INVESTMENT AND DISINVESTMENT UNDER UNCERTAINTY, FIRM HETEROGENEITY AND TRADABLE OUTPUT PERMITS

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Abstract

This paper develops an agent-based real options model which is capable of analyzing the investment and disinvestment decisions of heterogeneous competing firms under consideration of tradable output permits. A permit market is integrated in which the firms either act as demanders or as suppliers according to their investment or disinvestment behavior for production capacity. By means of a combination of genetic algorithms and stochastic simulation, the endogenous equilibrium price processes for both the product and the permits are simultaneously derived. Through this, the investment and disinvestment thresholds of the heterogeneous competing firms can be simultaneously determined. The empirical application to the EU dairy sector shows that tradable output permits can have considerable effects on investment and disinvestment decisions of competing firms, especially in markets with a high degree of firm heterogeneity. Amongst others, the results indicate that the recent abolishment of the EU milk production quota will ceteris paribus not lead to an accelerated exit of less efficient farms but ultimately have quite the opposite effect.

Keywords

Investment and disinvestment, real options, firm heterogeneity, tradable output permits

1. Introduction

Tradable output permits have become an accepted instrument of market regulation in agriculture and natural resource industries. Examples for this are milk production quotas, fishing quotas, public cattle-grazing permits, manure production rights and the recently discussed carbon emission allowances. Especially now, efforts are being made by politicians to either abolish existing tradable output permit systems with the aim of a further market liberalization (e.g. the EU milk and sugar beet quotas) or to implement new ones in order to limit production externalities (e.g. carbon emission allowances in intensive livestock farming).

Output permits constitute a (usually) scarce production factor. This causes a strong interdependence of firms' investment and disinvestment decisions: Firms usually cannot grow in size, that is invest, unless other firms shrink or exit the market, that is disinvest, since only hereby new factor supply can be provided (e.g. BALMANN et al., 2006). In consequence of the current implementation, intensified use or abolishment of output permit systems, changes in firms' investment and disinvestment strategies can be expected. Therefore, the analysis of investment and disinvestment decisions of competing firms and their respective interactions under tradable output permit systems is of particular interest.

Many investigations have shown that the real options approach (ROA), which exploits the analogy between a financial option and a real investment opportunity, is generally better suited to explain agricultural investments than traditional investment models based on the net present value (NPV) rule (e.g. ODENING et al., 2005; PURVIS et al., 1995; RICHARDS and PATTERSON, 1998). The reason is that agricultural investments are mostly afflicted by uncertainty of the future cash flows, irreversibility of the investment costs and temporal flexibility in conducting the investment. The ROA takes into account explicitly these characteristics by analysing investment decisions under dynamic-stochastic conditions and extending the NPV by the value of entrepreneurial flexibility, which is also called the value of waiting (e.g. DIXIT and PINDYCK, 1994).

However, the simultaneous analysis of investment and disinvestment decisions in the real options context in a competitive environment is complex (e.g. DIXIT and PINDYCK, 1994: ch. 8 and 9). The reason is that, in contrast to financial options, real investment opportunities are rarely exclusive. Due to this non-exclusiveness, similar responses of competitors can be expected when they are faced with aggregated uncertainty, for instance demand uncertainty. The joint reactions of competitors change sectoral supply and hence equilibrium prices. Consequently, the dynamics of the investment returns, for instance the stochastic process for the product price, which determine the value of investment as well as the optimal investment and disinvestment threshold, cannot be considered as exogenous.

To avoid a burdensome iterative derivation of the endogenous equilibrium price process, all existing real options applications explicitly or implicitly exploit Leahy's optimality property of myopic planning (LEAHY, 1993). He shows that an investor in a perfectly competitive market finds the same optimal investment and disinvestment threshold as a myopic planner who behaves like a price taker and ignores other firms' investment and disinvestment decisions. The implication of this result is that the firms' optimal investment and disinvestment thresholds can be determined straightforward in an analytical way by assuming an exogenous price process and hence ignoring competitive effects.

However, by assuming LEAHY's optimality property of myopic planning, the applicability of the ROA to real investments is very limited. Through merely focusing on the myopic planner, the assumption of homogeneous firms is implicitly made for which the determined investment and disinvestment threshold equally apply. However, there exists a relatively high degree of firm heterogeneity in many agricultural markets, which can result in different levels of efficiency (e.g. ALVAREZ and ARIAS, 2004; CLAASEN and JUST, 2011). From these arise different levels of the production costs and, with this, different optimal investment and disinvestment thresholds of the competing firms. This again causes an interdependence of investment and disinvestment decisions, for instance, the investment decisions of relatively efficient firms could cause intensified disinvestment decisions of less efficient firms. These interdependencies cannot be analyzed by models assuming myopic planning to be optimal. For this, a direct determination of the endogenous equilibrium price process in markets with firm heterogeneity would be required, which has not yet been conducted.

Moreover, the limitation of just focusing on the myopic planner complicates the applicability of the ROA to markets with tradable output permits even more, since permit trade relies on simultaneous investment and disinvestment decisions of heterogeneous firms. For instance, if some efficient firms intend to expand production and hence need to buy additional permits, a necessary condition could be that less efficient firms exit the market and release their permits (e.g. TURVEY et al., 2003). Thus, tradable output permits can be expected to have considerable effects on the investment and disinvestment decisions of heterogeneous firms. However, as the latter cannot be determined within the real options context up to now, the respective effects of tradable output cannot be analyzed either.

In the agricultural economics literature, only few studies have addressed investment and disinvestment decisions in the real options context in connection with tradable output permits so far. WENINGER and JUST (2002) analyze the effects of firm-level uncertainty on firms exit thresholds and output permit prices. ZHAO (2003) uses the ROA and derives a general equilibrium model which is capable of determining firms' optimal investment thresholds in irreversible abatement technologies under tradable emission permits. WOSSINK and GARDEBROEK (2006) develop a real options model that determines the impact of policy uncertainty on investments in tradable output permits. KERSTING et al. (2015) determine firms' optimal entry and exit decisions under firm-level uncertainty and given capacity constraints at sectoral level by means of a dynamic-stochastic equilibrium modeling approach. However, neither of these models considers heterogeneity of the firms when determining their optimal investment and disinvestment decisions. Additionally, and partially as a consequence, neither of them can directly model output permit trade between (heterogeneous) competing firms which would be caused by their investment and disinvestment decisions.

Hence, the objective of this paper is to analyze investment and disinvestment decisions of heterogeneous competing firms under uncertainty and tradable output permits. To achieve this goal, a permit market is integrated in which the firms either act as demanders or as suppliers for the permits according to their investment or disinvestment behavior for production capacity. The model is solved numerically by linking genetic algorithms (GAs) and stochastic simulation. Hereby, the endogenous equilibrium price processes for both the product and the permits can be simultaneously derived and, based on this, the firms' optimal investment and disinvestment thresholds determined. The model is exemplarily applied to the European dairy sector. The dairy sector is especially suited for this because, first, it is afflicted by uncertainty, irreversibility of the investment costs and temporal flexibility in conducting investments (e.g. ENGEL and HYDE, 2003; PURVIS et al., 1995; TAUER, 2006). Second, until recently the EU dairy sector was characterized by a tradable output permit system, the EU milk production quota scheme. The effects of the abolishment of the latter on the investment and disinvestment decisions of the firms and thus on structural change are exemplarily analyzed.

The next section develops an agent-based real options market model with an integrated tradable output permit market. The numerical solution procedure is subsequently explained. After the model parameters for the application to the EU dairy sector are described, the model results with regard to the effects of heterogeneity and tradable output permits on the firms' optimal investment and disinvestment decisions are discussed. The paper ends with a summary of the main findings and the derivation of some policy implications.

2. Model

The model which will be developed in this section takes the one of FEIL and MUSSHOFF (2013) as a basis. Their real options market model is capable of analysing simultaneously the investment and disinvestment thresholds, in specific the investment and disinvestment trigger prices, of competing firms in a market. This is achieved by directly deriving the endogenous equilibrium price process and thus overcoming some restrictive preconditions for applying Leahy's optimality principle of myopic planning. However, for complexity reasons their model does still assume homogeneous firms, whereby the interactions between the firms' investment and disinvestment decisions, which is caused by their heterogeneity, cannot be depicted. Therefore, the new model considers additionally two important aspects: First, this model allows for firm heterogeneity. Second, a market for tradable output permits is integrated in which the firms act simultaneously either as demanders or as suppliers according to their investment or disinvestment behavior for production capacity.

Within the model, a market consisting of $N = 100$ risk-neutral firms is considered, which compete to satisfy the same exogenous stochastic demand μ_t for a homogeneous commodity. The N firms can be split into groups, so that every firm n can always be uniquely assigned to a firm group. Within a firm group, the firms are homogeneous regarding their investment and production possibilities. However, across the groups the firms may be heterogeneous from each other, for instance with regard to their efficiency levels. The firms plan in discrete time, which is a necessary assumption of numerical options valuation procedures. Each firm has the option to repeatedly invest in production capacity within the period under the period of consideration T, until an exogenously given maximum output capacity X_{cap} is reached. Investment outlay and production output are proportional, which means that there are no economies of scale. The investment project has an unlimited useful lifetime and is subject to depreciation with geometric rate λ. After implementation, the investment can be abandoned and its costs partially reversed. Consequently, the production capacity of a firm n in t, resulting in a production output X_t^n, can be adjusted in two ways: Either through investments once per period to the extent of Y_t^n, resulting in an additional production output in the following period, or through disinvestments once per period to the extent of Z_t^n, resulting in a reduction in production output in the following period. Production thus follows:

$$X_{t+\Delta t}^n = X_t^n \cdot (1 - \lambda) + Y_t^n - Z_t^n. \qquad (1)$$

The aggregated production output of all firms represents the market supply for the homogeneous commodity X_t. Prices result from the reactions of all market participants on the exogenous stochastic demand parameter μ_t and hence, need to be determined endogenously within the model. Without loss of generality, the relationship between market supply X_t and price P_t is defined by an isoelastic demand function (e.g. Dixit, 1991):

$$P_t = D(X_t, \mu_t) = \left(\frac{\mu_t}{X_t}\right)^{\Pi} \qquad \text{with} \qquad \Pi = -\frac{1}{\eta} \qquad (2)$$

where η is the price elasticity of demand.

To be entitled to produce in a specific period, the firms have to own tradable output permits prior to investment. In a certain period $\tilde{t}$ the government issues permits to the market to the overall amount of $U_{\tilde{t}}$. In the model, the permits can be allocated among the firms as flexibly as needed, for instance even among all $N = 100$ firms in $\tilde{t} = 0$ or to the extent of the production capacity of every invested firm at a later point. In the period of the issue and all subsequent periods, the permits can be traded between the firms on a separate market according to their investment and disinvestment behavior. Permit prices Q_t result from the interplay of demand and supply and thus need to be determined endogenously within the model like the product prices. Consequently, the output permit stock of a firm can either be increased by additional purchases V_t^n or decreased by sales W_t^n. For the permit stock follows:

$$U_{t+\Delta t}^n = U_t^n + V_t^n - W_t^n. \tag{3}$$

According to the model of homo economicus, all firms maximize their expected NPV. Furthermore, all firms have complete information regarding the stochastic demand process as well as the investment and disinvestment behavior and the output permit trading behavior of all competitors. Based on this they build price expectations for the respective next period. Consequently, all firms should have the same optimal investment and disinvestment trigger prices in equilibrium. To derive this Nash equilibrium within the model, the competing firms interact by gradually adjusting their (initially different) investment and disinvestment trigger prices ($\bar{P}^n$, $\underline{P}^n$) as well as their (initially different) permit purchase and sales trigger prices ($\bar{Q}^n$, $\underline{Q}^n$), as explained in the next section. Within a period, it is assumed that all firms first make a disinvestment decision and then an investment decision. In this context, it is technically ensured that $\underline{P}^n < \bar{P}^n$ for all firms, that is a firm n will not make the decision to invest if it has decided to disinvest immediately before. Due to this system of chronological order, the disinvestments accumulated in a period impact the investment decisions of the same period, but not vice versa.

To derive the disinvestment volume of the firms in the first instance, it is assumed that firms with a higher disinvestment trigger price have a stronger tendency to abandon the investment. Accordingly, all firms are sorted according to their disinvestment trigger prices, starting with the highest, i.e. $\underline{P}^m \geq \underline{P}^{m+1}$. Consequently, firm $m+1$ does not disinvest if firm m has not already completely abandoned the investment. Likewise, it is obvious that if firm $m+1$ abandons the investment completely, firm m completely abandons the investment, too. Furthermore, in every period t, a marginal (or last) firm exists which disinvests to the extent that its disinvestment trigger price equals the expected product price of the next period. For the disinvestment volume of a firm n^* in t, corresponding to its additional production output in $t + \Delta t$, follows:

$$Z_{t+\Delta t}^{n^*}\left(\underline{P}^{n^*}\right) = \max\left[0, \min\left(\begin{matrix} X_t^{n^*} \cdot (1-\lambda), \\ \left(\sum_{n=1}^{\mathrm{N}} X_t^n \cdot (1-\lambda) + \sum_{n=1}^{n^*-1} \mathrm{Z}_{t+\Delta t}^n\left(\underline{P}^n\right)\right) - \frac{\hat{\mathrm{E}}(\mu_{t+\Delta t})}{\left(\underline{P}^{n^*}\right)^{-\eta}} \end{matrix}\right)\right] \tag{4}$$

The "max-query" of equation (4) ensures non-negativity of the disinvestment volume. Furthermore, the "min-query" makes sure that a firm cannot abandon more production capacity via disinvestments than it has built up in former periods. The "min-query" also guarantees that the total quantity of supply is just reduced as long as the disinvestment trigger price of the "last" firm equals the expected product price of the next period.

In contrast to the disinvestment volume, the actual investment volume is determined in three steps: First, merely the intended investment volume is determined as it is unclear at this point, whether the firm owns sufficient output permits to be entitled to produce the additional output. The intended investment volume is derived analogously to the disinvestment volume, i.e. firms with lower investment trigger prices have a stronger tendency to invest. All firms are sorted according to their investment trigger prices, starting with the lowest, i.e. $\bar{P}^n \leq \bar{P}^{n+1}$. Thus, firm $n+1$ does not potentially invest if firm n has not already potentially invested in production capacity up to

X_{cap}. In every period t, it is technically ensured that de facto a marginal (or last) firm exists which potentially invests to the extent that its investment trigger price would equal the expected product price of the next period. As a result of this and the relatively large number of firms ($N = 100$), the market within the model can be seen as an approximation of an atomistic market. For the intended investment volume of a firm n^* in t follows:

$$\tilde{Y}_{t+\Delta t}^{n^*}(\bar{P}^{n^*}) = \max\left[0, \min\begin{pmatrix} X_{cap} - X_t^{n^*} \cdot (1-\lambda)\,, \\ \frac{\hat{\mathrm{E}}(\mu_{t+\Delta t})}{(\bar{P}^{n^*})^{-\eta}} - \left(\sum_{n=1}^{\mathrm{N}} X_t^n \cdot (1-\lambda) + \sum_{n=1}^{n^*-1} Y_{t+\Delta t}^n(\bar{P}^n) + \sum_{n=1}^{N} Z_{t+\Delta t}^n(\underline{P}^n)\right)\end{pmatrix}\right] \tag{5}$$

Analogously to equation (4), the "max-query" of equation (5) ensures non-negativity of the intended investment volume. The "min-query" makes sure that a firm cannot build-up more production capacity via investments than it needs in order to produce its maximum production capacity X_{cap}. Additionally, the "min-query" ensures that the total quantity of supply is only expanded as far as the investment trigger price of the "last" invested firm equals the expected product price of the next period.

Second, based on its disinvestment respectively intended investment decision, a firm may get active on the permit market to adjust its permit stock. It either might be the case that the firm has to buy additional permits to be entitled to produce additional output caused by the investment decision according to equation (5). Or the firm can be in a position to sell excess permits caused by the disinvestment decision according to equation (4) and/or by depreciations in this and previous periods. Hence, the firms can either act as demanders or suppliers for output permits. The permit demand of a firm n in t is determined as follows:

$$\tilde{V}_t^n = \max[0; X_t^n \cdot (1-\lambda) + \tilde{Y}_{t+\Delta t}^n - Z_{t+\Delta t}^n - U_t^n] \tag{6}$$

Analogously, the permit supply of a firm n in t is derived as follows:

$$\widetilde{W}_t^n = \max[0; U_t^n - X_t^n \cdot (1-\lambda) - \tilde{Y}_{t+\Delta t}^n + Z_{t+\Delta t}^n] \tag{7}$$

The equilibrium permit price in each period is settled on a permit exchange on a bid-ask basis: The firms with an individual permit demand according to equation (6) place bids, that is, permit purchase trigger prices $\bar{Q}^n$, while those with an individual supply according to equation (7) set ask prices, that is, permit sales trigger prices $\underline{Q}^n$. The model then ranks and accumulates the quantity and price of the firms' permit demands as well as the quantity and price of the firms' permit supplies. The equilibrium permit price Q_t, which is the market-clearing price, thus is the price at which the accumulated demand equals the accumulated supply. Since demand equals supply, all offers to purchase at or above Q_t and all offers to sell at or below Q_t are satisfied. For the actual permit purchases and sales of the firms follows:

$$V_t^n\left(\overline{Q}^n\right) = \begin{cases} \tilde{V}_t^n(\bar{Q}^n) & if\ \ \bar{Q}^n \geq Q_t \\ 0 & otherwise \end{cases} \tag{8}$$

and

$$W_t^n\left(\underline{Q}^n\right) = \begin{cases} \widetilde{W}_t^n\left(\underline{Q}^n\right) & if\ \ \underline{Q}^n \leq Q_t \\ 0 & otherwise \end{cases} \tag{9}$$

Based on this, a firm n can derive its actual investment volume as a third and last step:

$$Y_{t+\Delta t}^n\left(\bar{P}^n, \bar{Q}^n, \underline{Q}^n\right) = \max\left[0, \min\begin{pmatrix} \tilde{Y}_{t+\Delta t}^n(\bar{P}^n)\,, \\ U_{t+\Delta t}^n\left(\bar{Q}^n, \underline{Q}^n\right) - X_t^n \cdot (1-\lambda) \end{pmatrix}\right] \tag{10}$$

The "max-query" of equation (12) guarantees non-negativity of the actual investment volume. The "min-query" ensures that the actual investment volume of firm n does not exceed the intended investment volume according to equation (5). Furthermore, it makes sure that firm n cannot build up more production capacity via investments than it is entitled to produce through its adjusted output permit stock for the next period.

Finally, an objective function needs to be established which determines the optimal investment and disinvestment strategies of the firms. According to the above assumptions, each firm aims to maximize the expected NPV of the future cash flows F_0^n, in the real options terminology also referred to as an option value, by choosing its firm-specific investment trigger price $\bar{P}^n$, its disinvestment trigger price $\underline{P}^n$, its output permit purchase trigger price $\bar{Q}^n$ and its output permit sales trigger prices $\underline{Q}^n$:

$$\max_{\bar{P}^n,\underline{P}^n,\bar{Q}^n,\underline{Q}^n} \{F_0^n\} = \max_{\bar{P}^n,\underline{P}^n,\bar{Q}^n,\underline{Q}^n} \left\{ \sum_{t=0}^{\infty} \left(\left(P_t - C^j - K^j\right) \cdot X_t^n\left(\bar{P}^n,\underline{P}^n\right) - (1-s) \cdot C^j \cdot \sum_{u=0}^{t} Z_u^n\left(\underline{P}^n\right) - L_t^n\left(\bar{Q}^n,\underline{Q}^n\right) \right) \cdot e^{-r\cdot t} \right\} \tag{11}$$

The interest rate r is time-continuous. C^j represents the constant capital costs of the investment outlay per output unit, which can have different levels for every firm group j due to different efficiency levels. The reversibility rate s determines what proportion of C^j can be recovered upon abandonment. All other operational costs to be paid (e.g. for material and labour) are depicted by K^j. Furthermore, L_t^n denotes the total permit costs of a firm n in t, which can be determined as follows:

$$L_t^n\left(\bar{Q}^n,\underline{Q}^n\right) = L_{t-\Delta t}^n + Q_t^p \cdot \left(U_t^n\left(\bar{Q}^n,\underline{Q}^n\right) - U_{t-\Delta t}^n\left(\bar{Q}^n,\underline{Q}^n\right)\right) \tag{12}$$

with Q_t^p being the perpetuity of the equilibrium permit price in t:

$$Q_t^p = Q_t \cdot \left(e^{r\cdot\Delta t} - 1\right) \tag{13}$$

3. Solution procedure

As no analytical solution exists for the optimization problem described in the previous subsection, the model is solved numerically by combining GAs with stochastic simulation. GAs are a heuristic search method that have been applied in many disciplines during the last two decades including economics in particular. Amongst others, they are used for optimisation problems and the identification of equilibria in strategic settings, respectively (e.g. ALTIPARMAK et al., 2006; GRAUBNER et al., 2011). GAs apply the evolutionary concepts of natural selection, crossover and mutation on a population of behavioural strategies (e.g. GOLDBERG, 1998). In the present analysis, the GA is used to examine optimal investment and disinvestment strategies of the competing firms and the respective effects of tradable output permits. For doing this, the GA approach is applied in the way that a firms' strategy is not just represented by one value, for instance merely its investment trigger price, but by a set of four values, that is, its investment and disinvestment trigger price as well as its permit purchase and sales trigger price. This set of four values is optimised simultaneously throughout the GA procedure.

In general, GAs have three standard features in common: a population of $N = 100$ genomes, a fitness function and GA operators. A population of genomes generally describes a collection of contender solutions to a given problem. In this case, each genome of a population represents a combination of the four trigger prices. The fitness function serves as the evaluation measure for the quality of a solution. Here, the fitness function is represented by the objective function of the model, which is the option value of a firm n (11). These option values are determined by means of stochastic simulation. Finally, the GA operators are applied to the population of genomes. Usually, as well as in this case, the GA operators consist of selection, mutation and crossover. The detailed technical implementation of the GA operators will not be further explained. However, it should be noted that their respective design does not affect the results itself, but merely the computational efficiency of the solution procedure. Through the utilization of this procedure, solutions with a high fitness function value are identified and new, possibly superior solutions are incorporated.

The result is a new population of genomes, consisting of four trigger prices each, on which the above procedure is applied again within a homogeneous firm group. This process is repeated until the population converges towards an equilibrium and the equilibrium combination of the optimal investment and disinvestment trigger prices for each homogeneous firm group as well as the equilibrium permit price for the overall market is hence determined. Accordingly, the GA can be stopped when the obtained strategies are both homogenous, that is, very similar to each other within one generation, and stable, i.e. very similar from one generation to the next. The specific design of the stop criterion of a GA depends on the complexity of the planning problem at hand. In the present case, the GA is stopped if the arithmetic mean of each of the four trigger prices of the ten fittest firms has not changed up to the third decimal place for at least 100 generations.

4. Application to the European dairy sector

To illustrate the developed model with practical realism, it is applied to the European dairy sector. This sector is highly competitive, comprising 708,170 producers either classified as specialized dairy farms, or as dairying, rearing and fattening combined farms in 2013 (EUROPEAN COMMISSION, 2016). At the same time, the European dairy sector is currently exposed to strong changes in its economic environment, especially through the recent abolishment of the tradable EU milk production quota scheme in 2015. In addition, and at least partially, because of these changes, there have recently been extreme milk price fluctuations. Additionally, dairy farms across the EU, and even within the different countries, are characterised by a high degree of heterogeneity, especially with regards to their efficiencies (e.g. ALVAREZ and ARIAS, 2004). All of these aspects support the applicability of the developed model framework to the European dairy sector. The used model parameters are summarized in Table 1 and their detailed determination is explained thereafter.

Table 1. Model parameters for the application to the EU dairy sector

Total number of firms N and firm group j	100 with 50 in group $j = 1$ and 50 in group $j = 2$
Milk yield	Group 1: 10,000kg per cow per year (resp. 7,000) Group 2: 7,000kg per cow per year
Period under consideration T	Infinite, approximated by 100 years
Capital costs for the investment outlay C^j (excluding costs for output permits)	$C^1 = 0.0328$ € per kg per year $C^2 = 0.0469$ € per kg per year
Reversibility rate of the investment costs s	50%
Useful lifetime of investment	Infinite
Geometric depreciation rate λ	4.25%
Operational costs K^j (after deducting sales revenues for old cows and calves)	$K^1 = 0.2136$ € per kg per year $K^2 = 0.3052$ € per kg per year
Risk-free time-continuous interest rate r	3.38%
Stochastic process of the demand parameter μ_t	Geometric Brownian motion (GBM)
Drift rate α	-2.97%
Volatility σ	19.59%
Time step length Δt	1.00 (i.e. one planning period equals one year)
Price elasticity of demand η	-0.99
Simulation runs S	50,000

Mainly because of data availability problems, it is practically impossible to directly estimate the stochastic demand process μ_t and its parameters empirically. Instead, following many other real options applications to agriculture in general and to the dairy sector in specific (cf. e.g. ENGEL and HYDE, 2003; PURVIS et al., 1995; TAUER, 2006), the stochastic price process and its parameters are estimated from available historic price data. Subsequently, the parameters of the stochastic price process can then be re-transformed into the parameters of the stochastic demand process μ_t (e.g. ODENING et al., 2007).

For the empirical estimation of the stochastic price process, it is crucial to use historical prices that have not, or to a minor extent, been affected by any market interventions. Hence, historical EU milk prices do not seem to be appropriate because of the EU milk price intervention system until 2007 and the existing EU milk quota system. In contrast, the dairy sector in New Zealand is not characterised by any significant political interventions and, therefore, the inflation-adjusted average prices for milksolid in New Zealand from 1973 to 2014 are taken as a basis (LIC, 2014). Applying a variance ratio test as well as an augmented Dickey Fuller test to this time series, it is shown that the null hypothesis of non-stationarity cannot be rejected at a 5% significance level. Following common practice of other real options applications, this test result can be seen as an indication that a geometric Brownian Motion (GBM) represents an adequate model for the price process.

In general, a GBM represents the solution of the stochastic differential equation (e.g. LEAHY, 1993):

$$\mathrm{d}\mu_t = \alpha \cdot \mu_t \cdot \mathrm{d}t + \sigma \cdot \mu_t \cdot \mathrm{d}z \tag{13}$$

where α denotes the drift rate and σ the volatility of the stochastic demand. Both parameters are assumed to be constant. $\mathrm{d}z$ is the increment of a Wiener process. If $\mathrm{d}\mu_t$ describes a demand shock, the stochastic demand process according to equation (13) can be translated into a stochastic price process (ODENING et al., 2007):

$$\mathrm{d}P_t = \hat{\delta}(P_t, X_t) \cdot \mathrm{d}X_t + \hat{\alpha} \cdot P_t \cdot \mathrm{d}t + \hat{\sigma} \cdot P_t \cdot \mathrm{d}z \tag{14}$$

with

$$\hat{\delta}(P_t, X_t) = -\Pi \cdot X_t^{-1} \cdot P_t, \qquad \hat{\alpha} = \Pi \cdot \alpha + \tfrac{1}{2} \cdot \sigma^2 \cdot (\Pi^2 - \Pi) + \lambda \cdot \Pi, \qquad \hat{\sigma} = \Pi \cdot \sigma$$

By using the available historic price data from New Zealand, the estimation of the parameters of the stochastic price process yields an estimated drift rate of $\hat{\alpha} = 1.31\%$ and a volatility of $\hat{\sigma} =$ 19.39%. To re-transform these into the parameters of the stochastic demand process α and σ by means of equation (14), the price elasticity of demand η and the geometric depreciation rate λ are needed: Thiele (2008) reports a price elasticity for dairy products in Germany of $\eta =$ -0.99. Furthermore, according to the German Association for Technology and Structures in Agriculture, a depreciation rate of $\lambda = 4.25\%$ p.a. for milk production capacity in Germany can be assumed (KTBL, 2014). With this information, the parameters of the stochastic price process $\hat{\alpha}$ and $\hat{\sigma}$ can be re-transformed into the parameters of the stochastic demand process α and σ, following equation (14), which yields $\alpha =$ -2.97% and $\sigma = 19.59\%$.

Since the GBM as stochastic demand process assumes infinitesimal time length steps and hence is impractical for simulation purposes, it is transformed into a time-discrete version. This can be done by the use of Ito's Lemma (cf. HULL and WHITE, 1987):

$$\mu_{t+\Delta t} = \mu_t \cdot e^{\left[\left(\alpha - \frac{\sigma^2}{2}\right) \cdot \Delta t + \sigma \cdot \varepsilon_t \cdot \sqrt{\Delta t}\right]} \tag{15}$$

with a standard normally distributed random number ε_t and a time step length Δt. Equation (15) represents an exact approximation of the time-continuous GBM according to equation (14) for any Δt. For the risk-free discount rate, the arithmetic mean of the inflation-adjusted monthly average yields of listed federal securities with 15-30 years residual maturity for the period from 1989 to 2013 is calculated at 3.44% per year (Bundesbank, 2014), which corresponds to a time-continuous interest rate of 3.38%.

With regard to the investment costs, a typical investment to build up milk production capacity in Germany with an initial investment outlay of 4,371 € per cow place or 0.62 € per kg milk is considered (KTBL, 2014). Looking at the firm efficiencies, milk yields of 7,000 kg per cow per year, which represents the average milk yield across Germany (KTBL, 2014), and 10,000kg, which could for instance refer to firms with higher management capabilities and which are no rarity in Germany, are considered to model the effects of firm heterogeneity. If 10,000kg represents the milk yield of the firms in group A and 7,000kg the milk yield of the firms in group B, then the resulting capital costs for the investment outlay are $c_A = 0.0328$ € and $c_B = 0.0469$ € per kg per year. Furthermore, the operational costs (e.g. for heifer, fodder, labour and veterinarian), after deducting the sales revenues for old cows and calves, are $k_A = 0.2136$ € and $k_B = 0.3052$ € per kg per year.

5. Results and discussion

Table 2 presents the model results for four different scenarios to illustrate the ceteris paribus effects of both firm heterogeneity and tradable output permits on the firms' optimal investment and disinvestment decisions. In Scenario A, the base scenario of homogeneous firms with a milk yield of 7,000 kg and no tradable output permits is presented. In Scenario B, heterogeneity between both firm groups is introduced in the way that the firms of group A become more efficient with a milk yield of 10,000 kg (e.g. through learning effects), while the efficiency of the firms of group B stays constant with a milk yield of 7,000 kg. Scenario 3 again considers homogeneous firms with a milk yield of 7,000 kg, but introduces a tradable output permit system. For the latter, it is assumed that the government issues output permits in period $t = 0$ to the amount of the actual aggregated market quantity of milk. The initial allocation of the permits to the firms is conducted in an auction, that is, the firm with the highest bid, that is its permit purchase trigger price $\bar{Q}^n$, purchases permits to the amount of its maximum output capacity X_{cap}, followed by the firm with the second highest trigger price, until all permits are sold. It should be noted that the permits can be initially allocated to the firms as flexibly as needed within the model with regard to the point in time and the modality. This just represents one out of many possibilities. Immediately afterwards and in all 100 consecutive periods, the firms can trade permits between each other according to their investment and disinvestment behavior, as explained in the model section. In Scenario 4 the effects of both firm heterogeneity and tradable output permits are depicted.

Table 2. Impact analysis of firm heterogeneity and tradable output permits on the firms' investment and disinvestment decisions

Scenario	Tradable output permits	Firm group	Milk yield (kg/year)	Investment trigger price (€/kg)	Disinvestment trigger price (€/kg)	Output permit trigger price (€/kg)
A	No	1	7000	0.4133	0.2784	n.a.
		2	7000	0.4133	0.2785	n.a.
B	No	1	10000	0.2895	0.1947	n.a.
		2	7000	0.4377	0.2859	n.a.
C	Yes	1	7000	0.3650	0.2946	0.4791
		2	7000	0.3649	0.2952	0.4792
D	Yes	1	10000	0.2760	0.1984	0.4804
		2	7000	0.3456	0.3132	0.4801

Note: GBM with $\alpha =$ -2.97% and $\sigma =$ 19.20%, $\eta =$ -0.99, $T = 100$, $c_A = 0.0328$€, $c_B = 0.0469$€/kg, $k_A = 0.2136$€, $k_B = 0.3052$€, $\lambda = 4.25\%$, $i = 50\%$, $r = 3.38\%$, $\Delta t = 1$ year.

The illustration of the pronounced real options effect (Scenario A): In the base scenario, the determined optimal investment trigger price of both firm groups is $\overline{P} = 0.4133$ €/kg and the disinvestment trigger price is $\underline{P} = 0.2784$ €/kg. These results illustrate the pronounced real options effect, which has already been observed in other real options applications to the dairy sector exploiting the optimality property of myopic planning (e.g. ENGEL and HYDE, 2003; PURVIS et al., 1995; TAUER, 2006). Accordingly, the investment trigger price of the model is considerably higher than the investment trigger price according to the classical NPV rule (the sum of the capital costs and operational costs, hence 0.3521 €/kg). Analogously, the disinvestment trigger price of the model is considerably lower than the one according to the classical NPV rule (the reversible share of the capital costs plus the operational costs, hence 0.3287 €/kg).

Additionally, it should be noted that this base scenario represent an approximation of a perfectly competitive market, because the firms are homogeneous, their number is relatively high ($N = 100$) and the model ensures that there is always a "last" investing firm, that is, the zero-profit-condition is fulfilled in this scenario (cf. Section 2). Due to this, the results of this scenario can be validated based on LEAHY' optimality property of myopic planning. This is achieved by solving the analytical system of equations of DIXIT and PINDYCK (1994: 216ff.) with the given parameters by means of iterative approximation.

The ceteris paribus effects of heterogeneity on the firms' investment and disinvestment decisions in markets without tradable output permits (comparison of scenario A and B): Through the improvement of the efficiency level of the firms in group 1 from 7,000 to 10,000 kg milk yield, their optimal investment as well as their disinvestment trigger price decreases considerably, so that they invest earlier and a have a higher inertia to abandon the investment once implemented. This is due to the associated reduction of the capital and operational costs per output unit of the firms in group 1, which can be compensated by a lower investment trigger price. Furthermore, the optimal investment trigger price of the firms in group 2 increases, so that these firms' willingness to invest decreases, although this group's efficiency level remains stable at 7,000 kg. This again can be explained by the positive market quantity effect, which is induced by the higher willingness to invest for the firms in group 1 in the first instance (see above). Hereby, expected milk prices decrease ceteris paribus, therefore leading to a lower expected profitability of the investment project for the firms in group 2. The investment trigger price at present, which needs to compensate for the unchanged capital and operational costs per output unit of the firms in group 2, hence needs to increase. In conclusion, it can be stated that efficiency changes of certain firms do not only affect their own investment and disinvestment decisions, but also the ones of firms with unchanged efficiency levels in the respective market.

The ceteris paribus effects of firm heterogeneity (comparison of Scenario A and B): Through the improvement of the efficiency to 10,000kg milk yield of the firms in group A, both their optimal investment and disinvestment trigger prices decrease considerably, that is, they invest earlier and a have a higher inertia to abandon the investment once implemented. This is due to the associated reduction of the capital and operational costs per output unit of the firms in group A, which can already be compensated by a lower trigger price for milk. Furthermore, the optimal investment trigger price of the firms in group B increases, that is, these firms' willingness to invest decreases, although this group's efficiency remains at 7,000kg. This again can be explained by the positive market quantity effect, which is induced by the higher willingness to invest of the firms in group A in the first instance (see above). Hereby, expected milk prices ceteris paribus decrease and, with this, the expected profitability of the investment project for the firms in group B. The investment trigger price at present, which needs to compensate the unchanged capital and operational costs per output unit of the firms in group B, hence needs to increase. Consequently, efficiency changes of certain firms do not only affect their own investment and disinvestment decisions, but also the ones of firms with unchanged efficiencies in the respective market.

The ceteris paribus effects of tradable output permits on the investment and disinvestment decisions of homogeneous firms (comparison of scenario A and C): Through the introduction of tradable output permits, the homogeneous firms' optimal investment trigger price decreases, leading to them investing earlier. There are two opposing effects that need to be considered here: On one hand, the firms additionally have to take into account the capital costs for the output permits to be entitled to produce. This has an increasing effect on the investment trigger price, as the overall investment costs increase. On the other hand, the aggregated quantity of milk supply is restricted in periods of high demand. Hereby, expected milk prices increase ceteris paribus and, with this, the expected profitability of the investment project. Hence, a lower investment trigger price at present can compensate for the capital and operational costs of the firms. In the present case, obviously the latter decreasing effect clearly over-compensates for the former increasing effect. Furthermore, the optimal disinvestment trigger price of the firms slightly increases through the introduction of tradable output permits. This can be explained by the fact that the permit price can be recovered on the permit market if needed and is thus perfectly reversible. In doing so, the firms are able to monetize a higher share of their investment costs straight away upon abandonment, which obviously represents an incentive for them to disinvest earlier. Consequently, this means that in markets with relatively homogeneous firms (or a low degree of firm heterogeneity), the introduction of tradable output permits ceteris paribus can foster structural change.

The ceteris paribus effects of tradable output permits on the investment and disinvestment decisions of heterogeneous firms (comparison of scenario B and D): Under firm heterogeneity, the decreasing effect of tradable output permits on investment trigger prices as well as the increasing effect on disinvestment trigger prices, which both could be observed in the case of homogeneous firms (comparison of scenario A and C), is weakened for the more efficient firms in group 1, while it is even intensified for the less efficient firms in group 2. Through the introduction of the output permit system, the associated restriction of the overall available market quantity especially affects the less efficient firms in group 2, because the more efficient firms in group 1 already invest earlier due to their lower disposable costs per output unit. This obviously forces the less efficient firms in group 2 to decrease the investment trigger price stronger. On the contrary, the disinvestment trigger price of the firms in group 2 would decrease by abolishing the tradable output permit system (going from Scenario D back to Scenario B), so that the firms would be more reluctant to abandon the investment project. This indicates that the recent abolishment of the EU milk production quota will ceteris paribus not lead to an accelerated exit of less efficient farms, which is consistent with the widespread opinion of politicians and lobbyists in the current public debate, but ultimately have quite the opposite effect.

The ceteris paribus effects of heterogeneity on the firms' investment and disinvestment decisions in markets with tradable output permits (comparison of scenario C and D): Through the improvement of the efficiency level of the firms in group 1 in a market, the optimal investment trigger price of the firms in group 1 decreases, because their unit costs decrease as well, as already described in the case of no tradable output permits (comparison of scenario A and B). However, this decreasing effect on the investment trigger price is less pronounced, because the market supply quantity is already restricted by the output permits in the reference scenario (scenario C). This has an increasing effect on the expected commodity price level, whereby the firms in group 1 can already afford to invest at a lower trigger price in the first place. In contrast to the effect of firm heterogeneity without tradable output permits (comparison of scenario A and B), the optimal investment trigger of the remaining firms in group 2, whose efficiency level stays as is, also decreases. This again can be explained by the restriction of the market supply quantity through the permits in the first place. As the firms in group 1 invest earlier (see above), the remaining market quantity available for the firms in group 2, until the overall market permit quantity is exhausted, decreases. This pressure forces them to decrease their investment trigger price to enter the market. This decreasing effect on the optimal investment trigger price of group 2 obviously over-compensates the increasing effect caused by the intensified investments of group 1 (comparison of scenario A and B). In result, the consideration of existing tradable output permits is important when analysing the ceteris paribus effects of different heterogeneity levels on structural change.

6. Conclusion

In light of the implementation, intensified use or abolishment of tradable output permit systems in agriculture and natural resource industries, changes in firms' investment and disinvestment strategies can be expected. Therefore, the analysis of heterogeneous firms' investment and disinvestment decisions and their respective interactions under tradable output permit systems is of particular interest. In this article, an agent-based real options model is developed which is capable of determining the optimal investment and disinvestment thresholds of heterogeneous competing firms. In the model, a permit market is integrated, where the firms either act as demanders or as suppliers according to their investment or disinvestment behavior for production capacity. Through a numerical solution procedure consisting of a combination of GAs and stochastic simulation, the endogenous equilibrium price processes for both the product and the permits can be simultaneously derived, along with the firms' optimal investment and disinvestment thresholds for production capacity.

The results of the model reveal new insights into the effects of tradable output permits on investments and disinvestments at firm level and on structural change at sectoral level. Therefore, the model can serve as an improved decision support for both entrepreneurs and politicians especially in agriculture and natural resource industries, where the abolishment or the introduction of tradable output permit system are currently being conducted or discussed. Amongst others, the results indicate that in markets with relatively homogeneous firms, which show relatively similar levels of efficiency, tradable output permits ceteris paribus can even foster structural change: The firms' investment thresholds decrease, leading them to invest earlier, while the disinvestment thresholds increase, leading to the earlier abandonment of production capacity. In markets with relatively heterogeneous firms, which therefore show greater differences in their levels of efficiency, this effect of decreasing investment thresholds and decreasing disinvestment thresholds is weakened for the more efficient firms, while it is even intensified for the less efficient firms. Interestingly, this finding clearly contrasts with the widespread opinion of the public debate that the recent abolishment of the EU milk production quota leads to an accelerated exit of smaller and, thus, less efficient farms. Therefore, it counters the main argument of politicians and lobbyist who call for the introduction of new support measures due to the milk production quota abolishment.

Although the model addresses some crucial aspects for analyzing investment and disinvestment decisions in competitive environments in reality, it still provides room for further extensions, which are out of scope for this article, but can be the basis for future research. Due to complexity reasons, the present model assumes a constant returns-to-scale technology of the firms, as all other existing real options models in the literature do. Although it can be expected that more complex input-output relationships will not qualitatively change the investigated effects of tradable output permits, their additional consideration could nevertheless lead to further improved forecasts of firms' adaption behaviors. Furthermore, no transaction costs are assumed for the firms with regard to output permit trade, which, however, are existent in reality (e.g. Stavins, 1995). Finally, heterogeneity could not only be manifested in the efficiency levels of the firms, but also in the risk preferences of their managers. To assess the respective impacts on the firms' investment and disinvestment decisions, future research could be beneficial.

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