty} L(YC) \cdot f_z dz \tag{34}$$

f_z is the p.d.f. of z. Expected output can be determined from expected employment and the expected utilization of employment, $\mathrm{E}(Y) = U_l \cdot \pi_l \cdot \mathrm{E}(L)$. Expected sales result as $\mathrm{E}(p \cdot Y) = U_l \cdot \pi_l \cdot \mathrm{E}(p \cdot L)$. Note that the expected utilization of employment is completely determined by the price elasticity of demand η and demand uncertainty at the time of the price and employment decision σ_ε, i.e. it is not stochastic and does not depend on the capacity decision.[27] The long-run optimization problem can be written as[28]

$$\max_{\to K} \quad \int_{-\infty}^{\overline{z}} [(p(w) \cdot \pi_l \cdot U_l - w] \cdot L(w) \cdot f_z dz$$

[27] Note that $\overline{\varepsilon}$ and the probabilities on the product market are also determined by η and σ_ε, i.e. they are also not stochastic and do not depend on the capacity decision.

[28] See eq. (26) for comparison.

$$+\int_{\overline{z}}^{\infty} [p(YC) \cdot \pi_l \cdot U_l - w] \cdot L(YC) \cdot f_z dz - c \cdot K. \tag{35}$$

This formulation of the optimization problem shows that the solution of the model can be performed correspondingly to the basic model of section 4.1. The first order condition with respect to the capital stock is given by[29]

$$\int_{\overline{z}}^{\infty} [p(YC) \cdot (1 + 1/\eta) \cdot U_l - w/\pi_l] \cdot \pi_k \cdot f_z dz - c = 0. \tag{36}$$

Note that capacities affect output, prices and employment only if capacities are the binding constraint for employment. The optimal $\overline{z}$ depends only on uncertainty about z, the price elasticity of demand η and relative factor costs (see appendix D, proposition D.1),

$$\overline{z} = \overline{z}\left(\eta, \sigma_z, \frac{c}{\pi_k}\frac{\pi_l}{w}\right). \tag{37}$$

$\overline{z}$ and σ_z, in turn, determine the probability of capacity constraints for employment $\text{prob}(YC < YL)$ (see appendix D, proposition D.2), i.e. the optimal $\overline{z}$ and the probability of capacity constraints for employment do not depend on $\overline{\varepsilon}$ and the utilization of employment. Demand uncertainty for prices and employment affects both production factors equally. The expected utilization of capacities $U_c := \mathrm{E}(Y)/YC$ depends on $\overline{z}$ and on the utilization of employment (see appendix D, proposition D.3). In addition, expected prices $\mathrm{E}(p)$ are determined again as mark-up on costs and the average price is determined as mark-up over corrected factor costs (see appendix D, proposition D.4 and D.5),

$$\frac{\mathrm{E}(p \cdot Y)}{\mathrm{E}(Y)} = \left(\frac{w}{U_l \cdot \pi_l} + \frac{c}{U_c \cdot \pi_k}\right) / (1 + 1/\eta). \tag{38}$$

Finally, optimal capacities are determined as[30]

$$\ln YC = \eta \cdot \ln p(w) + \ln \overline{Z} + \overline{z} + \overline{\varepsilon}. \tag{39}$$

The whole analysis corresponds to those in section 4.1 above; the only difference is that the (under)utilization of employment must be taken into account.

[29] The value of both integrands in eq. (35) at $z = \overline{z}$ is equal. Note that only $L(w)$ and $p(YC)$ are stochastic and only $L(YC)$ and $p(YC)$ depend on capacities.

[30] Eq. (39) results from inserting eq. (37) into eq. (33) and solving for YC.

5 Conclusions

In the paper, a theoretical model of price versus quantity adjustments of the firm is developed. The model is characterized by adjustment constraints, uncertainty about demand and imperfect competition on the product market. Capacity constraints are a reasonable assumption for the short- and medium-run adjustment of output, employment and prices and provide a microeconomic foundation of a monopolistically competitive market structure. A delayed adjustment of quantities under demand uncertainty permits an interpretation of the procyclical development of productivity in terms of optimal labour and capital hoarding during recessions. A delayed adjustment of prices introduces price stickyness and delivery lags.

The immediate adjustment of prices and quantities and perfect competition on the product market are contained as special cases. With uncertainty, prices are higher and quantities are lower due to the costs of labour hoarding and underutilization of capacities. In addition, uncertainty and persistent demand shocks introduce dynamics and expectation formation into the multiplier process. Within the model, the short run and the long run are distinguished by the flexibility of capacities, not by the stickyness of prices as in standard Keynesian models.

The microeconomic model of the firm is complemented by aggregation. The combination of imperfect competition and adjustment constraints yields reasonable macroeconomic effects for the determination of the short-run multiplier and the price adjustment during the business cycle. The model exhibits both classical and Keynesian features without recurrence to price rigidities. The aggregate model exemplifies the prominent role of capacity utilization as a business cycle indicator. The price adjustment is determined by a medium-run Phillips curve mechanism depending on production costs and capacity utilization; the medium-run demand and cost multipliers depend on capacity utilization which implies asymmetric price and quantity adjustments during the business cycle.

The capacity adjustment is determined through a flexible accelerator mechanism for investment which introduces a source of instability into the aggregate adjustment. However, the short-run multiplier process is limited by capacities. Embedding the model of the firm into a general (dis)equilibrium framework is on the agenda of future research. The model finally provides a framework to discuss the impact of demand uncertainty, expectation formation and competition on the adjustment. The only departures from the standard model are a delayed adjustment with uncertainty about demand and monopolistic competition on the product market.

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Appendix A: Delayed adjustment of prices and employment

Proposition A.1: $\overline{\varepsilon} = \overline{\varepsilon}(\sigma_\varepsilon, \eta)$, the optimal value of $\overline{\varepsilon}$ depend only on demand uncertainty σ_ε and the price elasticity of demand η.

Proof: Inserting the definition of expected output $\mathrm{E}(Y)$, eq. (15), into the first order condition w.r.t. prices, eq. (17) yields

$$(1+\eta) \cdot \int_{-\infty}^{\overline{\varepsilon}} YD \cdot f_\varepsilon d\varepsilon + \int_{\overline{\varepsilon}}^{\infty} YS \cdot f_\varepsilon d\varepsilon = 0. \tag{A.1}$$

Substituting demand YD from eq. (1) and supply YS through the definition of $\overline{\varepsilon}$ from eq. (16) yields

$$(1+\eta) \cdot \int_{-\infty}^{\overline{\varepsilon}} p^\eta \cdot Z \cdot \exp(\varepsilon) \cdot f_\varepsilon d\varepsilon + \int_{\overline{\varepsilon}}^{\infty} p^\eta \cdot Z \cdot \exp(\overline{\varepsilon}) \cdot f_\varepsilon d\varepsilon = 0. \tag{A.2}$$

Dividing this expression by $p^\eta \cdot Z \cdot \exp(\overline{\varepsilon})$ yields

$$(1+\eta) \cdot \int_{-\infty}^{\overline{\varepsilon}} \exp(\varepsilon - \overline{\varepsilon}) \cdot f_\varepsilon d\varepsilon + \int_{\overline{\varepsilon}}^{\infty} f_\varepsilon d\varepsilon = 0. \tag{A.3}$$

For the normalized random variable $z = \varepsilon/\sigma_\varepsilon$, this expression can be rewritten by changing integration variables as

$$(1+\eta) \cdot \int_{-\infty}^{\overline{\varepsilon}/\sigma_\varepsilon} \exp(z \cdot \sigma_\varepsilon - \overline{\varepsilon}) \cdot f_z dz + \int_{\overline{\varepsilon}/\sigma_\varepsilon}^{\infty} f_z dz = 0. \tag{A.4}$$

Eq. (A.4) determines $\overline{\varepsilon}$ in terms of σ_ε and η.

Proposition A.2: The probability of demand constraints and the expected utilization of supply depend only on demand uncertainty σ_ε and the price elasticity of demand η.

Proof: The probability of demand constraints is determined as

$$\mathrm{prob}(YD < YS) = \int_{-\infty}^{\overline{\varepsilon}} f_\varepsilon d\varepsilon. \tag{A.5}$$

The expected utiliation of supply is determined as

$$U_l := \frac{\mathrm{E}(Y)}{YS} = \int_{-\infty}^{\overline{\varepsilon}} \frac{YD}{YS} \cdot f_\varepsilon d\varepsilon + \int_{\overline{\varepsilon}}^{\infty} f_\varepsilon d\varepsilon. \tag{A.6}$$

Substituting demand YD from eq. (1) and supply YS through the definition of $\overline{\varepsilon}$ from eq. (16) yields

$$U_l := \frac{\mathrm{E}(Y)}{YS} = \int_{-\infty}^{\overline{\varepsilon}} \exp(\varepsilon - \overline{\varepsilon}) \cdot f_\varepsilon d\varepsilon + \int_{\overline{\varepsilon}}^{\infty} f_\varepsilon d\varepsilon. \tag{A.7}$$

Since $\overline{\varepsilon}$ depends only on σ_ε and η, prob$(YD < YS)$ and U_l also depend only on σ_ε and η.

Proposition A.3: In case of sufficient capacities, the optimal price is determined by unit labour costs, the price elasticity of demand and the expected utilization of employment, $p(w) = w/[U_l \cdot \pi_l \cdot (1 + 1/\eta)]$.

Proof: Inserting the first order condition with respect to prices, eq. (A.3), for the first integral in eq. (A.7) above yields

$$U_l = \frac{1 - \mathrm{prob}(YD < YS)}{(1 + 1/\eta)}, \tag{A.8}$$

i.e. the expected utilization of supply can be determined from the probability of demand constraints and the price elasticity of demand. Inserting eq. (A.8) into eq. (23) yields eq. (24) in the main text.

Appendix B: Delayed adjustment of capacities

Proposition B.1: $\overline{\varepsilon} = \overline{\varepsilon}(\sigma_\varepsilon, \eta, \frac{c}{\pi_k}\frac{\pi_l}{w})$, the optimal value of $\overline{\varepsilon}$ depend only on demand uncertainty σ_ε, the price elasticity of demand η and relative unit factor costs $\frac{c}{\pi_k}\frac{\pi_l}{w}$

Proof: From eqs. (5), (8) and (9) follows

$$p(YC) = p(w) \cdot \exp[(\overline{\varepsilon} - \varepsilon)/\eta] \quad \text{and} \quad p(w) = \frac{w}{\pi_l}/(1 + 1/\eta). \tag{B.1}$$

Inserting these expressions into the first order condition, eq. (27), yields

$$\int_{\overline{\varepsilon}}^{\infty} (\exp[(\overline{\varepsilon} - \varepsilon)/\eta] - 1) \cdot f_\varepsilon d\varepsilon - \frac{c}{\pi_k}\frac{\pi_l}{w} = 0. \tag{B.2}$$

For the normalized random variable $z = \varepsilon/\sigma_\varepsilon$, this expression can be rewritten by changing integration variables as

$$\int_{\overline{\varepsilon}/\sigma_\varepsilon}^{\infty} \{\exp[(\overline{\varepsilon} - z \cdot \sigma_\varepsilon)/\eta] - 1\} \cdot f_z d_z = \frac{c}{\pi_k}\frac{\pi_l}{w}. \tag{B.3}$$

Eq. (B.3) determines $\overline{\varepsilon}$ in terms of σ_ε, η and $\frac{c}{\pi_k}\frac{\pi_l}{w}$.

Proposition B.2: $\overline{\varepsilon}$ and σ_ε determine the probability capacity constraints and the expected utilization of capacities U_c.

Proof: The probability of demand constraints is defined as

$$\mathrm{prob}(YD < YC) = \int_{-\infty}^{\overline{\varepsilon}} f_\varepsilon d\varepsilon. \tag{B.4}$$

The expected utiliation of capacities is defined as

$$U_c := \frac{\mathrm{E}(Y)}{YC} = \int_{-\infty}^{\overline{\varepsilon}} \frac{YD}{YC} \cdot f_\varepsilon d\varepsilon + \int_{\overline{\varepsilon}}^{\infty} f_\varepsilon d\varepsilon. \tag{B.5}$$

Substituting demand YD from eq. (1) and capacities YC through the definition of $\overline{\varepsilon}$ from eq. (9) yields

$$U_c = \int_{-\infty}^{\overline{\varepsilon}} \exp(\varepsilon - \overline{\varepsilon}) \cdot f_\varepsilon d\varepsilon + \int_{\overline{\varepsilon}}^{\infty} f_\varepsilon d\varepsilon. \tag{B.6}$$

Proposition B.3: $\mathrm{E}(p) = (w/\pi_l + c/\pi_k)/(1 + 1/\eta)$, the expected price is determined as mark-up over unit factor costs.

Proof: The first order condition w.r.t. the capital stock, eq. (27), can be rewritten as

$$\int_{\overline{\varepsilon}}^{\infty} p(YC) \cdot f_\varepsilon d\varepsilon = \int_{\overline{\varepsilon}}^{\infty} p(w) \cdot f_\varepsilon d\varepsilon + \frac{c}{\pi_k}/(1 + 1/\eta) = 0. \tag{B.7}$$

Expected prices are defined as

$$\mathrm{E}(p) = \int_{-\infty}^{\overline{\varepsilon}} p(w) \cdot f_\varepsilon d\varepsilon + \int_{\overline{\varepsilon}}^{\infty} p(YC) \cdot f_\varepsilon d\varepsilon \tag{B.8}$$

Inserting eq. (B.7) for the second integral yields the requested result.

Proposition B4: The *average* price is determined as a mark-up over corrected factor costs.

Proof: Expected sales are determined as

$$\mathrm{E}(p \cdot Y) = \int_{-\infty}^{\overline{\varepsilon}} p(w) \cdot Y(w) \cdot f_\varepsilon d\varepsilon + \int_{\overline{\varepsilon}}^{\infty} p(YC) \cdot YC \cdot f_\varepsilon d\varepsilon. \tag{B.9}$$

Inserting eq. (B.7) for the second integral yields

$$\mathrm{E}(p \cdot Y) = p(w) \cdot \int_{-\infty}^{\overline{\varepsilon}} Y(w) \cdot f_\varepsilon d\varepsilon + p(w) \cdot \int_{\overline{\varepsilon}}^{\infty} YC \cdot f_\varepsilon d\varepsilon + YC \cdot \frac{c}{\pi_k} / (1 + 1/\eta). \quad \text{(B.10)}$$

The sum of the first two integrals is equal to expected output $\mathrm{E}(Y)$.

$$\mathrm{E}(p \cdot Y) = p(w) \cdot \mathrm{E}(Y) + YC \cdot \frac{c}{\pi_k} / (1 + 1/\eta). \quad \text{(B.11)}$$

Dividing this expression by expected output yields eq. (29) in the main text. Note that expected sales are determined by expected costs and the mark-up:

$$\mathrm{E}(p \cdot Y) = \left(\mathrm{E}(Y) \cdot \frac{w}{\pi_l} + \frac{c}{\pi_k} \cdot YC \right) / (1 + 1/\eta). \quad \text{(B.12)}$$

The term in paranthesis is the sum of capital costs and expected labour costs.

Appendix C: The optimal capital-labour ratio

In case of a Cobb-Douglas production function,

$$Y = \theta \cdot L^\alpha \cdot K^{1-\alpha} \text{ and } \pi_l = \theta \cdot k^{1-\alpha}, \pi_k = \theta \cdot k^{-\alpha}. \quad \text{(C.1)}$$

The relation of the elasticities of the factor productivities with respect to the capital-labour ratio is equal to the relative output elasticities, and the optimal capital-labour ratio is determined as

$$k = \frac{\pi_l}{\pi_k} = \frac{1-\alpha}{\alpha} \cdot \frac{w \cdot U_c}{c}. \quad \text{(C.2)}$$

i.e. k depends on the relative output elasticities of the factors and relative factor costs. In case of a CES production function,

$$Y^{-\rho} = \delta \cdot (\theta_l \cdot L)^{-\rho} + (1 - \delta) \cdot (\theta_k \cdot K)^{-\rho}. \quad \text{(C.3)}$$

The elasticities of the factor productivities with respect to the capital-labour ratio are given by

$$\frac{\partial \pi_l}{\partial k} \cdot \frac{k}{\pi_l} = (1 - \delta) \cdot \theta_k^{-\rho} \cdot {\pi_k}^\rho, \qquad \frac{\partial \pi_k}{\partial k} \cdot \frac{k}{\pi_k} = -\delta \cdot \theta_l^{-\rho} \cdot {\pi_l}^\rho. \quad \text{(C.4)}$$

ρ is the substitution parameter, δ is the distribution parameter and θ_l, θ_k are the efficiencies of labour and capital. Inserting these expressions into the first order condition with respect to the capital-labour ratio, eq. (32) in the main text, yields

$$\frac{w \cdot U_c}{c} \cdot \frac{\pi_k}{\pi_l} = \frac{\delta \cdot \theta_l^{-\rho} \cdot {\pi_l}^{\rho}}{(1-\delta) \cdot \theta_k^{-\rho} \cdot {\pi_k}^{\rho}}, \tag{C.5}$$

and the optimal capital-labour ratio is determined as

$$k = \frac{\pi_l}{\pi_k} = \left(\frac{w \cdot U_c}{c}\right)^{1/(1+\rho)} \cdot \left(\frac{\delta}{1-\delta}\right)^{1/(1+\rho)} \cdot \left(\frac{\theta_l}{\theta_k}\right)^{-\rho/(1+\rho)}. \tag{C.6}$$

$\rho = 1/\sigma - 1$ and σ is the elasticity of substitution.

Appendix D: A three-step decision structure

The proofs of this model correspond largely to those above in appendix B.

Proposition D.1: $\overline{z} = \overline{z}(\sigma_z, \eta, \frac{c}{\pi_k}\frac{\pi_l}{w})$, the optimal value of $\overline{z}$ depend only on uncertainty about z, the price elasticity of demand η and relative unit factor costs $\frac{c}{\pi_k}\frac{\pi_l}{w}$

Proof: From eqs. (22), (24) and (33) follows

$$p(YC) = p(w) \cdot \exp[(\overline{z} - z)/\eta] \quad \text{and} \quad p(w) = \frac{w}{\pi_l \cdot U_l}/(1 + 1/\eta). \tag{D.1}$$

Inserting these expressions into the first order condition, eq. (36), yields

$$\int_{\overline{z}}^{\infty} (\exp[(\overline{z} - z)/\eta] - 1) \cdot f_z dz - \frac{c}{\pi_k}\frac{\pi_l}{w} = 0. \tag{D.2}$$

Rewriting eq. (D.2) for the normalized random variable z/σ_z yields an expression which determines $\overline{z}$ in terms of σ_z, η and $\frac{c}{\pi_k}\frac{\pi_l}{w}$.

Proposition D.2: $\overline{z}$ and σ_z determine the probabilities of capacity constraints for employment.

Proof: The probability of capacity constraints for employment is defined as

$$\text{prob}(YC < YL(w)) = \int_{\overline{z}}^{\infty} f_z dz. \tag{D.3}$$

Proposition D.3: The expected utilization of capacities U_c is determined by $\overline{z}, \sigma_z$ and the expected utilization of employment U_l.

Proof: The expected utiliation of capacities is defined as

$$U_c := \frac{\mathrm{E}(Y)}{YC} = \left(\int_{-\infty}^{\overline{z}} \frac{YL(w)}{YC} \cdot f_z dz + \int_{\overline{z}}^{\infty} f_z dz \right) \cdot U_l. \tag{D.4}$$

Substituting $YL(w)$ from eq. (25) and capacities YC through the definition of $\overline{z}$ from eq. (33) yields

$$U_c = \left(\int_{-\infty}^{\overline{z}} \exp(z - \overline{z}) \cdot f_z dz + \int_{\overline{z}}^{\infty} f_z dz \right) \cdot U_l. \tag{D.5}$$

Proposition D.4: $\mathrm{E}(p) = (w/\pi_l + c/\pi_k)/(1 + 1/\eta)$, the expected price is determined as mark-up over unit factor costs.

Proof: The first order condition w.r.t. the capital stock, eq. (36), can be rewritten as

$$\int_{\overline{z}}^{\infty} p(YC) \cdot f_z dz = \int_{\overline{z}}^{\infty} p(w) \cdot f_z dz + \frac{c}{U_l \cdot \pi_k} / (1 + 1/\eta) = 0. \tag{D.6}$$

Expected prices are defined as

$$\mathrm{E}(p) = \int_{-\infty}^{\overline{z}} p(w) \cdot f_z dz + \int_{\overline{z}}^{\infty} p(YC) \cdot f_z dz \tag{D.7}$$

Inserting the first order condition for the second integral and $p(w)$ from eq. (24) yields the requested result.

Proposition D.5: The *average* price is determined as mark-up over corrected factor costs.

Proof: Expected sales are determined as

$$\mathrm{E}(p \cdot Y) = \left(\int_{-\infty}^{\overline{z}} p(w) \cdot YL(w) \cdot f_z dz + \int_{\overline{z}}^{\infty} p(YC) \cdot YC \cdot f_z dz \right) \cdot U_l. \tag{D.8}$$

Inserting the first order condition for the second integral yields, substituting expected output $\mathrm{E}(Y)$ and dividing by expected output yields eq. (38) in the main text (see appendix B, proposition B.4 above).