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Thesis

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Interrelationship Models in Energy Markets

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Interrelationship Models in Energy Markets

by

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Abstract

This thesis aims to make two types of academic contributions. It includes both methodological insights about the application of quantitative methods to the study of network industries and theoretical results concerning the economics of energy markets. The theoretical literature on interconnectors has established their potential to mitigate local market power, but the relationship between capacity utilisation and locational market splitting has not been studied empirically. Thus, in the first essay of the thesis I apply Vector Autorregressive (VAR) modelling techniques to data from the Bacton (UK)-Zeebrugge (Belgium) natural gas pipeline. The analysis identifies a threshold of capacity utilisation after which the UK and Continental markets split. The relationship between local price differences and capacity use is increasing and convex. A difference between the UK and Continental markets is that while there are extensive crossholdings in the Continent, UK firms remain in general independent from each other. This raises the issue of how crossholdings affect the firms' ability to coordinate in higher prices. Hence, the second essay presents a set of simulations in which computational agents try to optimise their profit using parameters adapted from the Roth and Erev (1995) reinforcement algorithm. The auction setting is a double-sided stylisation of the European energy markets. The results indicate that market transparency leads to higher prices, that the functional form of the crossholdings to prices relationship is not linear but concave and that more downstream competition reduces the influence of information on wholesale prices. The model in the third essay is complementary to the crossholdings research and incorporates key aspects of the interlinked operations of gas and electricity wholesale markets in the short-run. These sequential multiple-unit auctions present many non-Pareto ranked equilibria and we propose another Roth and Erev (1995) simulation as an alternative. The simulations unveil a new market power mechanism that explains why vertical market power can be observed in the energy industry.

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List of Abbreviations

ABS	Agent-Based Simulations
EFET	European Federation of Electricity Transmission
EU	European Union
LOOP	Law of One Price
NBP	National Balancing Point
R&E (1995)	Roth and Erev (1995) algorithm
SBU	Strategic Business Unit
TOP	Take-Or-Pay (contracts)
UK	United Kingdom
VAR	Vector Autorregressive Representation

List of Symbols

A and B	Two (hypothetical) markets
t	Time
$P_{A,t}$	Price in A at time t
$C_{U,t}$	Utilised capacity
C_{MAX}	Maximum capacity
$P_{s,t}$	Shadow price
$P_t = a - bQ_t$	(Inverse) linear demand function
$\bar{C}$	Capacity utilisation threshold
$P_{NBP,t}$	Price at National Balancing Point
$P_{ZEEB,t}$	Price at Zeebrugge hub
ρ_t	Difference between the NBP and Zeebrugge prices
APX_t	Dutch power price
$NETA_t$	England and Wales power price
$TEMP_t$	Temperature
$BRENT_t$	Oil price

$i = 1...n$	Producers (wholesalers)
$j = ...m$	End-user suppliers (wholesale buyers)
c	Marginal cost
Ψ	End user tariff (redemption value)
k_i and k_j	Capacities
$x_i(t)$	Quantity sold by producer i
$x_{\sim i}(t)$	Quantity sold by (crossheld) rival $\tilde{}i$
Φ	(Symmetric) seller crossholdings
$x_j(t)$	Quantity bought by supplier j
$s = 1...S$	Strategy grid
r_s^i	Propensity of s to play strategy i
$\Pi_i(t)$	Profit
$r_s^i(1)$	Initial propensities
λ	Chosen strategy
δ	Persistent local experimentation parameter
γ	Gradual forgetting parameter
μ	Extinction in finite time
$r_s^i(t)'$	Pre-extinction propensity of s to play strategy i
$privateprob_{i,s}(t)$	Probability of i playing strategy s at time t (private information case)
$publicprob_{i,s}(t)$	Probability of i playing strategy s at time t (public information case)

$g = 1...A$	Natural gas shippers
$e = 1...B$	Electricity generators
$r = 1...C$	Electricity retailers
K^g	Individual capacity of a gas shipper
K^e	Individual capacity of an electricity generator
K^r	Individual capacity of an electricity retailer
$\overline{P}^i(t)$	Maximum possible bid
$P^i(t)$	Uniform market price
$Q^i(t)$	Inelastic demand curve
$\bar{Q}^r$	Expected end-user demand
ε	Demand uncertainty
$P^g(t)$	Price of wholesale gas
$P^e(t)$	Price of wholesale electricity
$P^r(t)$	Retail price
$Q^g(t)$	Quantity of wholesale gas
$Q^e(t)$	Quantity of wholesale electricity
$Q^r(t)$	Quantity of retail electricity
$\pi^g_a(t)$	Profit of gas firm a
$\pi^e_b(t)$	Profit of electricity wholesaler b
$\pi^r_c(t)$	Profit of electricity retailer c
$\Omega^g_1(t)$	Incentive function gas
$\Omega^e_1(t)$	Incentive function wholesale electricity
α	Reward interdependence
$A^i(t)$	(Variable) strategy grid

Acknowledgments

Well, well, well... it really feels like yesterday when I moved into a dodgy flat close to LBS with a sinister Russian couple and started my work towards the completion of a Ph.D. Now, I find myself in Switzerland and realise that, whatever the quality of the outcome, I would not have managed to get here without a great deal of help.

The person that really made this thesis possible is Prof. Derek Bunn, and that is due to two reasons. The first, and pre-condition for all the rest, is that he decided that I should get accepted to the programme, which I still find amazing: he thought it interesting to work with me. And the second reason is that we indeed worked together and he became a terrific adviser. There is something about meetings with Derek: you are completely free to make your own decisions. However, every time you tell him about your "great" research achievements, you just have the strange feeling that he already knew what you were going to do, just three months before you did. Great. John Morecroft, Bruce Weber (in the transfer), Michael Crew and Ann Van Ackere (in the Ph.D. *viva voce*) were my examiners and I thank them for that (see, I just became an academic and already show signs of masochism....).

Before starting at LBS, I was not at all sure about whether it was the right place for me. I accepted the offer because I liked the idea of working with Derek but also because I felt that this programme was managed by very professional people. The leader of that group is of course Judith Fry, to whom, in my opinion, all of us doctoral students owe a big slice of its steady quality improvement. Out of those in the Ph.D. programme office, I would also like to single out Kirsten Gonzales (Portuguese? Spanish?) and Sarah Green, who were far more than programme managers to me.

Fellow students have supported and born with me more than they would want to believe.

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Chapter 1

Introduction

The European Union (EU) electricity and natural gas industries are undergoing fundamental changes leading to a more liberal regime and the alteration of their business logic. The political driver for this transformation is the EU's objective of bringing about a common market for goods and services across its members, articulated through regulation promoting competition (e.g. EU, 1996,1998 and 2003). In economic terms, the main goal of these Directives is a reduction in end-user prices, attained by the emergence of a "level playing field" and less market dominance (EU, 2003).

The process has already started to affect both the profits accruing to electricity and natural gas firms and the structural relationship between the two industries (e.g. Finon and Midttun, 2004; Stern, 1998). Companies have responded to the new structural challenges with risk mitigation strategies. Some companies have integrated vertically within the same product (electricity generation to electricity supply) or between products (e.g. gas supply to electricity generation). The liberalisation has also induced some generators to buy foreign retail assets, both to gain new customers and benefit from possible arbitrage opportunities. Others have turned their attention to the horizontal dimension, building a European shareholdings portfolio, in pursue of an EU-wide consolidation (Finon and Midttun, 2004). Industry observers suggest at least two ways in which electricity and natural gas markets interact: gas is a fuel for power generation and often bundled to electricity in the end-user market.

The advantages of gas-for-power are economic and environmental (Arentsen and Kunneke, 2003). Gas generation involves low capital and operating costs, short construction lead times and smaller scale facilities, which increases the diversity and flexibility of the firms' portfolio. On the environmental side, natural gas plants are relatively clean, efficient, and can be fitted with heat production technologies. As a consequence, gas is expected to be the reference fuel for power generation in the medium term (Stern, 1998). Many firms are also turning their downstream businesses into multi-energy utilities supplying electricity and natural gas. Their objectives are to increase the revenue per customer by expanding the array of products on offer and to respond to the threat of new entrants (Finon and Midttun, 2004). This trend is also expected to continue as the two industries become more integrated.

Further, the liberalisation is leading to the progressive substitution of simple pricing rules by sophisticated financial trading arrangements (Pilipovic, 1997). Prices in the new energy hubs are volatile and often characterised by regime switching and strategic learning, which makes them difficult to characterise with simple structural models. The limitations of conventional economic methods have prompted the application of new methodological tools to study the electricity and natural industries. Recent developments in time series analysis make it possible to understand, *ex-post*, the dynamic behaviour of energy prices. Further, simulations have emerged as a natural way to study market mechanisms *ex-ante* (Roth, 2002).

This thesis applies time series econometrics and agent-based simulations to study some features of the interlinked electricity and natural gas spot markets, taking as a focal point the European wholesale natural gas industry.

The theoretical literature on interconnectors has established their potential to mitigate local market power. However, the relationship between capacity utilisation and locational market splitting has not been studied empirically. The first essay covers part of that gap, applying Vector Autorregressive (VAR) modelling techniques to data from the Bacton (UK)-Zeebrugge (Belgium) natural gas pipeline. The focus is on two research questions:

- *What is the relationship between market splitting and the degree of interconnector utilisation?*

- *What is the mediating role of the interconnector utilisation on the dynamic relationship between the two local spot prices?*

The analysis identifies a threshold of capacity utilisation after which the UK and Continental markets split. The relationship between spot price differences and capacity use is increasing and convex. Moreover, there are traces of both convergence and leader-follower features relating the two prices, with the more developed British hub taking a predominant role.

The study also reveals that the UK market is more competitive than its European counterpart and raises the question of why. Market structure and design are generally perceived as key in limiting the firms' ability to influence wholesale energy prices (e.g. Wilson, 2002). Continental markets tend to be quite opaque and crossholdings widespread across country boundaries and industry intelligence indicates that these might lead to market power. In the UK, on the contrary, trading rules are transparent and crossholdings almost non-existent. The second essay therefore aims at contributing to the small financial interests and informational regimes debates by modelling three issues:

- *What is the shape of the crossholdings / market price relationship?*

- *Which informational regime, public or private, is more conducive to the exertion of market power in settings characterised by crossholdings?*

- *How does industry concentration mediate on the impact of information and crossholdings on prices?*

These questions are addressed through a set of simulations in which computational agents try to optimise their profit using parameters adapted from the Roth and Erev (1995) reinforcement algorithm. The auction setting is a double-sided stylisation of electricity and natural gas trading rules in Europe. The results indicate that more information facilitates bidding coordination, that the functional form of the crossholdings to prices relationship is not linear but concave and that more downstream competition reduces the influence of information on spot prices.

The focus of the third chapter is on the issue of vertical integration. The literature has established that firms can achieve market power through vertical "foreclosure" (i.e. the possibility of raising rivals' costs through price discrimination or trade internalisation). However, a question remains open as to whether higher market prices can be achieved in sequential, compulsory, uniform price auctions. These are common in the energy industry and would seem to impede internalisation and discrimination behaviours. The issues studied in this part are:

- *Does the foreclosure logic operate in sequential compulsory, uniform price auctions like those in the energy industry?*

- *Are there any other market power mechanisms in these settings?*

The simulation incorporates key aspects of the interlinked operations of gas and electricity wholesale markets in the short-run. Gas is a crucial input to produce electricity. Generators buy gas from shippers and sell electricity to retailers that face, in turn, an inelastic end-user demand. These sequential multiple-unit auctions present many non-Pareto ranked equilibria and Roth and Erev (1995) simulations are proposed again as a modelling alternative.

The computational experiment shows how the firms' configuration and incentive structures (e.g. stock options) improve vertical coordination. Moreover, it unveils a new market power mechanism that, while superficially compatible with the foreclosure argument, relies on a different logic. Therefore, it provides a possible explanation of why vertical market power can be observed in energy markets, even when trading is compulsory and based on uniform price auctions.

Overall, the thesis is positioned in the intersection of decision science, industrial economics and business strategy, with a quantitative methodological approach and focusing on the deregulated energy industry. Accordingly, it builds upon a large body of research, to which it contributes in two ways: first, through methodological advancements on the use of agent-based simulations for market design. Secondly, by solving practical questions that, while identified in the literature, might not be tractable through closed-form methodologies.

The structure of the thesis is as follows. The three subsequent chapters explore the above themes as self-contained research essays. A final chapter then summarises the findings, puts them in a wider context, discusses some limitations and suggests avenues for future research.

Chapter 2

Two Markets and a Weak Link

2.1 Introduction

As network-based infrastructure industries are liberalized around the world, interconnectors have become important competitive linkages between otherwise isolated markets, and thus have the potential to mitigate local market power. This chapter[1] studies interconnector congestion and its role in splitting local spot markets, using data from the Bacton (UK)-Zeebrugge (Belgium) natural gas pipeline.

The empirical literature provides evidence of market integration once gas and electricity hubs become inter-linked (e.g. De Vany and Walls, 1993; De Vany and Walls, 1999; Siliverstovs et al., forthcoming; Spulber, and Doane, 1994). However, strategically created congestion has been studied mainly in the electricity context and rationalized through theoretical models of physical capacity withholding in oligopoly (Bushnell, 1999; Joskow and Tirole, 2000). A firm's price setting ability depends on the degree of market competition at the margin and so, in these models, one usually finds a direct link between the degree of capacity utilization and its marginal price, which should result in the local markets splitting before the interconnection reaches technical congestion levels.

In contrast, models based on the Law of One Price (LOOP) often conclude that market splitting would not occur unless the interconnection is constrained (e.g. Hogan, 1992). Their

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[1] Versions of this chapter have been presented at the Applied Infrastructure Research 2004 (Berlin), IAEE-2005 (Bergen) and EARIE-2005 (Porto) conferences.

reasoning is as follows: the interconnectors' main cost component is typically fixed and sunk, while marginal transportation costs are close to zero. Hence, if those holding rights and those interested in excising them traded competitively, arbitrage would tend to equalize the local prices and interconnector charges would be low. Thus, under homogeneous marginal costs and without transportation costs or congestion, the commodity should be uniformly priced, making arbitrage impossible. Further, a somewhat surprising corollary follows: as long as interconnector capacity is large enough, no output might actually flow along the interconnector (Borenstein et al., 2000). The threat of competition and arbitrage will be all that is needed for effective integration of the two markets even in an oligopoly, and the infrastructure may appear to be under-utilised.

Some of these results have been phrased as testable hypotheses. If the LOOP were to hold between the two markets, their price differences would generally be stationary and the interconnector would remain either idle or totally constrained (Bower, 2002).[2] "*One great attraction of this perspective is that there is no need to define transmission at all: users of the network never transmit power across the network, they merely sell at some nodes and buy at others. All transmission is implicit*" (Hogan, 1992). The mere threat of competitive entry becomes a restraining influence on the dominant sellers in each local market, causing them to become more competitive, regardless of whether the imports are realised (Borenstein et al. 2000). Moreover, arbitrage would homogenize the two prices' dynamic structure, for example with "convergence to the mean" (Cremer and Laffont, 2002) and leader-follower processes. If there were some form of market power inefficiencies (as in Joskow and Tirole, 2000), however, one could expect a significant relationship between the interconnector physical capacity utilization and local price differences and that its full capacity will be seldom utilised. Moreover, the two prices could remain largely independent and their dynamic econometric structures different.

To study empirically these issues, a natural setting in which a number of circumstances concur is desirable: First, it should consist of two oligopolistic markets with a single capacity-constrained transportation interconnection between them. Secondly, the interconnection physical rights' market should be unregulated and its main owners should be also active in the local markets, so as to have both the opportunity and incentive to withhold capacity. Third,

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[2] Unless the capacity of the interconnector was greater than the amount of transfer needed to equalise prices.

the economic fundamentals of the individual markets should be different, in order to help us determine whether the linkage results in a homogenization of price dynamics. Finally, the link should ideally suffer from unexpected flow disruptions separating the two, so as to provide an exogenous benchmark to assess the effects of market integration. The market would then potentially be subject to technical as well as economic splitting. One such natural setting is the liberalized European natural gas market and, specifically, the new situation that emerges around the building of the interconnector between the UK and the Continent.

There are two main wholesale trading gas hubs in Western Europe, Zeebrugge (Belgium) and the National Balancing Point (NBP) in the United Kingdom. The only linkage between them is the recently built Zeebrugge-Bacton natural gas pipeline -the "interconnector"-, whose ownership is shared among some of the largest players in the industry.[3] This pipeline is weak in a double sense: its capacity is limited[4] and subject to unexpected technical disruptions.[5] Hence, market splitting could emerge due to exogenous technical factors ("technical splitting"), as well as via the exertion of market power in the interconnector ("economic splitting"). Although some capacity is sold on long-term contracts, there is also a liquid bilateral day-ahead market that sets marginal prices, which are known to the main players only.

While continental markets are extremely concentrated and still undergoing a slow liberalization, the UK has been competitive for some years. Before the interconnector opened, it is well documented that NBP prices depended mainly on the value of natural gas for electricity generation (e.g. Stern, 1998). As a result, its dynamics were quite linked to those of the England and Wales spot electricity market. Features of electricity spot price processes include mean reversion, high volatility and specific seasonal patterns.

In contrast, prices in the Zeebrugge area have traditionally been linked to long-term take-or-pay (TOP) agreements even before the liberalization started. TOP contracts are established between large national incumbents and indexed using different formulae that usually reflect the

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[3] Firms holding interests in the interconnector and their respective percentages follow: Amerada Hess (5%); BP (10%); BG Energy (25%); Conoco-Phillips (10%); Distrigas (10%); Eni (5%); International Power (5%); Gazprom (10%); Ruhrgas (10%); TotalFinaElf (10%). Source: www.interconnector.com.

[4] It can only carry up to ca. 25% of British or 6% of continental consumption (20 billion cubic metres per annum, bcm/year) towards the Continent. Alternatively, it can carry up to 8.5 bcm/year in the opposite direction.

[5] Although maintenance operations may be scheduled ahead of time, the interconnector has also suffered a number of unexpected flow interruptions due to system breakdown.

net-back principle, pricing gas at a discount with respect to its competitors (mainly oil products), which are generally less volatile, mean reverting and seasonal than electricity (Pilipovic, 1997).

Hence, at the outset, both the market structure and the economic fundamentals of gas prices in the European continent were very different from those in the UK and one could expect that they still differentiate their dynamic specification. Whether that is the case or not after the opening of the interconnector is an not clear.

The Bacton-Zeebrugge gas pipeline is hence a powerful natural experiment in which to test the linkage between interconnectors and reciprocal market dynamics. The first novel issue that this chapter addresses how well the arbitrage and market splitting models describe the pipeline capacity pricing. The second main question concerns the influence of the degree of interconnector utilisation on the local markets, both in terms of price levels and their dynamic structure. More synthetically, the research questions in this essay are:

What is the relationship between market splitting and the degree of utilisation of their interconnection?

What is the mediating role of the interconnector utilization on the dynamic relationship between the local prices?

The essay is organised as follows: Part 2.2 is an outline of how the capacity withholding and arbitrage theories relate to the research questions. In Part 2.3 we discuss the data set. Part 2.4 includes the empirical results. Finally, a discussion and some concluding remarks are presented in Part 2.5.

2.2 Arbitrage and Interconnection Market Power

Consider two natural gas markets, A and B, linked by a single weak interconnection, whose access rights are controlled by a small number of firms and discretionally sold on a daily basis (time indexed as t) to those wishing to transport the commodity. $C_{U,t}$ is the utilised capacity and takes a value $0 \leq C_{U,t} \leq C_{MAX}$.

Now, suppose that transportation costs are very low. If utilized capacity were to be below maximum capacity ($C_{U,t} < C_{MAX}$), firms hold some capability to react instantly to price differences by engaging in three simultaneous transactions: purchase the commodity in the low price market, buy physical transportation rights and sell in the high price market. In this context, one can think of at least three theories of the relationship between interconnection utilisation and local market prices.

Physical Arbitrage: With oligopoly pricing and $P_{A,t} > P_{B,t}$, then a producer selling at B would prefer to withdraw from B, and ship to A, until the point in which $P^*_{A,t} = P^*_{B,t}$ for a $C_{U,t} > 0$. Earning $P^*_{B,t}$ would be a better outcome than originally selling in B. With this physical transmission model one would therefore expect the shadow price of the interconnection, $P_{s,t} = |P_{A,t} - P_{B,t}| = 0$, as well as, $C_{U,t} > 0$.

Financial Arbitrage: If the oligopolists were able to anticipate the physical arbitrage reasoning, the two local prices would be equal and, following Hogan (1992), no firms would be interested in shipping gas. In other words, rational expectations would remove arbitrage opportunities. The financial arbitrage model therefore predicts: $P_{s,t} = 0$ and $C_{U,t} = 0$.

Combining the physical and financial arbitrage perspectives, small arbitrage operations could be enough to equilibrate the two markets. In that case, one might even observe in practice that large price differences trigger small arbitrage volumes in the interconnector so that the relationship between $C_{U,t}$ and $P_{s,t}$ is decreasing.

Further, if the interconnection were congested ($C_{U,t} = C_{MAX}$), one would expect local prices to diverge. In practice, there are also some reasons for congestion to arise for some $C_{U,t} < C_{MAX}$, with a subsequent increase in $P_{s,t}$. Those include the use of contingency constraints by the interconnector operator, but also other causes related to the economics of the system (e.g. incomplete information and uncertainty might result in situations in which market players anticipate that the interconnection will be constrained but it is not).

In addition, the flow should always circulate from the low to the high price market. However, in the natural gas case, flow reversals are not instantaneous but require 24 hours once the sign of $P_{s,t}$ changes. It is therefore likely that, in the one or two days preceding that change, the flow will be directed "against market forces", from the expensive to the cheap market, which will result in low $C_{U,t}$.

Capacity Withholding: The arbitrage logic in Borenstein et al. (2000) assumes that the linkage is "operated by an entity that attempts to maximise social welfare by providing price signals to induce efficient use" of the infrastructure. However, market power on the available capacity might allow some type of capacity withholding, for example à la Cournot.[6] If the oligopoly were able to exert that sort of market power, there would be a positive link between $C_{U,t}$ and the extent of the two markets' splitting (i.e. $P_{s,t}$) that, in the simple Cournot case with linear demand, could be postulated as convex quadratic:[7]

$$P_{S,t} = -\frac{b}{q_t}\left(\frac{C_{U,t}}{C_{MAX}}\right)^2 \tag{2.1}$$

Where b is the slope of a linear (inverse) demand function, $P_t = a - bQ_t$, and q_t is the quantity sold by any (homogeneous) individual firm in time period t.

In this formulation, $P_{S,t}$ depends on the market share of each individual firm at the margin. If this were the case, agents holding both physical interconnection rights and positions in the local markets could benefit in two ways (Bushnell, 1999; Joskow and Tirole, 2000): a/ Increasing the selling value of the commodity in the local markets; but also by b/ Increasing the value of the transportation rights.

In summary, one important difference between the "arbitrage" and "capacity withholding" models is that the latter predicts increasing market splitting as $C_{U,t}$ grows whereas the former predicts no relationship. Moreover, the arbitrage view could result in a negative relationship between $C_{U,t}$ and $P_{s,t}$.

Taking together the arbitrage and withholding models, it would be plausible to conjecture a new functional relationship in which market power would become exercisable above a level of capacity, $\bar{C}$, at which point there is sufficient concentration in the residual market for oligopoly capacity reductions to occur. One could then expect a non-significant relationship between $C_{U,t}$ and $P_{s,t}$ up to $\bar{C}$ and an increasing (convex quadratic) thereafter, when market concentration applies. With collusion, $P_{s,t}$ would increase more steeply against $C_{U,t}$ and $C_{U,t}$ would be lower, unless C_{MAX} was reached first.

Does the arbitrage model hold in practice? Does the withholding logic apply? What is the performance of the hybrid model via a threshold specification? How much arbitrage is required

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[6] That is, under tighter capacity, it is possible that fewer firms will hold unsold physical rights (i.e. are residual suppliers), which increases their price setting ability.

[7] The quadratic functional form would follow from the standard Cournot oligopoly model with equal interconnector ownership shares (e.g. Tirole, 1988)

to equilibrate the two markets? These questions have not been answered collectively in the empirical literature. Hence, in this essay, the withholding and arbitrage models are contrasted for the case of the Zeebrugge - NBP natural gas pipeline.

2.3 Data

Wholesale natural gas prices are extracted from daily Heren indices at the UK's National Balancing Point (NBP) and Continental Europe (Zeebrugge), denominated in British pence per therm. The indices are assembled with data by traders in both markets, collected and made available daily by Heren, a newsletter provider (http://www.heren.com). They reflect the price range of the commodity on the day, weighted for volume of the transactions and are considered the standard indices in both hubs, with a reported cut-off time of 5:30pm GMT. The correlation coefficient between these two prices is 0.918 in the data set (Figures 2-1 and 2-2). In the beginning of the operations at Zeebrugge, some days presented no trading and hence the lack of 87 observations in the first part of the data set, which consists of 1512 observations in total.

Daily flows were downloaded from http://www.interconnector.com, the pipeline operator's web-site. Daily electricity prices in the UK were taken from UKPX, the main power exchange for the NETA England and Wales bilateral market (http://www.elexon.co.uk). The continental reference was obtained from the Dutch APX spot market web-site (http://www.apx.nl). The Zeebrugge and APX data-sets encompass observations from 12-Mar-1999 to 20-Dec-2002. Brent prices were downloaded from the Datastream database. Finally, weather data in the UK is based on average daily temperatures in Southeast England and measured in degrees Celsius by the Met Office (http://www.metoffice.com).[8]

The interconnector was open throughout the considered period except for a some instances (less than 20% of the observations) in there were scheduled repair works or unexpected breakdowns. These closures are documented in the pipeline operator's web-site and have been used to partition the data.

The data set has been modified in three ways: First, observations for the day before any

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[8] The exact location of the temperature observations is London Heathrow airport.

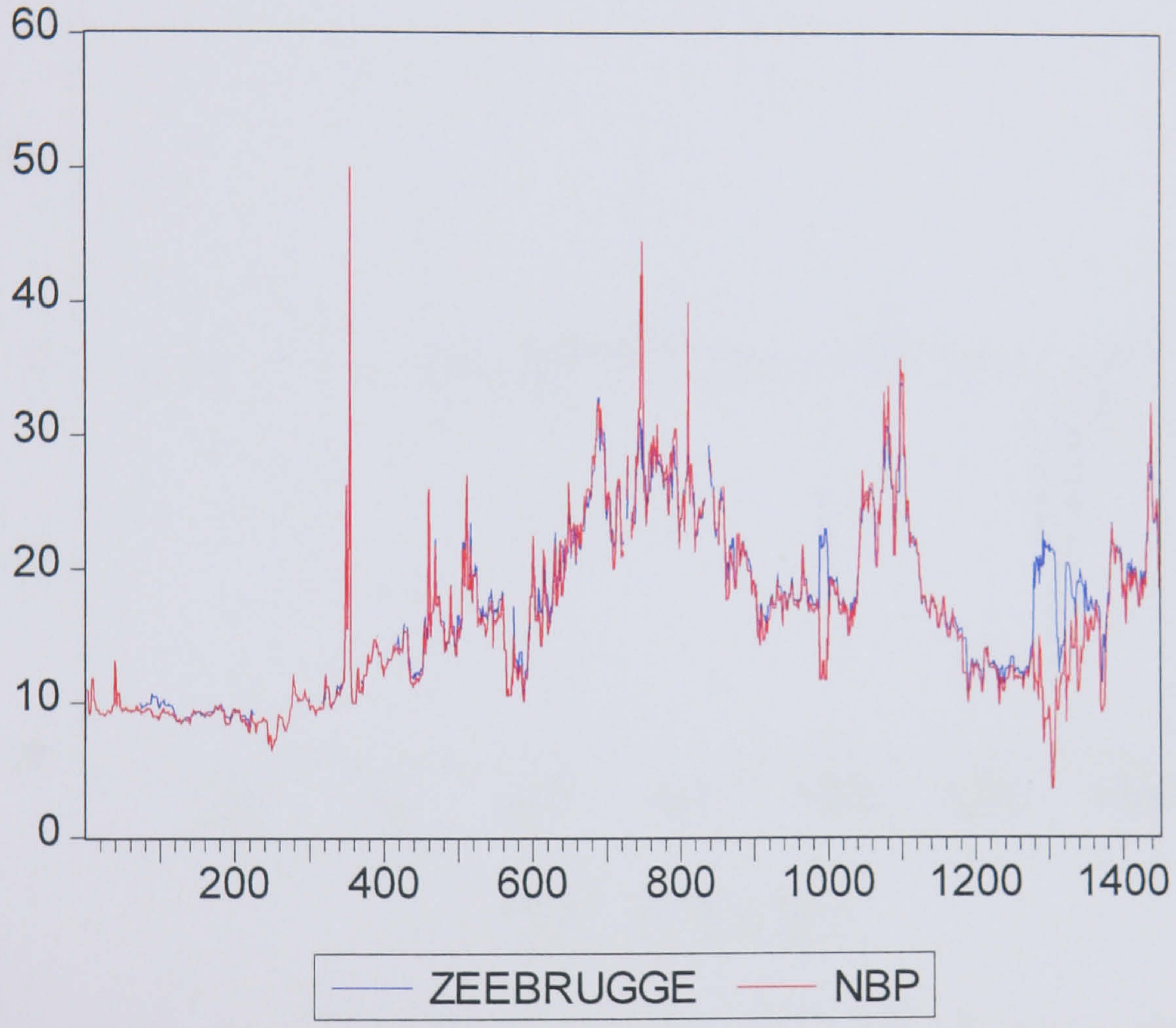

Figure 2-1: NBP and Zeebrugge price series. Vertical axis: pence per therm. Horizontal axis: days in the sample period.

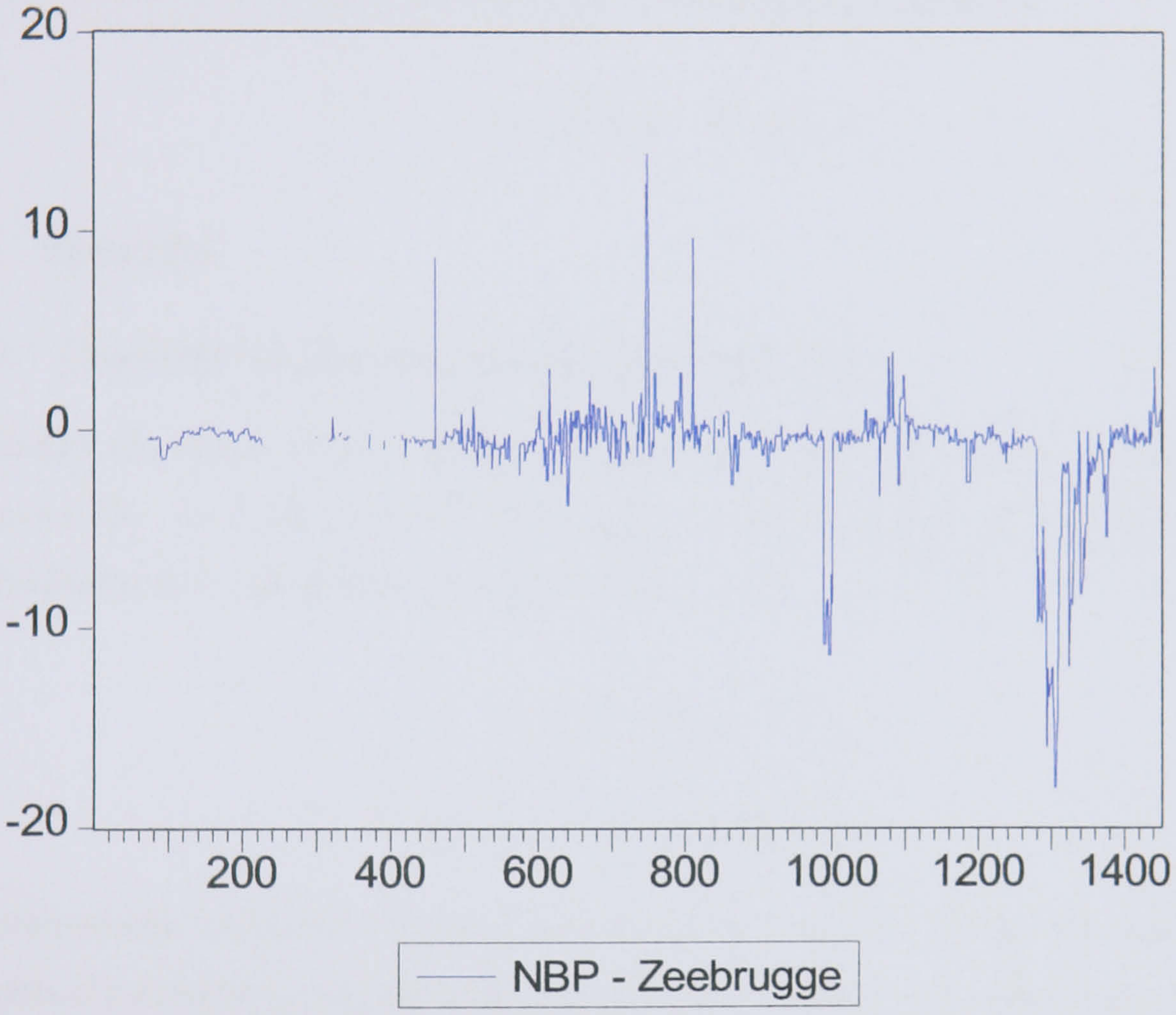

Figure 2-2: (NBP - Zeebrugge) difference. Vertical axis: pence per therm. Horizontal axis: days in the sample period.

changes in flow direction were excluded since they would misrepresent the economics of the system. Second, capacity utilization ratios are measured against the historically maximum rather than nominal capacity values. That was done in order to reduce the effect of technical contingency measures taken by the pipeline operator. Finally, interconnector access prices are confidential. Therefore, following the method used by the UK energy regulator (Ofgem, 2004), these are substituted by their absolute value market spread equivalent:

$$\rho_t = |P_{NBP} - P_{ZEEB}|_t \,. \tag{2.2}$$

2.4 Results

2.4.1 Capacity Utilisation and Market Splitting

Estimating the shape of the relationship between ρ_t and $C_{U,t}$ involves determining its sign and rationale. As a first step, we estimate linear and, following the basic Cournot capacity withholding model, quadratic expressions for $C_{U,t} \neq 0$:

$$\rho_t = \alpha + \beta_1 C_{U,t} + u_t \tag{2.3}$$

$$\rho_t = \alpha + \beta_1 C_{U,t} + \beta_2 C_{U,t}^2 + u_t. \tag{2.4}$$

Alternatively, inspired by popular regime switching models of price forecasts in electricity and natural gas markets, successive tests of structural stability were undertaken. These included dummy parameters (D) that influence the intercepts and slopes of the relationship pre- and post-threshold:

$$\rho_t = \alpha_1 + D\alpha_2 + \beta_1 C_{U,t} + D\beta_2 C_{U,t} + u_t, \tag{2.5}$$

where α_1 and β_1 are the intercept and slope coefficients before each threshold, $\bar{C}$, assumption, while α_2 and β_2 are the differentials between the pre- and post-$\bar{C}$ situations. A structural change would be suggested if significant post-threshold values were found.

The linear and quadratic models (Table 2-1) elicit a positive relationship between ρ_t and $C_{U,t}$ (sig. $< .001$), indicating that, as the splitting between NBP and Zeebrugge grows, more interconnector capacity is used. The estimations of possible capacity thresholds, indicated that

Linear Model			Quadratic Model	
Variable	Coeff.	Sig.	Coeff.	Sig.
α	.1004	.3267	.8711	.0121
C_U	1.0711	$< .001$	-1.7928	.1494
C_U^2	–	–	2.4441	.0202
$Adj.R^2$	.0477		.0534	
$F - value$	38.2946		21.9708	

Table 2.1: Interconnector Utilisation and Local Price Differences

Variable	Coeff.	Sig.
α	4.7620	$< .001$
D	10.6751	$< .001$
C_U	-21.9240	$< .001$
DC_U	-18.4862	$< .001$
DC_U^2	27.8913	$< .001$
$Adj.\ R^2$	.1640	
$F - value$	44.1552	

Table 2.2: Linear Interconnector Models

$0.50 \leq \bar{C} \leq 0.60$ with maximum explanatory power for $\bar{C} = 0.57$, $F = 698.474$ (Table not included).

In addition, we consider a model including linear pre-threshold and quadratic post-threshold specifications (Table 2-2). All parameters are significant and the fit improves visibly ($R^2 =$ 16.4% vs. 4.77% and 5.34%). This specification also reveals a downward slopping relationship between the two variables, driven by a few outlier points with low utilisation and high market splitting. These points result from small arbitrage operations due to short term market separation instances between Zeebrugge and NBP. These do not seem to conform with the conventional arbitrage and withholding theories but relate better with the hybrid model.

Arbitrage is the main driving force between ρ_t and $C_{U,t}$. However, there are also traces of inefficiencies, including market power. In high interconnector utilization days, those holding rights manage to split the two markets to some extent, so the relationship between the two variables is increasing and convex. The threshold after which this occurs was estimated as $\bar{C} = 0.57 \times C_{MAX}$.

Variable	$R1 : C_{U,t} = 0$ Coeff.	 Prob.	$R2 : 0 < C_{U,t} \le \bar{C}$ Coeff.	 Prob.	$R3 : C_{U,t} \ge \bar{C}$ Coeff.	 Prob.
α	16.1272	.0000	2.6428	.0000	3.5469	.0000
NBP_t	.3571	.0000	.8759	.0000	.8317	.0000
Adj. R^2		.5985		.9040		.8449
$Prob.F - stat.$		.0000		.0000		.0000

Table 2.3: Static Interconnector Models

2.4.2 The Relative Behaviour of NBP and Zeebrugge Prices

A related issue is whether the regimes governing the ρ_t vs. $C_{U,t}$ relationship mediate in the econometric linkage between P_{NBP} and P_{ZEEB}. To investigate that effect, the data is separated into three subsets, depending on whether there is technical market splitting (i.e. the interconnector was closed - Regime 1 (R1): $C_U = 0$, 87 observations), or open ($C_U > 0$) and, for the latter, whether capacity utilisation was below (Regime 2 (R2): $0 \le C_U \le 0.57$, 1456 observations) or above (Regime 3 (R3): $0.57 \le C_U \le 1$, 26 observations) the estimated threshold.

We proceed sequentially for the three subsets, starting with tests of simple static integration relationships, followed by slightly more elaborated dynamic specifications, towards a full vector auto-regressive representation (VAR) model, which reveals general causality insights.

First, to measure the degree of co-movement, the following expression is tested:

$$P_{ZEEB,t} = \alpha + \beta P_{NBPt} + u_t. \tag{2.6}$$

In these models, α provides an estimate of the systematic differences between prices in the UK and Belgium caused by the different interconnector status. In addition, β measures the relative volatility of the two series.

The static models linking P_{NBP} and P_{ZEEB} present significantly positive intercepts, suggesting that continental prices are consistently above those in Britain and $0 < \beta < 1$ (Table 2-3).

There are substantial differences depending on whether the interconnector is open or not, i.e. between $R1$, on the one hand, and $R2$ and $R3$ on the other. First, α is larger under technical splitting, $R1$. Second, β is considerably smaller under $R1$ than under integration $R2$

	$R1 : C_{U,t} = 0$		$R2 : 0 < C_{U,t} \leq \bar{C}$		$R3 : C_{U,t} \geq \bar{C}$	
Variable	Coeff.	Prob.	Coeff.	Prob.	Coeff.	Prob.
α	$-.6036$	.337	$-.0055$	.8783	.1723	$< .001$
ρ_{t-1}	0.8566	$< .001$	$-.9330$	$< .001$	$-.1710$	$< .001$

Table 2.4: Dynamic Interconnector Models

or economic splitting $R3$ (0.3571 vs. 0.8759 and 0.8317). That suggests not only that prices are as expected positively correlated but also that the natural volatility of P_{ZEEB} is smaller than that of P_{NBP} and that an open connection results in larger volatility in Zeebrugge. This may be due to the transmission of P_{NBP}'s electricity-based fundamentals through the interconnector.

Also as one would expect, the model's fit is at its lowest point under $R1$. However, the parameters are highly significant and the $adjusted - R^2$ and $F - values$ are high $(adj.R^2 = 0.5985; F = 85.96)$. Moreover, it is interesting to note that both $adj.R^2$ and F are higher under low capacity utilisation values, $R2$, than when the interconnector is more congested, under $R3$.

Nevertheless, low Durbin-Watson (DW) statistics suggest mis-specification in the models as a result of auto-correlations. Hence, as a second step, the reciprocal dynamic adjustment between the two prices is tested through

$$\rho_t = \alpha + \chi \rho_{t-1} + u_t. \tag{2.7}$$

The integration hypothesis is checked through a unit root test of χ: if the LOOP holds, ρ_t is expected to be stationary. The estimated results shown in Table 2-4 support market integration in all cases. Finally, the one-lag term is very significant but further lags were not, which is consistent with inter-temporal efficiency arising from continuous trading.

Further, it is interesting to assess how the dynamic price structures change as a function of interconnector utilisation. A set of more complete dynamic models includes some determinants of the natural gas demand in the two markets:

$$\rho_t = \alpha + \chi \rho_{t-1} + \phi_1 APX_t + \phi_2 NETA_t + \phi_3 TEMP_t + \phi_4 BRENT_t + u_t. \tag{2.8}$$

The new variables are lagged ρ values, electricity prices (APX in the Netherlands and

	$R1: C_{U,t} = 0$		$R2: 0 < C_{U,t} \leq \bar{C}$		$R3: C_{U,t} \geq \bar{C}$	
Variables	Coeff.	Sig.	Coeff.	Sig.	Coeff.	Sig.
α	.7427	.8774	$-.1231$	.7496	1.0841	.1645
ρ_{t-1}	.9044	.0000	.9528	.0000	.8535	.0000
apx	$-.0018$	.8269	.0007	.5909	$-.0011$	.4862
$neta$	.0525	.0642	$-.0075$	.5983	$-.0096$	.5465
$temperature$	$-.0508$	.6975	$-.0075$	.4699	$-.0023$	.2301
$brent$	$-.0783$	.7157	.0040	.8065	$-.0358$	.2367
DW		2.4655		1.7753		1.4091
$Adj.\ R^2$		.7826		.9237		.7293
$Prob.F - stat.$		.0000		.0000		.0000

Table 2.5: Price Determinants

	$R1: C_{U,t} = 0$		$R2: 0 < C_{U,t} \leq \bar{C}$		$R3: C_{U,t} \geq \bar{C}$	
Variables	Coeff.	Sig.	Coeff.	Sig.	Coeff.	Sig.
α	-6.6954	.0000	-1.0250	.0000	-1.0522	.0000
$apx - neta$	$-.0038$	.7459	.0071	.0062	.0044	.0570
DW		.2091		.1020		.1843
$Adj.\ R^2$		.0000		.0192		.0110
$Prob.F - stat.$		.7459		.0062		.0570

Table 2.6: Electricity Links

NETA in England and Wales),[9] temperatures and Brent oil prices, all relating to economic fundamentals. The lagged price difference, ρ_{t-1}, seems to capture the dynamic structure of ρ_t so that no other variable is significant to explain ρ_t (Table 2-5). This underlines again the importance of arbitrage between the two hubs and suggests that it is executed on their interface through the interconnector, rather than across the local natural gas, electricity and oil markets.

A regression of the differences against one another elucidates whether there is a link in the arbitrage opportunities between electricity and natural gas across the two regions:

$$\rho_t = \alpha + |NETA - APX|_t + u_t. \tag{2.9}$$

Results are presented in Table 2-6. One can notice that electricity price differences between the Continent and the UK are not econometrically significant under $R1$ (*sig.* 0.7459), very

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[9] Natural gas, electricity and, perhaps, oil prices might be endogeneously co-determined. In this model, however, we are not interested in the price relationships per se but rather in how they change as a function of capacity utilisation. Hence, pricing mechanisms presented here could be slightly innacurate.

significant under $R2$ (*sig.* 0.0062) and only approximately so under $R3$ (*sig.* 0.057). When the interconnector is open, there is an arbitrage link between the two electricity prices, which becomes weaker with more capacity utilisation.

In summary, the separate consideration of three capacity utilisation sub data-sets is both a simple and useful way to understand some of the dynamics between $P_{NBP,t}$ and $P_{ZEEB,t}$. When the interconnector is open, $P_{NBP,t}$ is higher and $P_{ZEEB,t}$ more volatile. Relative congestion, "economic splitting" as defined by $R3$, makes arbitrage more difficult but, in general, the two markets are econometrically integrated and long-lasting inefficiencies small. Finally, we have been able to identify an electricity link in the Zeebrugge series that could indicate a migration in the econometric structure $P_{NBP,t}$ of towards $P_{ZEEB,t}$.

2.4.3 Transmission of Dynamic Structures

We estimate a Vector Auto-regressive Representation (VAR) model including $P_{NBP,t}$, $P_{ZEEB,t}$, $ZEEB_t$ and $BRENT_t$. Migration might be suggested by evidence of a causal relationship between the UK electricity and Zeebrugge prices and / or the existence of a Brent oil linkage in the UK natural gas market:

$$\begin{bmatrix} P_{NBP,t} \\ P_{ZEEB,t} \\ NETA_t \\ BRENT_t \end{bmatrix} = \begin{bmatrix} \alpha_1 \\ \alpha_2 \\ \alpha_3 \\ \alpha_4 \end{bmatrix} + \begin{bmatrix} \gamma_{11} & \cdots & \cdots & \gamma_{14} \\ \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \\ \gamma_{41} & \cdots & \cdots & \gamma_{44} \end{bmatrix} \begin{bmatrix} P_{NBP,t-1} \\ P_{ZEEB,t-1} \\ NETA_{t-1} \\ BRENT_{t-1} \end{bmatrix} + \begin{bmatrix} u_{1,t} \\ u_{2,t} \\ u_{3,t} \\ u_{4,t} \end{bmatrix} \qquad (2.10)$$

The results in Table 2-7 reflect the existence of different economic linkages between $P_{NBP,t}$ and $P_{ZEEB,t}$ depending on the interconnector utilization. $P_{NBP,t}$ is related to $NETA_t$ under $R1$ and $R3$ ($R1$: $t - value$ = 1.49664; $R3$: $t - value$ = 1.51812) while the oil link to the Continent emerges only under the $R2$ ($t - value$ 1.7729). This vertical relationship between electricity and natural gas prices in the UK was confirmed by its mirror image relationship between $P_{NBP,t-1}$ and $NETA_t$.

Concerning $P_{ZEEB,t}$, the pricing structure includes some traces of $P_{NBP,t}$ on top of oil prices under $R2$ and also of $NETA_t$ under $R3$ ($t - value$ = 1.8539). Moreover, the oil link emerges

	$R_1 : C_U = 0$		$R_2 : 0 < C_U \leq \bar{C}$		$R_3 : C_U \geq \bar{C}$	
	NBP_t	$ZEEB_t$	NBP_t	$ZEEB_t$	NBP_t	$ZEEB_t$
NBP_{t-1}	.9861	-.0505	.9663	.0225	1.0100	.1615
t-values	9.2694	.6585	37.9296	1.0487	16.3182	2.9215
$ZEEB_{t-1}$	.1588	.9268	.0035	.9478	-.0256	.8334
t-values	1.0737	8.6918	.1092	35.0440	.4004	14.5717
$NETA_{t-1}$	.0349	-.0102	.0007	-.0007	-.0046	-.0050
t-values	1.4966	.6045	.4540	.4613	1.5181	1.8539
$BRENT_{t-1}$	-.0992	0.0269	-.0425	-.0414	-.0343	.0049
t-values	1.9731	.2902	1.7729	0.2938	.7890	2.9064
ctant	-1.3012	1.6018	1.4967	1.5905	1.4373	0.4149
t-values	.2395	.4089	2.0806	2.6279	1.1571	.3739
Adj. R^2	.8589	.7388	.9425	.9329	.9261	.9303
Prob.F	46.6440	22.2111	1186.539	1005.0560	639.8936	681.8042

Table 2.7: VAR (1) Interconnector Models

in the absence of integration to the UK ($R1 : t - value = 1.9739$; $R3 : t - value = 2.9064$) and dissolves under $R2$ ($t - value = -0.2938$).

In spite of the low significance of some of the parameters, the VAR (1) model supports the hypothesis of different regimes depending on whether arbitrage is possible or not along the interconnector. When the interconnector is open, $P_{NBP,t}$ and $P_{ZEEB,t}$ receive the influence of each other and their economic determinants, identified by the existence of oil linkages in the UK and NETA in Zeebrugge. In cases of market splitting, though, each series reverts to its traditional dynamics. Finally, there is a relevant econometric relationship between oil prices and NETA via $R2$.

The VAR model provides general evidence of the migration in dynamic econometric structures between $P_{NBP,t}$ and $P_{ZEEB,t}$ depending on the degree of interconnector utilisation as defined in the three separated data sets. We found an oil link to $P_{NBP,t}$ under $R2$ and $NETA_t$ and $P_{NBP,t}$ links to $P_{ZEEB,t}$ under $R2$ and $R3$, respectively. Moreover, we identified some evidence of structural integration between the two gas prices under $R2$.

2.5 Discussion

Overall, the empirical evidence is consistent with previous research on energy market integration (De Vany and Walls, 1993; De Vany and Walls, 1999; Siliverstovs et al., forthcoming; Spulber, and Doane, 1994). This study builds upon that literature and extends it by focusing on the relationship between interconnector utilisation and local market integration. The main research finding is that *neither the arbitrage nor the capacity withholding model explain adequately that relationship, but their combination via a capacity utilisation threshold is more appropriate.*

The economic value of the Zeebrugge-Bacton natural gas interconnector should be determined by the price divergence between the two hubs, ρ_t. Without capacity constraints and under an efficient markets hypothesis, no arbitrage would occur, the interconnector would remain idle and both $P_{ZEEB,t}$ and $P_{NBP,t}$ would move within the boundaries of marginal transportation costs (i.e. close to zero). If that were not the case, one would expect the pipeline to operate regularly and that those holding both transportation and local market positions obtained arbitrage rents.

We have found a convex relationship between ρ_t and C_U, and that market splitting emerges at a threshold, $\bar{C}$, of around 55-60%. Hence, the separate consideration of interconnector closures ($R1$, "technical splitting"), low ($R2$, "integration") and high interconnector utilisation ($R3$, "economic splitting") cases has proven to be a step in the direction of establishing the mediating role of congestion in the operation of the LOOP. Moreover, the dynamic results provided subtle insights about the actual price interrelationships.

Firstly, as predicted by Borenstein et al. (2000) arbitrage can be effective in forcing convergence but, interestingly, prices have been shown to diverge under "technical splitting". The static models indicate that interruptions in the pipeline service lead to systematic increases in the differential between the two local prices. When the interconnector closed, P_{ZEEBt} grew and $P_{NBP,tt}$ decreased, as foreseen by market players:

> "The scheduled shut down of the UK-Belgium gas Interconnector has had the predicted effect on the NBP prompt and prices have dropped on Monday, traders said" (Platts, 8-Sept-2003).

The LOOP operates as a process of convergence to the mean in levels so the interconnector has so far resulted in a price subsidy from British to continental European wholesale buyers. Factors that favour the emergence of more competition (and lower prices) in the UK include a larger number of buyers and sellers, larger volumes of free natural gas at the electricity generation margin, more market transparency and the role of Ofgem as successful industry watchdog. Thus, the British government idea of the interconnector providing the means by which they could export both their gas and their liberalisation philosophy to the Continent (Stern, 1998) has been replaced in recent years by purchasing cartels (Financial Times, 2000), and official allegations of anti-competitive firm behaviour (Financial Times, 2001).

Second, arbitrage influences not only the absolute $P_{NBP,t}$ and $P_{ZEEB,t}$ levels but also their structural formation. This result is consistent with those obtained analytically by Hogan (1992) and, empirically, by De Vany and Walls (1999; 1993) for the US electricity and natural gas markets. Traditionally, prices in the UK depended on the dynamics of the wholesale electricity market while in the Continent they were pegged to those of oil. Now, commentators refer to the interconnector becoming a channel of an "oil linkage" to British natural gas prices. Its logic is conventional wisdom among industry experts:

> "A higher oil price acts as an incentive to develop associated fields, which automatically brings more gas as well as more oil onto the market. In the interests of fostering the healthy growth, which continues to characterize the gas market, the gas industry will always have to remain alert to the price differential between gas and alternative oil products. Oil indexation is no more than an expression in mathematical terms of what is an economic fact of life" (Verberg, 2000)[10]

The argument works in the long run and also as a justification for the existence of indexed contractual arrangements in the Continent. It might explain why Brent price should influence Zeebrugge but not why it should influence day-ahead UK prices, unless the interconnector funnels the linkage. We found evidence of a migration of price structures that largely homogenizes their dynamics and that depends upon the existence of arbitrage opportunities. Consistent with economic theory, the effect emerges only when physical and economic market integration occur and there is sufficient idle capacity (i.e. below $\bar{C}$). That is often the case, and so $P_{NBP,t}$ and $P_{ZEEB,t}$ have become very interrelated due to the interconnector opening. The results indicate, though, that when either technical ($R1$) or economic splitting ($R3$) takes place, the

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[10] The reference to market players that are able and, indeed, should manage the "healthy growth" in the gas industry evidences of the degree of market power still available to incumbents.

two markets separate. A relatively low capacity utilisation threshold results on $P_{NBP,t}$ and $P_{ZEEB,t}$ not being arbitraged as well as one would have learned to expect.

A third general lesson concerns the causality relationship between the two prices. There is substantial evidence of $P_{NBP,t}$ driving $P_{ZEEB,t}$ but not the other way around. A number of factors might explain this dependence: 1. The UK trading mechanism is more mature and liquid; 2. Information is more reliable and easier to access in the UK; 3. The connection between electricity and natural gas markets is stronger there, and; 4. Blending capacity is limited in the Zeebrugge area. These explanations fit well the empirical data and suggest that, in general, when a well-developed market integrates with another that is embryonic, the former tends to take the driving causality role.

Moreover, although logically the two should be determined simultaneously, we found that ρ_t preceded $C_{U,t}$. A possible explanation for this effect might have to do with the timing of information availability. Real time interconnector data is more difficult to obtain than local market information and might become, as a consequence, subordinate in the price determination process. If that were the case, more interconnector information would not only facilitate market scrutiny but local competition, too.

Finally, if prices had been found to be econometrically equivalent during disruptions, it would have been plausible to argument against the economic rationale for having an interconnector in the first place. One would have expected the LOOP to hold at all times so the interconnector's economic value would not have depended upon its arbitrage role but simply as balancing instrument. Congestion (and the economic value of the interconnector) would have been very small under these circumstances (Bower, 2002). In general, though, it was found that the interconnector has sufficient capacity to integrate the two markets.

The empirical literature examining the relationship between transportation capacity utilisation and locational prices is sparse. The above results provide new insights on the management of interconnection infrastructures, which are pertinent to understand the dynamics of the European competitive energy industry and, in general, of inter-related markets.

This study has reinforced prior intuitive views about the existence of market power in the European natural gas industry and exposed the Continental energy market as less competitive than the UK. That raises the question of which are the structural differences between the two and whether these have an effect on price outcomes that, at least partially, justify the results.

For instance, one of the aspects in which the UK and continental Europe differ is in their approach to the provision of information to wholesale energy traders. Transparency appears to be a crucial aspect of market design in Britain, and it is both stressed in official reports and used as a practical principle in the design of energy trading arrangements. In contrast, other European markets have an uneven record and are, in general, quite opaque (EFET, 2003). Moreover, while crossholdings are generalised on the Continent, the large UK energy firms remain mostly independent from one another.

The literature indicates that crossholdings have a positive effect on the firms' market power, but the coordination effects of small crossholdings remains unexplored. An interesting question is therefore whether these yield some form of seller coordination, so that the relationship between crossholdings and prices is discontinuous. The next chapter presents a series of agent based computational experiments to study the price effects of various degrees of producer crossholding, combined with transparent and opaque market information rules under different market structures.

Chapter 3

Crossholdings, Concentration and Information in Capacity-Constrained Sealed Bid-Offer Auctions

3.1 Introduction

This essay[1] is motivated by the issue of how crossholdings may enhance trading coordination in the European energy markets. Despite being a common feature of many industries, comparatively little anti-trust attention is generally paid to the implications of small "silent" financial interests between rivals.[2] Yet crossholdings are known to increase prices (Reynolds and Snapp, 1986; Flath, 1991), because they link "the fortunes of actual or potential competitors, producing a positive correlation among their profits" (Farell and Shapiro, 1990). Although, in a continuous interaction setting, larger crossholdings may soften the punishment that follows defection on collusion (Malueg, 1992), partial ownership arrangements tend to be more profitable (a) the larger the percentage of partial ownership; (b) the more competitive the market, *ex-ante* and; (c) the smaller the number of competitors (Reitman, 1994; Macho Stadler and Verdier,

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[1] Earlier versions of this paper were presented at the IAEE-2003 (Prague), EARIE-2003 (Helsinki) and INFORMS-2003 (Atlanta) conferences.

[2] *Small cross-holdings when firms maintain autonomy over pricing and output decisions* (Brenashan and Salop, 1986).

1991). Also computational (e.g. Amundsen and Bergman, 2002) and empirical approaches (Alley, 1997; Parker and Röller, 1997; Dietzenbarcher, E. et al., 2000) provide solid support for a direct connection between cross-holdings and prices in several markets.

From the lack of regulatory attention that these operations receive,[3] one may infer that the regulators' implicit working assumption is that they will not significantly affect consumers because they are individually so small. That is, their effect on prices is assumed to be convex. However, the mere existence of any amount of crossholding could act as a communication device and aid trading coordination between firms. In that case, the relationship between crossholdings and market prices could be concave and even characterised with a threshold model. Hence, the main research issue that we propose in this chapter is "*What is the shape of the crossholdings / market price relationship?*"

Public market information could mediate in the importance of crossholdings as a coordination instrument. On the one hand, making public all bid (quantities and profit) information lowers uncertainty, facilitates price discovery and reduces the likelihood of bidders facing the "winner's curse" which, in turn, increases competition (e.g. Huck et al., 1999). However, Vincent (1992) also developed the opposite perspective on the effects of information and Offerman et al. (2002) are even more conclusive: "[when information on quantities and profits is available] *the main candidate to serve as a behavioural rest point is the collusive outcome*". Furthermore, Albæk et al. (1997) provide an industry example of collusion being the outcome of legal requirements to provide market information. Their conclusion is that more information makes it easier for firms to observe each other and, as a result, collusion may be readily signalled with a high frequency of trading interactions and even better enforced.

Hence, the collusive and winner's curse arguments have opposite effects on the firms' behaviour (Cramton and Schwartz, 2000) and could lead to contradictory public recommendations in industries where there are crossholdings. Following the trading coordination logic, one would expect the marginal value of crossholdings to be smaller when there are other synchronization alternatives available. One such alternative is public access to market information and hence it can be argued that crossholdings should be more valuable in private information environments.

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[3] In the case of the European Union (EU), for example, although the main applicable regulation refrains from setting clear-cut guidelines, it refers to the acquisition of a "controlling interest" but does not go further than that in defining its size (European Union, 1989).

If the winner's curse argument dominates, though, one would expect the opposite effect to emerge.

A recent paper arguing for market transparency describes the level of information release in the European electricity industry of "at best, patchy" and adds that while "some markets - notably the UK and Nordic markets - are incredibly transparent [...] many other markets remain frustratingly opaque" (EFET, 2003).[4] While crossholdings are widespread in the European electricity industry, their marginal value has not been researched under different informational regimes. The second research issue, therefore, that we seek to inform is "*Which informational regime, public or private, is more conducive to the exertion of market power in settings characterised by crossholdings?*"

Further, if information is connected to the exertion of market power, its effects could be linked to the number of market players (i.e. the more players there are, the more each of them might be able to learn from the others). Therefore, the third question that we inform is "*Is there a relationship between the number of industry players and the impact of crossholdings and information on prices?*"

These questions are analysed through a set of stylised agent-based simulations with computational learning. The essay is structured as follows. In part 3.2., the specific simulation setting is motivated and presented. Parts 3.3. and 3.4. describe the results and how they relate to the research questions. A short discussion follows in part 3.5.

3.2 The Computational Approach

3.2.1 Motivation

The capacity constrained uniform price auction is well established in the wholesale electricity modelling literature (e.g. Von der Fehr and Harbord, 1991) and responds to a one sided environment with generation bidding. In recent times, though, regulators have become more keen on incorporating the demand side in the electricity trading arrangements as it "*stimulates*

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[4] Mixed approaches are also possible: during the first few months of operations in the Spanish electricity pool, the market operator provided all bidding information within 24 hours, so agents could learn trading behaviour. Later, the delay was extended to one month and, currently, bids are only made public after three months, in order to limit collusion opportunities (Centeno et al., 2003).

competition between suppliers, leading to more competitive buying of electricity; and in turn places competitive pressure on generators" (Ofgem, 2002). This has lead to modelling electricity markets as capacity constrained double-sided uniform price auctions in computational (e.g. Kian et al., 2005; Nicolaisen et al., 2001) and experimental environments (e.g. Denton et al., 2001, Rassenti et al., 2002, Rassenti et al., 2003). Related literature includes a number of simulations that study double (oral) auctions, with varying degrees of behavioural sophistication (e.g., Gode and Sunder, 1993; Van Boening and Wilcox, 1996; Jamal and Sunder, 1996; Gjerstad and Dickhaut, 1998; Gode and Sunder, 2004).[5]

Experimental economics, using either human or artificial agents, is increasingly becoming a tool to inform market design issues (Roth, 2002). Within this tradition, agent-based simulations (ABS) (Tesfatsion and Judd, forthcoming) have also started to receive increasing attention in strategy and economics. Techniques that have received special attention in the management science literature include NK-landscapes (e.g. Rivkin, 2001; Rivkin and Siggelkow, 2003a, 2003b; Siggelkow and Levinthal, 2003) and genetic algorithms (e.g. Midgley et al., 1997). ABS emerge as a method bringing together evolutionary economics (Nelson and Winter, 1982), computation and strategy research. They try to bridge the behavioural and rational views of business strategy simulating the firm's behaviour via a path dependent search for optimality. ABS techniques treat agents as boundedly rational in terms of their ability to evaluate the consequences of their choices, with the aim of characterising the firm's adaptation in presence of rivals.

Nicolaisen et al. (2001) report the results of agent-based simulations to assess market power in an artificial bid-offer discriminatory electricity auction and benefit from a version of the Roth and Erev (1995) algorithm (hereafter, R&E (1995)), which we will also use in this essay. Although somewhat restrictive and backward looking, the R&E (1995) learning model is widely cited and is used here as a first approximation to behavioural modelling of electricity auctions. The algorithm is grounded on two standard laws of psychology: the "law of effect" which says that choices that have led to good outcomes in the past are more likely to be repeated in the future, and the "law of practice", according to which learning curves tend to be steep initially,

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[5] Most of these papers are motivated by financial, rather than energy, markets so the double auctions are modelled as continuous and bilateral.

and then flatter and "recency", in which choices that have led to good outcomes in the distant past are less likely to be repeated in the future than those that led to good outcomes recently. The parameters in the algorithm represent these laws mathematically.

The R&E (1995) learning model is hence grounded on well-established traits of human behaviour, but also practical to implement, robust to changes in the parameters and has been shown to be relatively accurate in matching simple laboratory experiments (e.g. Roth and Erev (1995), Rapoport et al. (1997), Erev and Rapoport (1998), Erev and Roth (1998) and Feltovich (1999)). In addition, the use of a well-known computational reinforcement algorithm presents at least two advantages. First, it facilitates the generation of large data sets incorporating many market structure, cross-ownership and informational variations. Second, it allows the analysis of how the reinforcement features are connected to the simulation outcomes. The issue of whether R&E represents actual bidding in energy auctions is an interesting complementary question deserving empirical research.

The simulation consists of supply demand bidding and common valuations bounded between common marginal cost and redemption values.[6] This bargaining game has an important analytical shortcoming: it presents a large number of non-Pareto ranked pure strategy equilibria. Think of the case in which all price bids and offers equal an arbitrary price within the simulation bounds, $\tilde{p}$, all demand is satisfied and capacity is fully utilised. Sellers would not gain by making offers different from $\tilde{p}$. Lower offers would have no effect on output or market price. Offers above $\tilde{p}$ would lead to the seller supplying nothing. Similarly, if a buyer raised her bid above $\tilde{p}$, she would have no effect on the volume purchased or the market price, while a reduction would mean that she obtained nothing. All pure strategies in which the firm is inframarginal are possible Nash equilibria, as long as the marginal offer equals the marginal bid, capacity is fully utilised and independently of crossholdings. Thus, there are a manifold of non-Pareto ranked Nash equilibria leading to each possible market price. We propose simulations to examine how crossholdings and information alter the market power balance between buyers and sellers in this type of auctions.

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[6] These can be interpreted as "maximum reasonable prices" and are instrumental to set some bounds to the simulation.

3.2.2 Model Specification

The research process presented in this chapter is as follows: a sealed bid-offer auction market is simulated for several hundred periods using an adapted version of the R&E (1995) algorithm, until it reaches a stationary state. The exercise is repeated many times for different market concentration, informational and crossholding assumptions. Finally, the simulated results are characterised.

Market Rules

The model depicts an oligopoly wholesale commodity market linking $i = 1...n$ "producers", i.e. wholesale sellers, and $j = ...m$ "end-user suppliers", i.e. wholesale buyers. We model a uniform,[7] mid-point,[8] price, compulsory, capacity constrained sealed bid-offer auction (Smith, 1982) without bilateral trading. Although relevant in the medium term, there is no entry and exit of firms, variation in end-user demand or capacity expansion.

All players are homogeneous: producers (wholesalers) face a constant marginal cost, normalised at $c = 0$, and wholesale buyers sell at an exogenously determined tariff (redemption value) in the end-user market ($\Psi = 100$). Capacities (k_i and k_j) are also homogeneous within tiers. There is no excess capacity: total potential wholesale demand equals total potential supply and is set exogenously ($\sum_{j=1}^{m} k_j = \sum_{i=1}^{n} k_i = 100$). Players choose their pricing strategies from the set of 101 natural numbers in $[c, \Psi]$, all with the same initial probability. Hence, all firms obtain non-negative profits.[9]

In every simulation period (time indexed as t), firms are willing to sell (or buy) up to their capacity at a price equal to the single price bid submitted. Supply and demand curves are constructed *ad hoc* from the firms' bid and ask choices, before the market clears. The simulation pseudo-code is as follows:

1.- Buyers and sellers choose and submit bids;

2.- The market clears, determining the uniform market price and the quantities assigned to each buyer and seller;

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[7] i.e. All agent's pay / receive the same market clearing price.

[8] i.e. If the marginal buyer bids 10 and the marginal seller bids 8, the market price is 9 monetary units.

[9] The chosen c and Ψ values influence absolute price levels but not the qualitative implications of the analysis.

3.- Buyers and sellers calculate their profits;

4.- Buyers and sellers reinforce strategies and re-calculate the probabilities to play each of them in the next period;

5.- Back to 1.

Behavioural Rules

Clearly, the wholesalers want to sell all their capacity at a market price as close to Ψ as possible. Wholesale buyers, on the other hand, want the price to be as close to c as possible.[10] The extent to which these two types of players reach their goals depends on market structure and, crucially, on their ability to exert market power and learn bidding strategies that approach their respective optima.

Cross-holdings are assumed on sellers' side in duopoly.[11] Sellers are provided with a "financial rights" profit maximisation objective function. Although there is some controversy in the literature about whether these or "ownership rights" are appropriate,[12] the financial approach provides a more conservative estimation of the coordination effects between the two cross-held agents and, as a result, it is favoured in the current setting. That is, we look into the consequences of two (or more) sellers buying holdings of each other but keeping their bidding decisions independent: we assume that seller 1 exerts no control over seller 2 and does not influence its bidding behaviour. However, seller 1 does benefit from the profits that accrue to it as shareholder of seller 2, and vice versa. Sellers are motivated to attain a higher profit level

$$MAX_p \Pi_i(t) = (p - c)(x_i(t) + \Phi x_{\sim i}(t)), \tag{3.1}$$

in which $(p - c)$ is the gross margin, Φ is the symmetric percentage of cross-holding and $x_i(t)$ and $x_{\sim i}(t)$ are the quantities that i and its cross-owned rival $\sim i$ have managed to sell in the period. End-user suppliers (that act as buyers in the wholesale market) also try to maximise

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[10] When more than one marginal bidder draw in their bids, quantities are shared proportionally by all of them.

[11] The analysis could be generalised easily to the buyers' without unexpected qualitative changes in the results.

[12] As an illustration, in the case of two companies with 20% crossholdings, under the financial configuration approach, managers are motivated by an objective function including 100% of their own and 20% of the opponent's profit. In the ownership rights model, the percentages would be 80% and 20%.

profit

$$MAX_p \Pi_j(t) = (\Psi - p)x_j(t), \tag{3.2}$$

where $x_j(t)$ units are bought wholesale and sold retail by each "buyer" $j = 1...m$ at $\Psi > p$.

At the beginning of every period the agents choose pure pricing strategies and, at the end of it, try to learn how to improve their bidding behaviour. They achieve this via a discrete set of strategies, indexed as k for sellers and l for buyers, with homogeneous initial probability and sequential experimentation through the use of the R&E (1995) parameterised features. The algorithm actualises the propensities assigned to each pure pricing strategy ($r_s^i(t)$ and $r_l^j(t)$) and increases the probability of those that yield better results.

How the propensity of each strategy at *t+1* is established as a function of $\Pi_i(t)$ and $\Pi_j(t)$ follows. Each seller i plays each possible action $s = 1...S$ with a given "propensity", r_s^i. The concept of propensity is related to that of probability but allows their sum to add up to a number higher than one. The probability that i plays s is given by its propensity divided by the sum of the propensities of all possible actions,

$$p_s^i(t) = \frac{r_s^i(t)}{\sum_{s=1}^{S} r_s^i(t)}. \tag{3.3}$$

Propensities are initialized to the firms' maximum profit, i.e. $r_s^i(1) = \Psi k_i$ for all s, so that all actions have the same initial probability. At the end of each round, traders update their propensities according to the results obtained by the actions played. We simulate their individual behaviour following an adapted version of the Roth and Erev (1995) algorithm during T periods. Namely, traders reinforce the selected action, λ, through an increase in its propensity by $\Pi_i(t)$. Therefore, all strategies resulting in a positive payoff are reinforced to some extend and there is a strong incentive for firms to trade. Those that do not place firms "on the money" will not be reinforced.

Moreover, actions that are similar, i.e. $\lambda - 1$ and $\lambda + 1$, are also reinforced, but to a lesser extent, through an increase in their propensity by $\Pi_i(t)(1 - \delta)$ where $0 < \delta < 1$ ("persistent local experimentation"). Independent of trading performance, the importance of past experience is reduced by discounting all propensities by γ ("gradual forgetting"). Finally, actions whose probability falls below a certain threshold are removed from the choice space ("μ, extinction in finite time"). The propensities are computed in two steps. Firstly, the pre-extinction propensities $r_s^i(t)'$ are

$$r_s^i(t)' = \begin{cases} (1-\gamma)r_s^i(t)(t-1) + \Pi_i(t) & \text{if } s = \lambda \\ (1-\gamma)r_s^i(t-1) + (1-\delta)\,\Pi_i(t) & \text{if } s = \lambda - 1 \text{ or } s = \lambda + 1 \\ (1-\gamma)r_s^i(t-1) & \text{if } s \neq \lambda - 1,\ s \neq \lambda \text{ and } s \neq \lambda + 1 \end{cases} \tag{3.4}$$

Secondly, the propensities are corrected when the the "extinction in finite time" feature is binding,

$$r_s^i(t) = r_s^i(t)' I_{\left\{\frac{r_s^i(t)'}{\sum_{s=1}^{S^i} r_s^i(t)'} > \mu\right\}}, \tag{3.5}$$

where I is an indicator function that takes value 1 if the condition is satisfied and 0 otherwise. The algorithm is analogously used on the buyers' side with the corresponding indices.

Once the probabilities for playing particular strategies are determined, the agents may modify them, depending on the information available. In private information environments, the market operator does not make public the agents' strategies or their outcome. Sellers know how much overall profit they are making through the participation in their rival but still try to optimise profits based exclusively on their own past experience:

$$privateprob_{i,s}(t) = \frac{r_s^i(t)}{\sum\limits_{\forall s} r_s^i(t)}, \tag{3.6}$$

where the probability of wholesaler i playing a pricing strategy s at time t, is her propensity to play s, $r_s^i(t)$, over the sum of the propensities of all her possible strategies, $\sum\limits_{\forall s} r_s^i(t)$. The probabilities on the demand side are calculated as:

$$privateprob_{j,s}(t) = \frac{r_s^j(t)}{\sum\limits_{\forall s} r_s^j(t)}. \tag{3.7}$$

Public information, in contrast, is assumed to result in a form of social mimicry between market participants. Each firm's price bid is based on a randomisation over a common information pool consisting of the strategies used by all players and their outcomes.[13] We assume that strategy

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[13] As an approximation, public and private information are defined exogenously and independently of each

fine-tuning becomes not only the result of the individual agent's experience but also of her opponents'. The public information probabilities ($publicprob_{i,k}(t)$) are modelled as the average of all sellers' $privateprob_{i,k}(t)$:

$$publicprob_{i,s}(t) = \frac{\sum\limits_{i=1}^{n} privateprob_{i,s}(t)}{n}. \tag{3.8}$$

Demand firms average the private probabilities across buyers:

$$publicprob_{j,s}(t) = \frac{\sum\limits_{j=1}^{m} (privateprob_{j,s}(t))}{m}. \tag{3.9}$$

The simulation results are presented in the next section. The discussion part includes further analyses of asymmetric informational assumptions, trading sophistication and the agents' trading behaviour.

3.3 Simulation Results

The initial simulation includes 51 seller crossholding cases (Φ), those in the 0-50% range with a discrete interval of one percent. The number of observations (simulation runs) for each crossholding assumption is 20, with 500 trading periods in each run. The simulations converge to stationary outcomes[14] in approximately 300 periods (Augmented Dickey-Fuller tests were carried out and the unit-root null hypotheses rejected in all instances ($p<.01$). Consistent with findings by Roth and Erev (1995), I ran simulations with a large variety of different parameter values, and found that the choice of parameters influenced the speed of convergence without varying the qualitative insights from the model. Results presented are for the following values: $\delta = 0.2$, $\mu = 0.001$ and $\gamma = 0.01$. These were chosen because they provided good convergence in reasonable computational times and allowed the agents to gain a significant

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other. However, it is possible that in reality there might be some dependencies between them. Cross-holdings, for example, could lead firms to share information with each other, increasing the degree of market transparency even in the private information setting.

[14] i.e. present constant means and variances and the covariances between two points only depend on the distance between them and not on where they are located.

amount of experience before the results starting to converge

The analyses is based on the price average for periods [301, 500] in each run.[15] [16] The presentation starts with a comparison of the results emerging from two market structures, "case A" ($n = m = 2$) and "case B" ($n = 2$; $m = 10$). Sample size is $51 * 20 * 4 = 4,080$, with one half of the observations corresponding to each case and within that, one half to each informational assumption.

3.3.1 The Shape of the Crossholdings to Market Price Relationship

Figures 3-1 through 3-4 present a summary of the simulated market prices, with 95% confidence intervals of the mean estimation (note that for an easier presentation of the results, the vertical axes is scaled between 40 and 100 monetary units). The relationship between prices and crossholdings is increasing under all conditions. This coincides with the general observation in the literature that crossholdings lead to higher prices (e.g. Reynolds and Snapp, 1986; Farell and Shapiro, 1990; Flath, 1991).

Moreover, the figures indicate the existence of a concave threshold effect around 5-10% of crossholdings which seem to be robust across market structures and informational assumptions. While the relationship between the two variables is very steep for the initial Φ values, these do not seem to have a significant impact on market prices beyond that point. The mere presence of crossholdings seems to trigger the sellers' coordination, so that small Φ result in market prices close to the simulation ceiling ($\Psi = 100$).

As a clear example, case A is totally symmetric under $\Phi = 0$ and results in a market price of 50, which is equidistant between the price range minimum ($c = 0$) and Ψ. This market balance is quickly altered by small crossholdings, which bring market prices to around 90, very close to Ψ under both information regimes.

Result 1: The crossholdings vs. market prices relationship is not convex but better specified by a (concave) threshold specification.

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[15] The updating procedure assigns positive reinforcements not only to strategies that perform well but also to their "neighbours" on the grid. As a consequence, strategies remain mixed even at the end of the simulation.

[16] Results are robust to changes in the initial conditions.

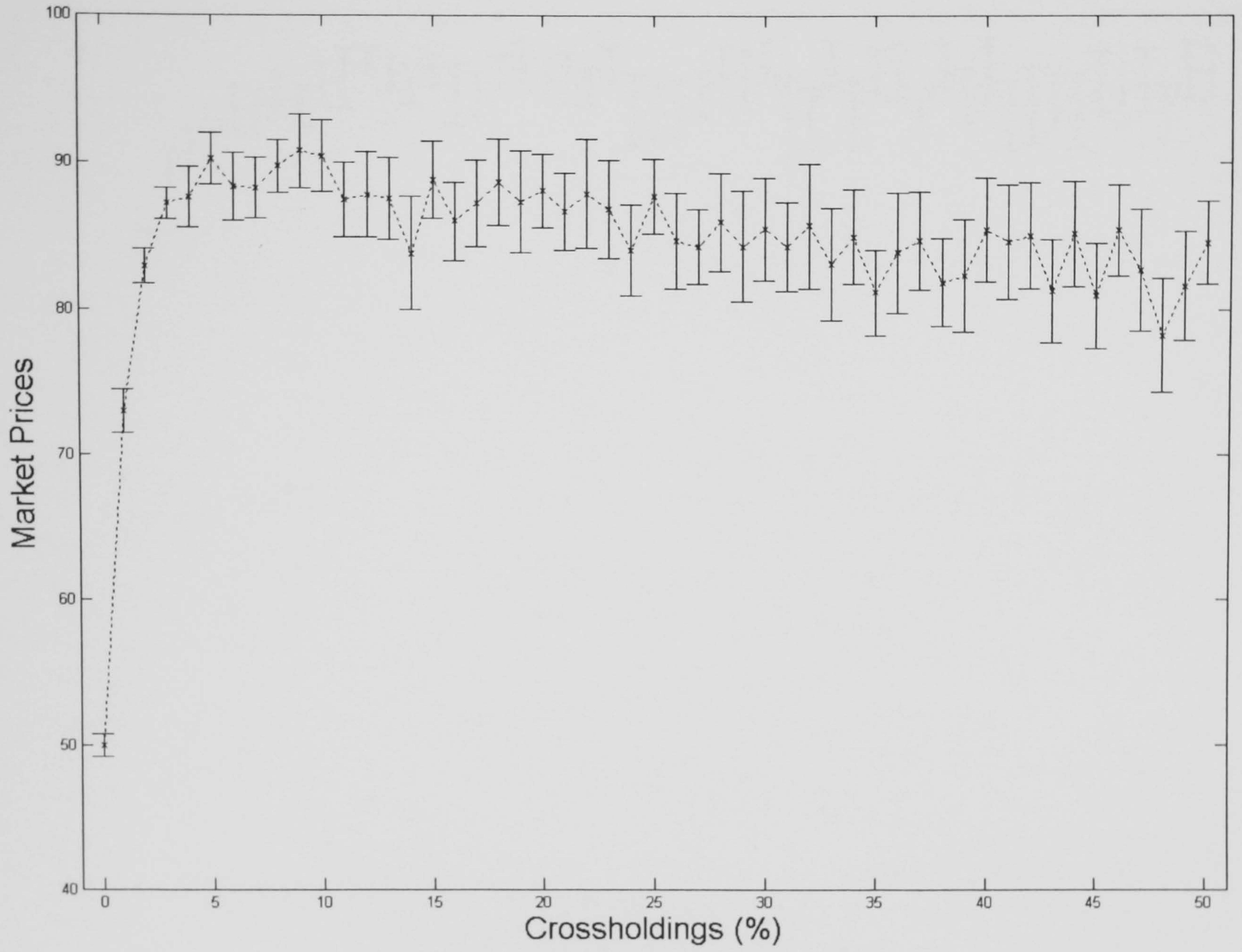

Figure 3-1: Market prices private information, case A

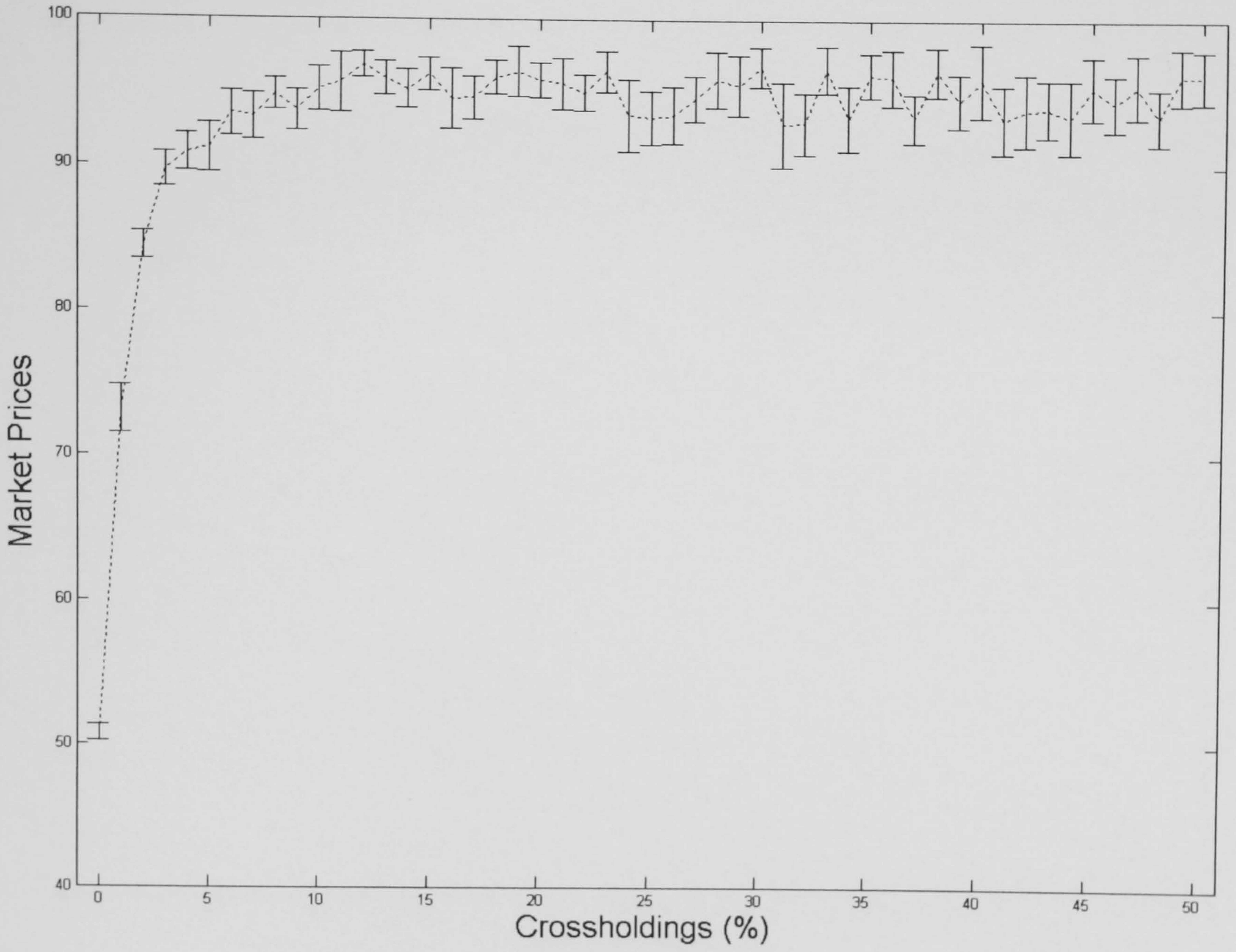

Figure 3-2: Market prices public information, case A

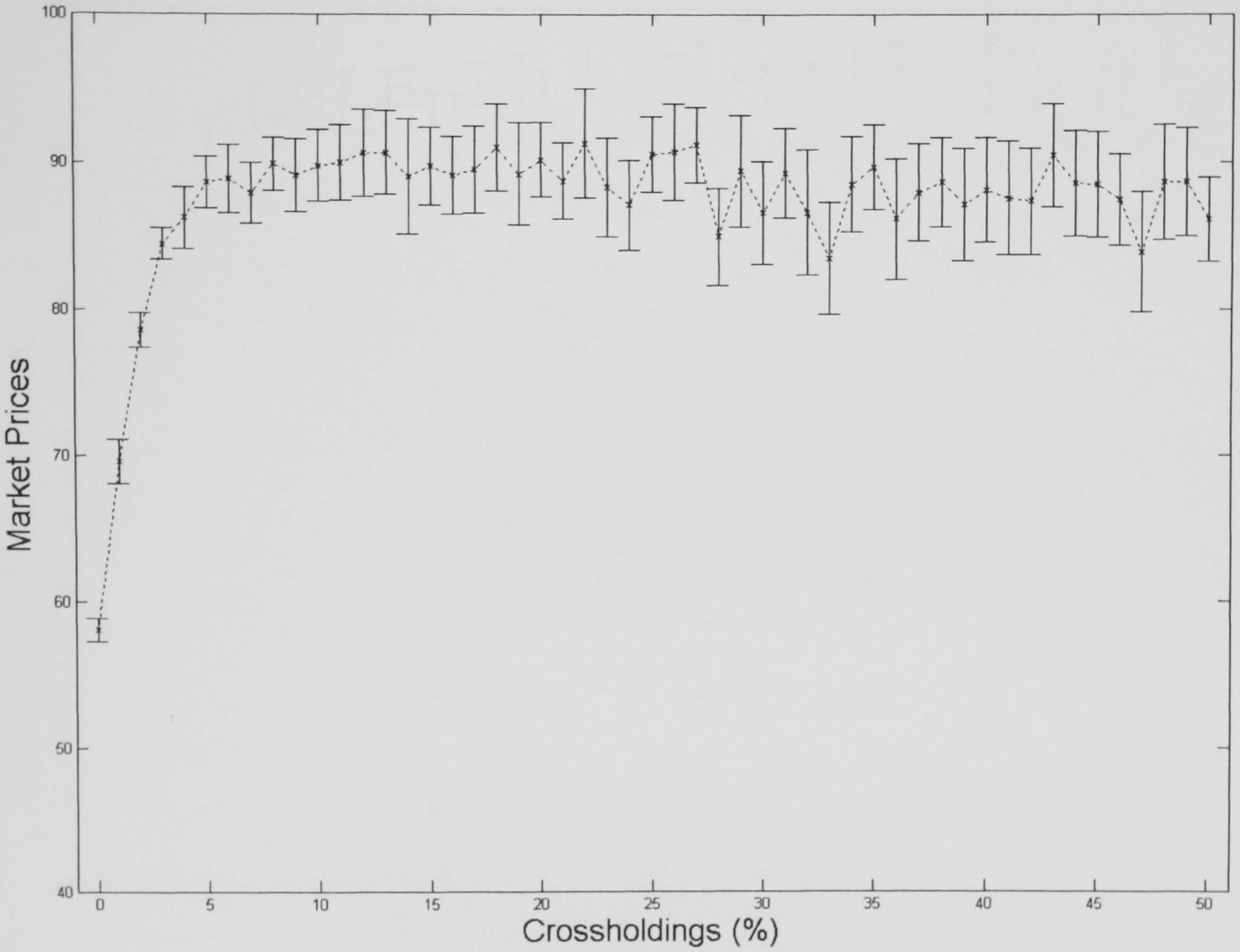

Figure 3-3: Market prices private information, case B

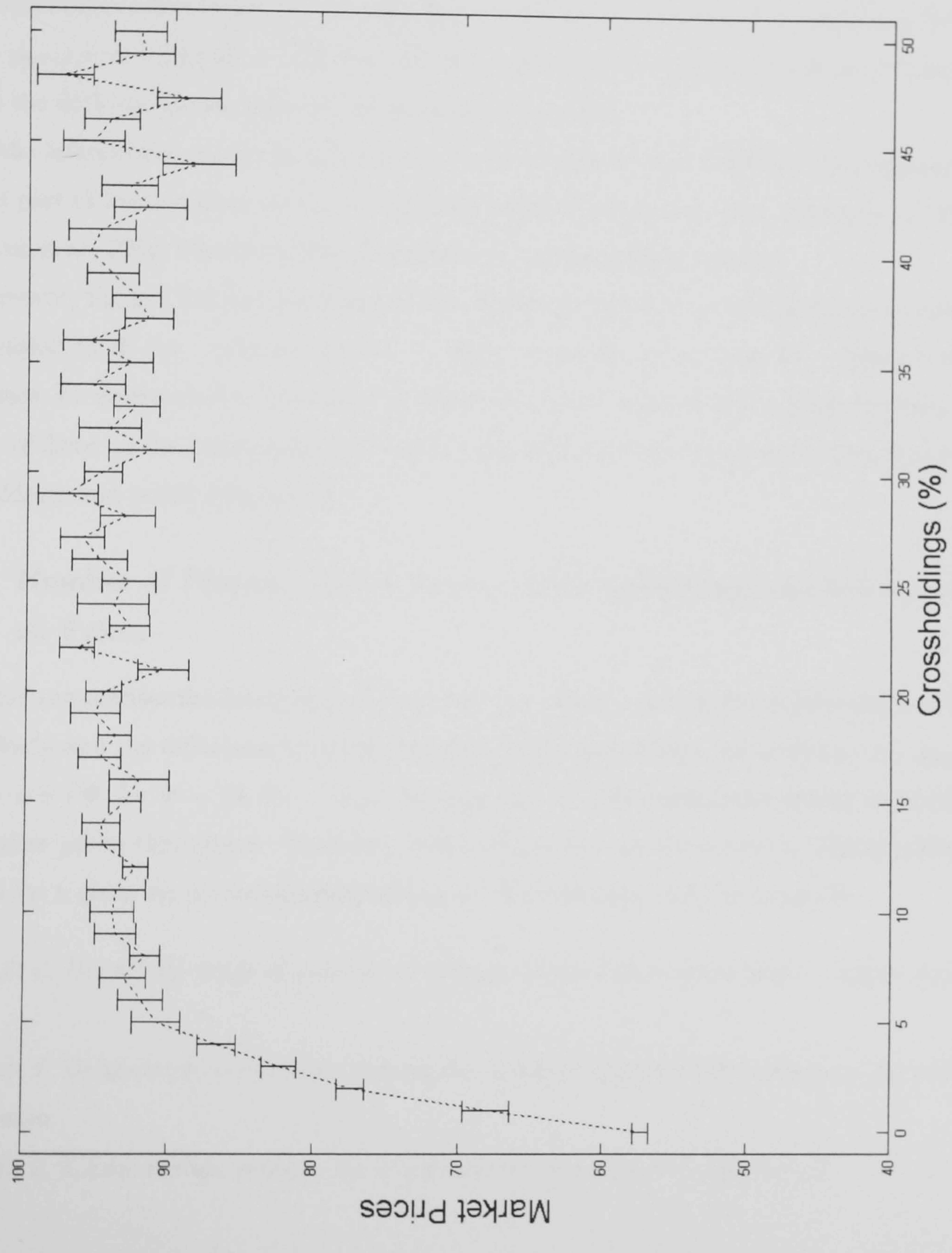

Figure 3-4: Market prices public information, case B

3.3.2 Informational Regimes and Market Power in Crossholding Settings

To measure the effect of keeping information private under crossholdings, the data from the two informational cases is subtracted and the resulting series extended as a function of Φ (i.e. $(p_{pub} - p_{priv}) = \alpha + \beta\Phi$; for $n = 2$, $\Phi = \{0, .01, ..., .50\}$ and $m = \{2, 10\}$. Figures 3-5 and 3-6 include the 95% confidence intervals of the mean estimations.

Public information results in higher prices in both "case A" and "case B". The simulations support part of the literature on the coordination value of information (e.g. Albæk et al., 1997; Offerman et al. 2002; Vincent, 1992) and extend it to crossholding settings.

Moreover, Figures 3-5 and 3-6 indicate that while the relative value of public information is increasing in Φ (i.e. positive slopes), it seems to be flatter in "case B". These results can, hence, be understood as indicative evidence of a more complex relationship between the number of firms on the demand side, m, and the coordination benefits emerging from upstream crossholdings and public information.

3.3.3 Number of Players and the Impact of Crossholdings and Information on Prices

Figure 3-7 summarises the linear regressions across $m = \{2, 3, ..., 10\}$ of the relationship between crossholding and the difference between simulated public and private information (i.e. $(p_{pub} - p_{priv}) = \alpha + \beta\Phi$; for $\Phi = \{0, .01, ..., .50\}$), keeping $n = 2$. The public information simulations yield higher prices throughout. Moreover, while public information results in higher prices as Φ grows for a given m, its coordinating effects are decreasing in m for constant Φ.

Result 2: For a wide range of simulation settings, public information leads to higher market prices.

Result 3: Downstream competition reduces the influence of public information on the sellers' coordination.

Result 4: Crossholdings increase the coordination value of public information.

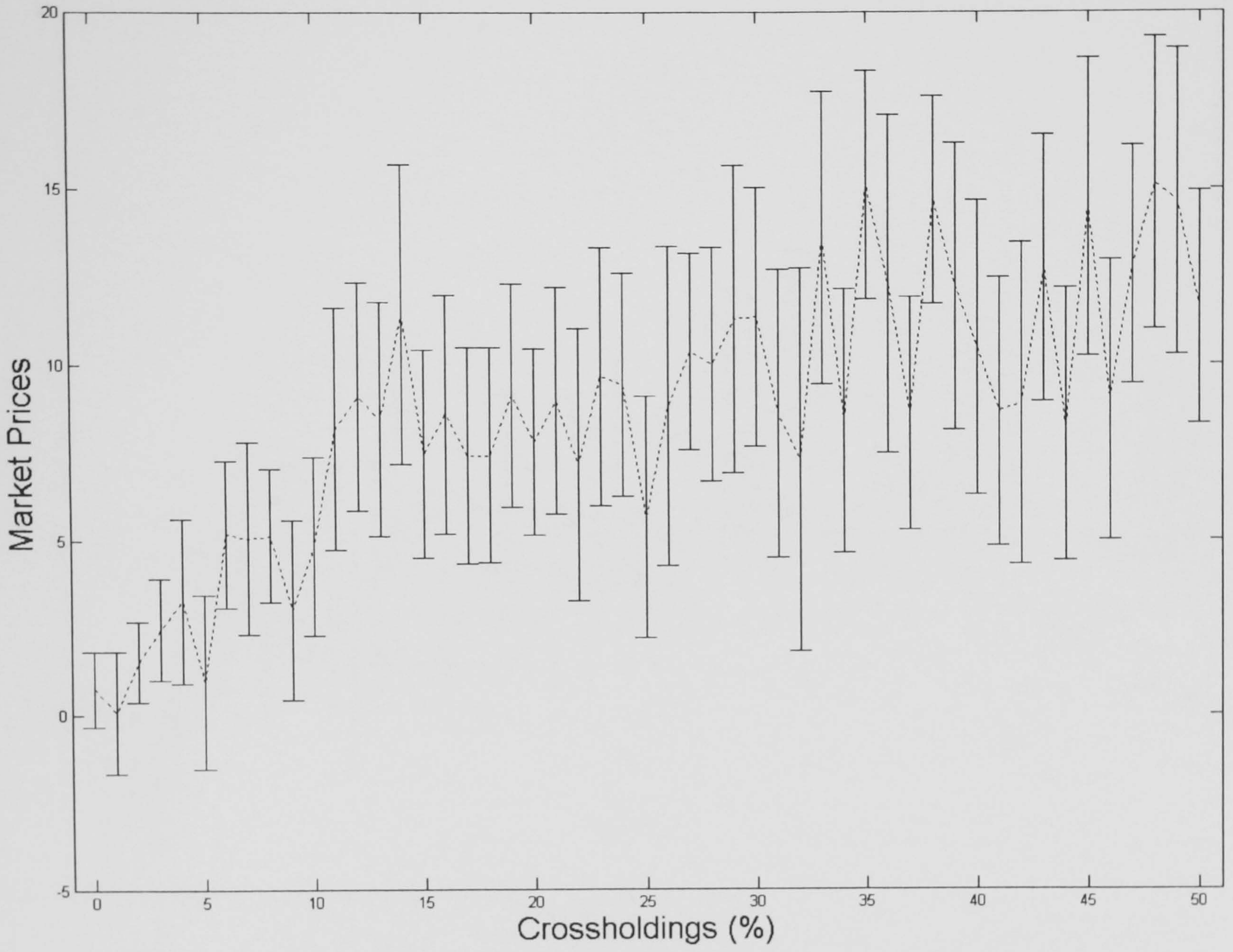

Figure 3-5: Value of public information, $\Phi = \{0, ..., .50\}$, $m = 2$

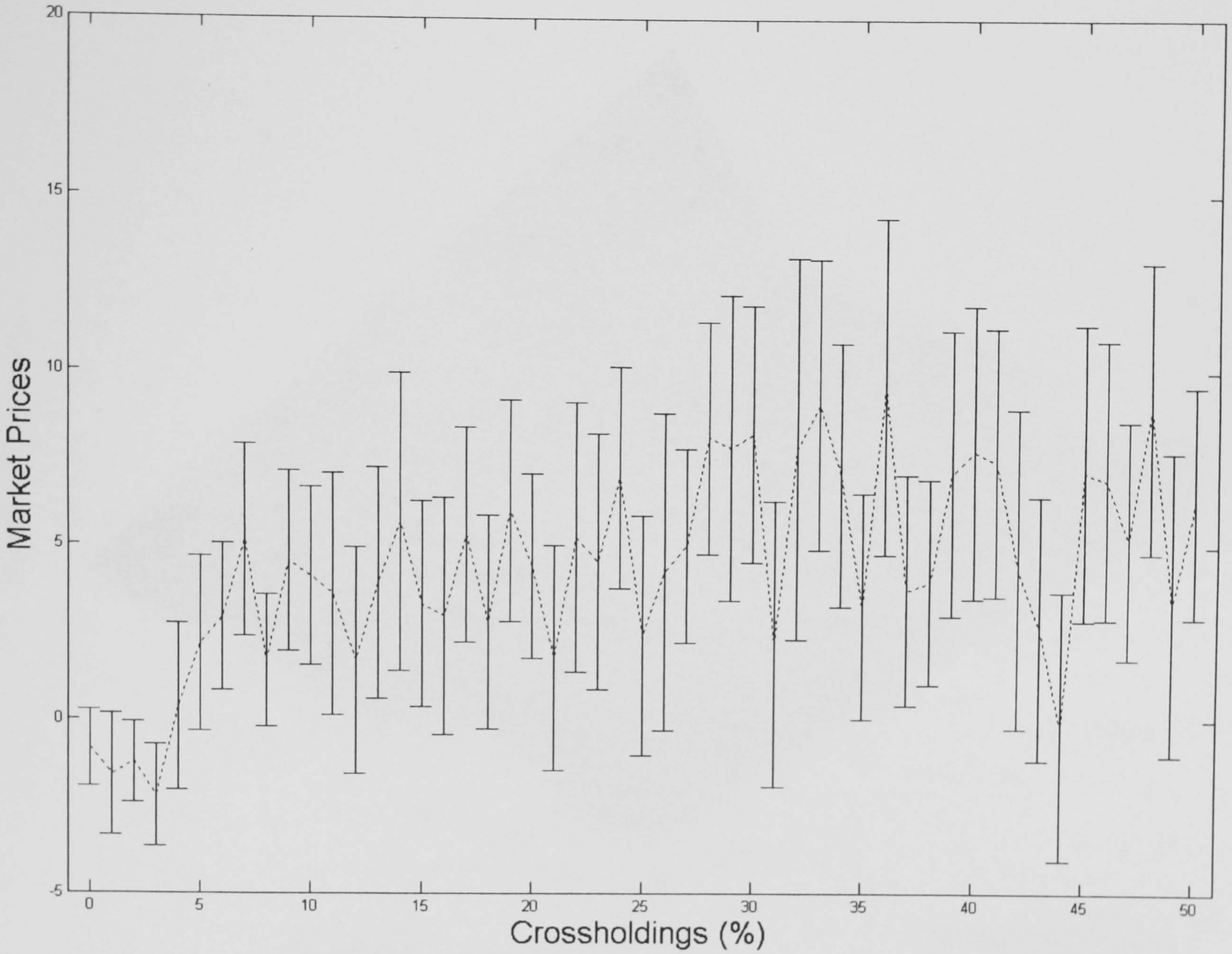

Figure 3-6: Value of public information, $\Phi = \{0, ..., .50\}$, $m = 10$

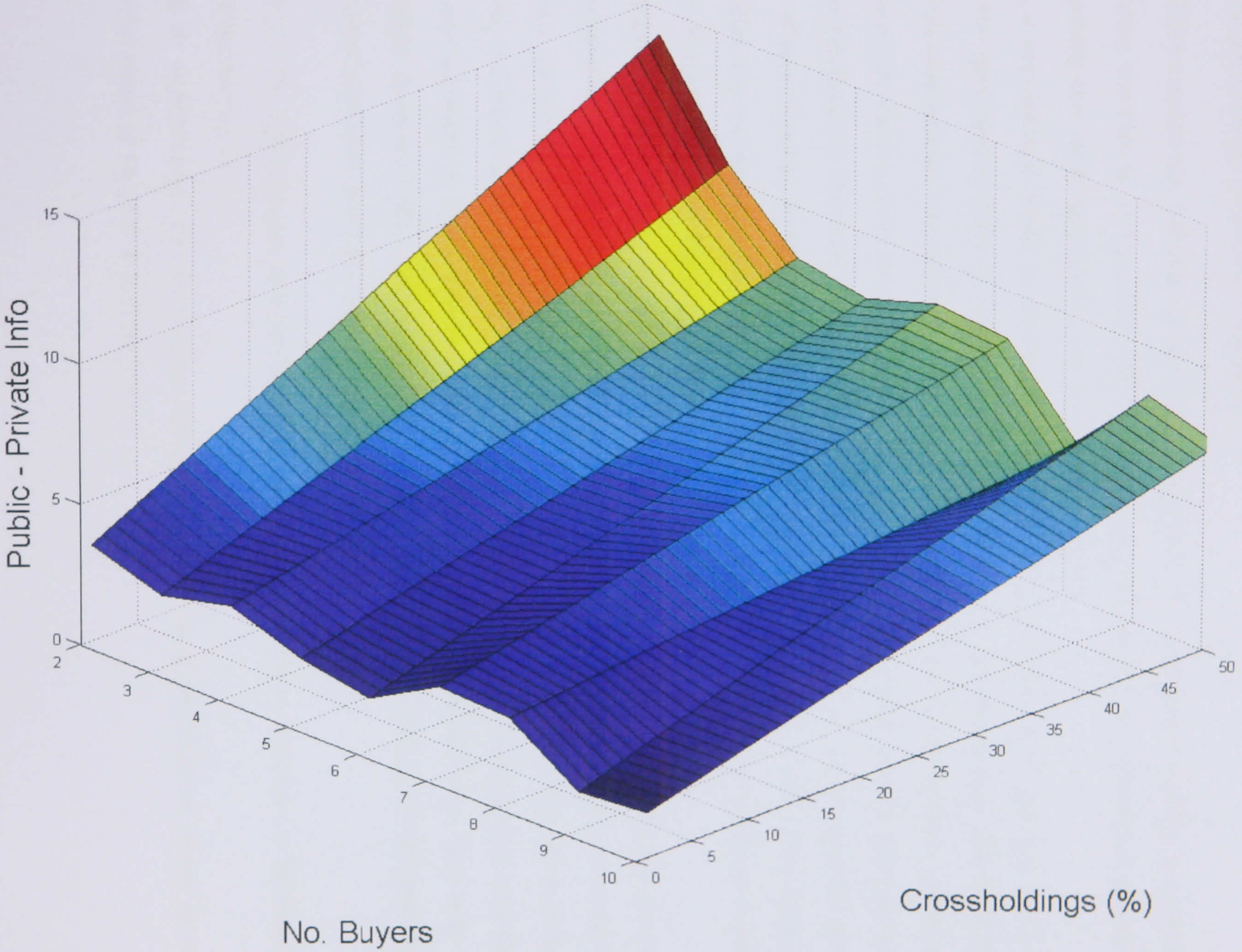

Figure 3-7: Value of Public Information , $m = \{2, \ldots 10\}$, $\Phi = \{0, ..., .50\}$

3.4 Information and Strategic Trading

3.4.1 Asymmetric Trading Regimes

It is possible to isolate the influence of information on the buyers and sellers' bidding behaviour by simulating the case in which public information is provided to only one of them at a time, and comparing the resulting prices to the purely private case.

Thus, a hypothetical model in which public information is provided upstream only is used to study the information effect on duopolists' behaviour when m and Φ increase (Figure 3-8). The vertical axis includes the difference between prices under the "*public information upstream and private information downstream*" assumption and those of the pure private information case. The relationship obtained is increasing on Φ and decreasing on m, which suggests that the price effects of public information observed in Figure 3-7 (i.e. results 3 and 4) are mainly due to higher bid coordination on the sellers', rather than more competition on the buyers' side (note the similarity between Figures 3-7 and 3-8).

Secondly, the effects arising on the demand side are isolated with a simulation for the case of public information downstream only. Figure 3-9 compares the results obtained against those of pure private information. On the vertical axis, we include the difference between prices under the "*public information downstream and private information upstream*" assumption and the pure private information case. The relationship appears to be not significative, with only a possible slight downward effect arising for high m and Φ values. In general, public information on the buyers' side does not have a large market price effect.

Result 5: The effectiveness of information as a coordination device upstream is increasing on Φ and decreasing on m.

Result 6: Information does not have a significative effect as a coordination device downstream for a range of m and Φ parameters.

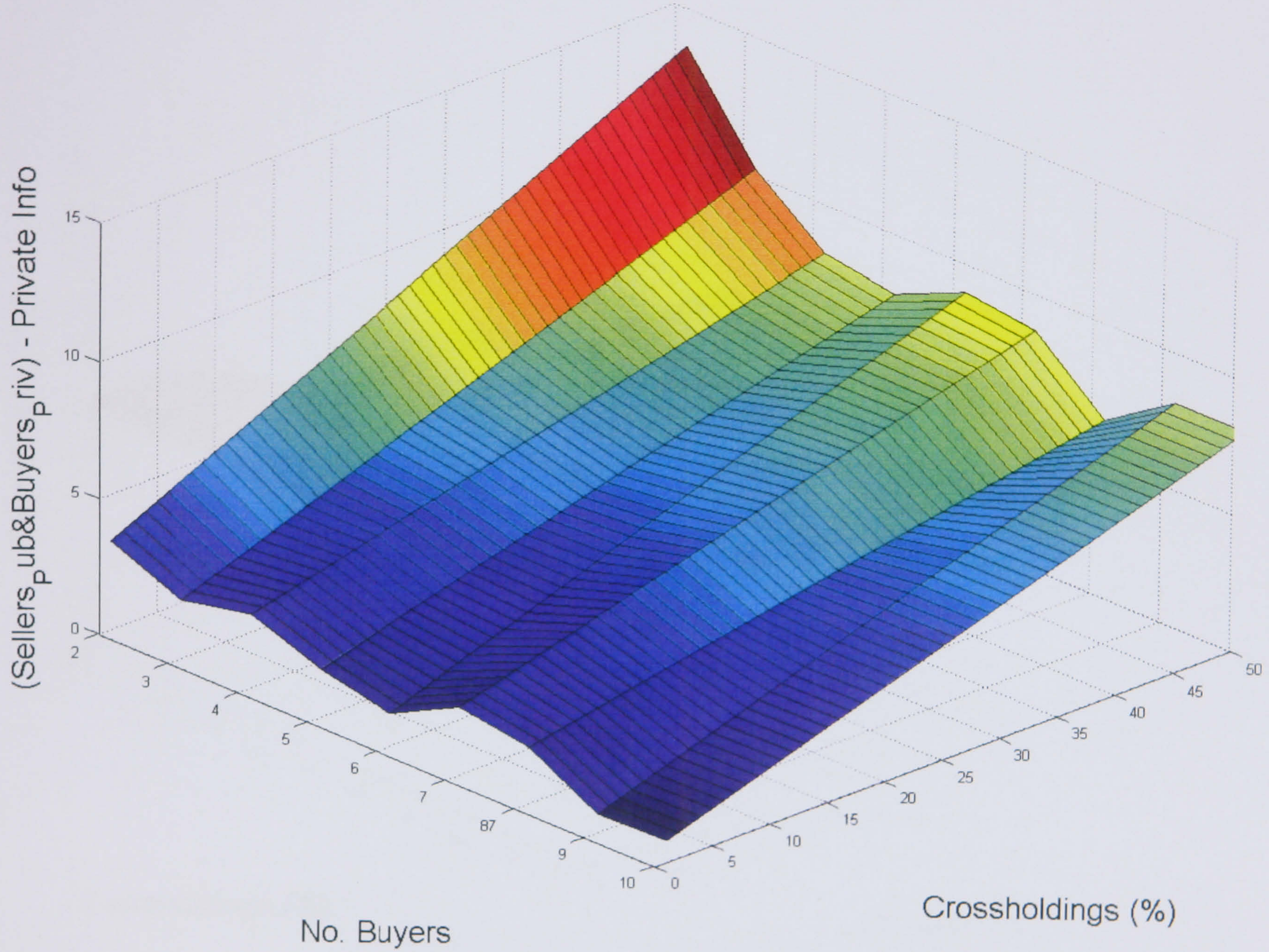

Figure 3-8: Price difference between private information and a setting in which there is public information on the sellers' side and private information on the buyers' side, $m = \{2, \ldots 10\}$, $\Phi = \{0, ..., .50\}$

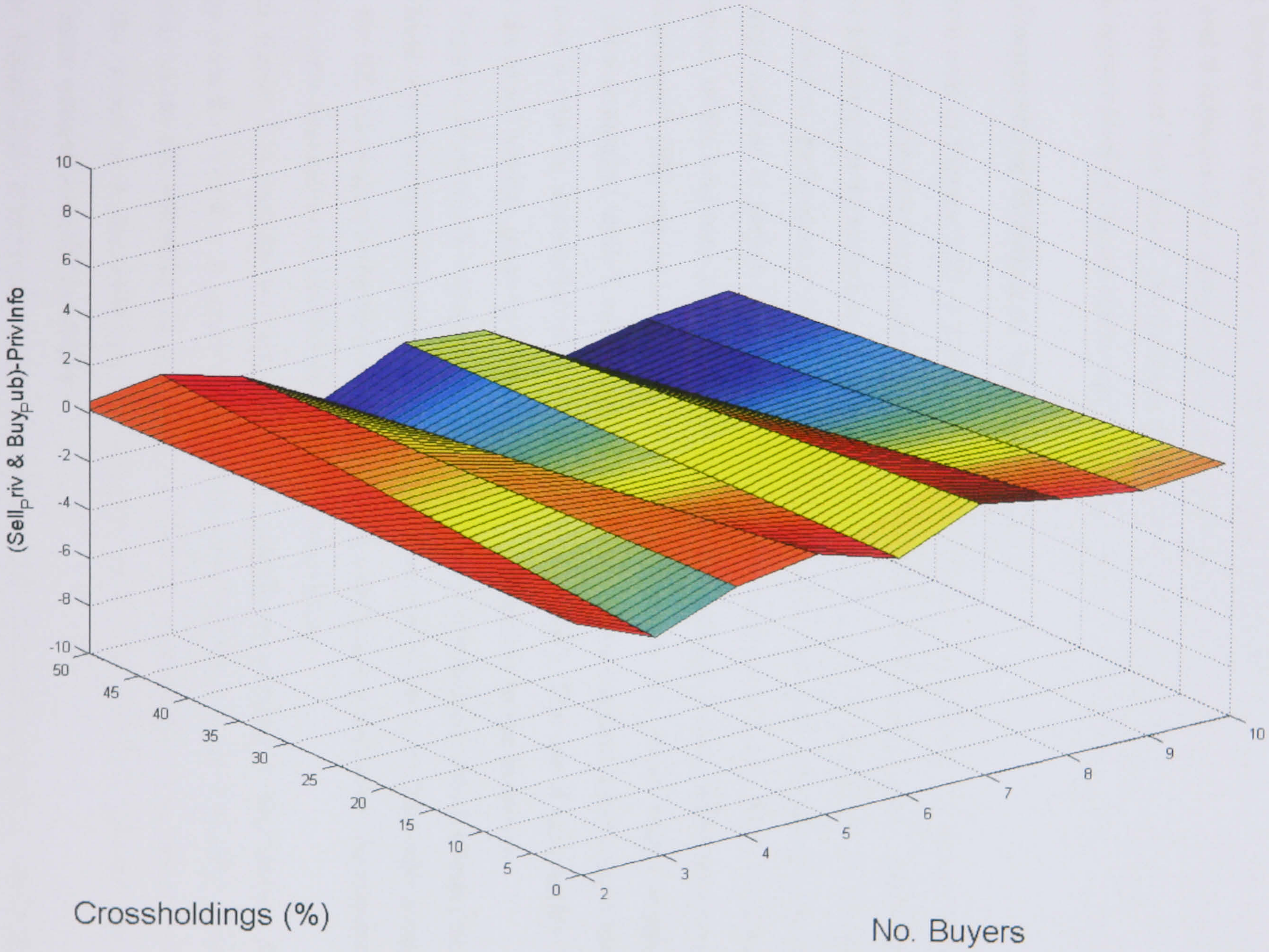

Figure 3-9: Price difference between private information and a setting in which there is public information on the buyers' side and private information on the sellers' side, $m = \{2, \ldots 10\}$, $\Phi = \{0, ..., .50\}$

Note that *Results 3 to 6* are effectively unveiled through the multi-agent simulation approach, with strategic behaviour on both sides of the market, and would be elusive to a model in which buyers were aggregated as a demand curve. They indicate that the informational rules, m and Φ influence how information is transmitted between rivals, which, in turn, affects strategic behaviour and, hence, the intensity of competition. These relations materialise at the individual agent's level on the set of strategies prioritised by the R&E (1995) learning algorithm.

3.4.2 Competitive Bidding at the Agent Level

The vertical axes in Figures 3-10 to 3-12 represent cumulative probabilities at the end of simulation for a representative buyer and seller using the R&E reinforcement rules. These were calculated following the formulations in equations 3 through 6, for each action in the strategy space, identified on the horizontal axes. The concentration of probabilities was largely invariant across a large number of periods once the market reached convergence and, thus, the figures are a summary of the long-term mixed bidding strategy for each agent type. Seller movements to the "Southeast" (SE) are an indication of more coordination (i.e. more weight assigned to higher price strategies) while a movement to the SE for buyers suggests more competition. The opposite is true for movements towards the Northwest (NW). The use of this method to represent the firms' bidding priors is a methodological contribution to the literature.

First, Figure 3-10 shows the change in the firms' cumulative probability distributions due to a change from $m = 2$ to $m = 10$, under private information and for $\Phi = .5$. The seller's curve moves to the SE. As m grows, the seller's behaviour becomes more coordinated. As expected, the buyer's curve also moves to the SE due to more competition.

Second, Figure 3-11 includes the change in firms' cumulative probability distributions due to a change from $\Phi = 0$ to $\Phi = .5$, under private information and for $m = 10$. The seller's curve moves visibly to the SE, reflecting the coordination effect of crossholdings. It is interesting to note how the change in Φ also influences the behaviour on the non-crossheld demand agents, making it more competitive (SE movement).

Finally, Figure 3-12 corresponds to the variation in the representative firms' cumulative probability distributions due to a change from private to public information, for $\Phi = .5$ and $m = 10$. Both the seller and buyer's trading behaviour become more coordinated (movements to the SE and NW, respectively). The changes in prices observed in Figure 3-6 emerge from this new balance of trading behaviour, which benefits the more concentrated selling side.

Overall, the figures show that information, crossholdings and market concentration influence the agents' underlying bidding probabilities, producing different degrees of competition. Hence, market rules and structures, observed bidding behaviour and market prices are intertwined through the R&E reinforcement rules.

3.5 Discussion

A series of simulations clarifies the effects of market information, crossholdings and concentration on prices. The setting, a double sided version of Von der Fehr and Harbord's (1993) electricity market, describes well some aspects of the energy trading in Europe but includes a very large number of non-Pareto ranked pure strategy equilibria. Thus, computational learning algorithms offer a number of practical advantages for economic analysis.

The main question in the essay concerned the shape of the market price vs. crossholdings relationship under both private and public bidding information. This was found not to be convex but better defined by concave threshold specifications (Result 1).

The second result was that informing agents about their rivals' quantities and profits increased market prices for a wide range of crossholding and market structures. The strategic advantage resulting from transparency was stronger on the less competitive upstream side of the market and translated into higher prices. The transmission of information (i.e. social mimicry) between rivals explains the result, and coincides with findings by, among others, Albaek et al. (1997), Offerman et al. (2002) and Vincent (1992).

Thirdly, the simulations also explored the effects of varying degrees of market concentration on prices. In general, a positive relationship was found between how concentrated one side of the market is and how much advantage it gains from access to public information. The mechanism would not have been unveiled in a model without strategic behaviour on both sides, e.g. with an aggregated demand curve, and somewhat vindicates the value of the multi-agent simulations.

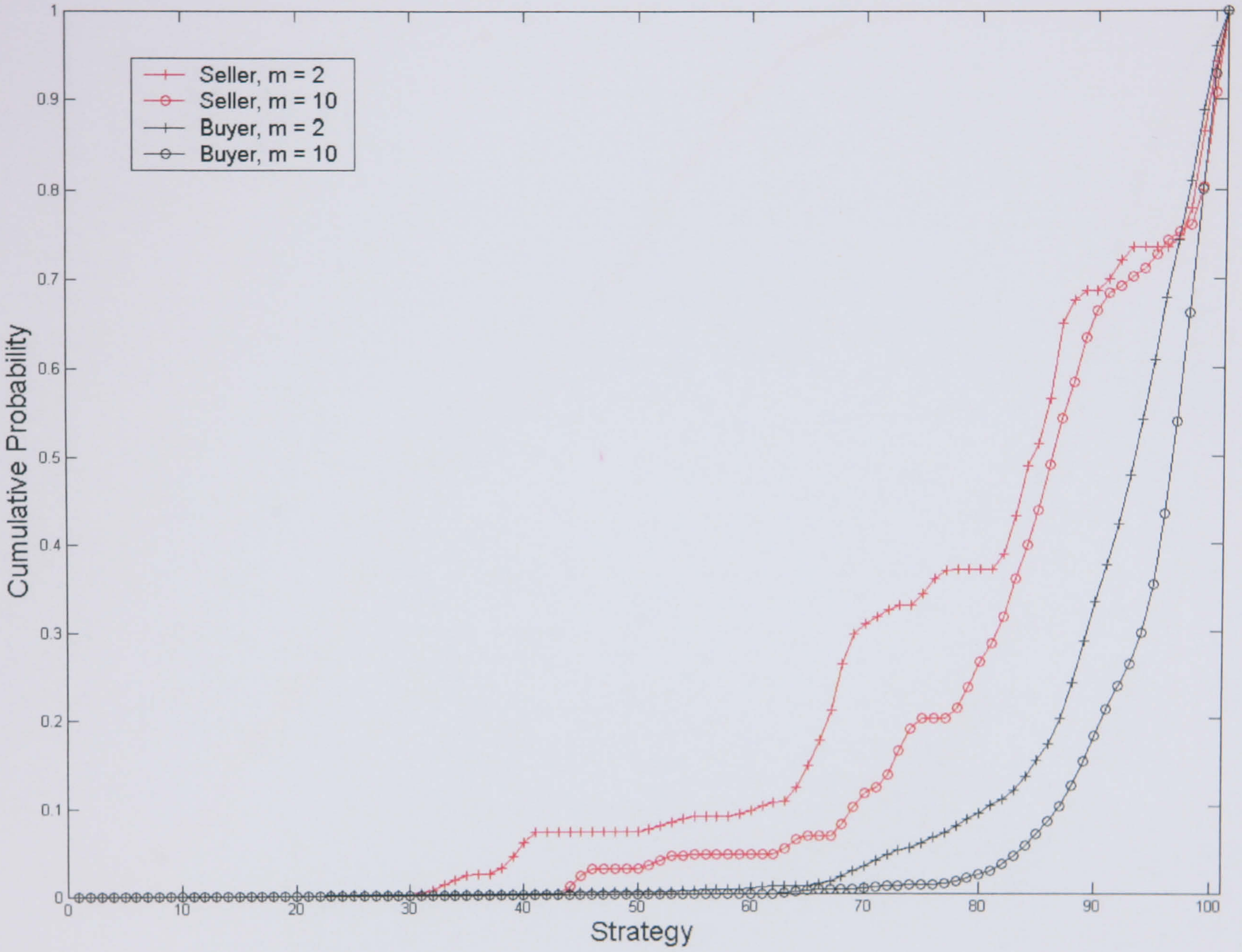

Figure 3-10: Change in cumulative distribution of strategies due to change from, $m = 2$ to $m = 10$, under private info and $\Phi = 50$

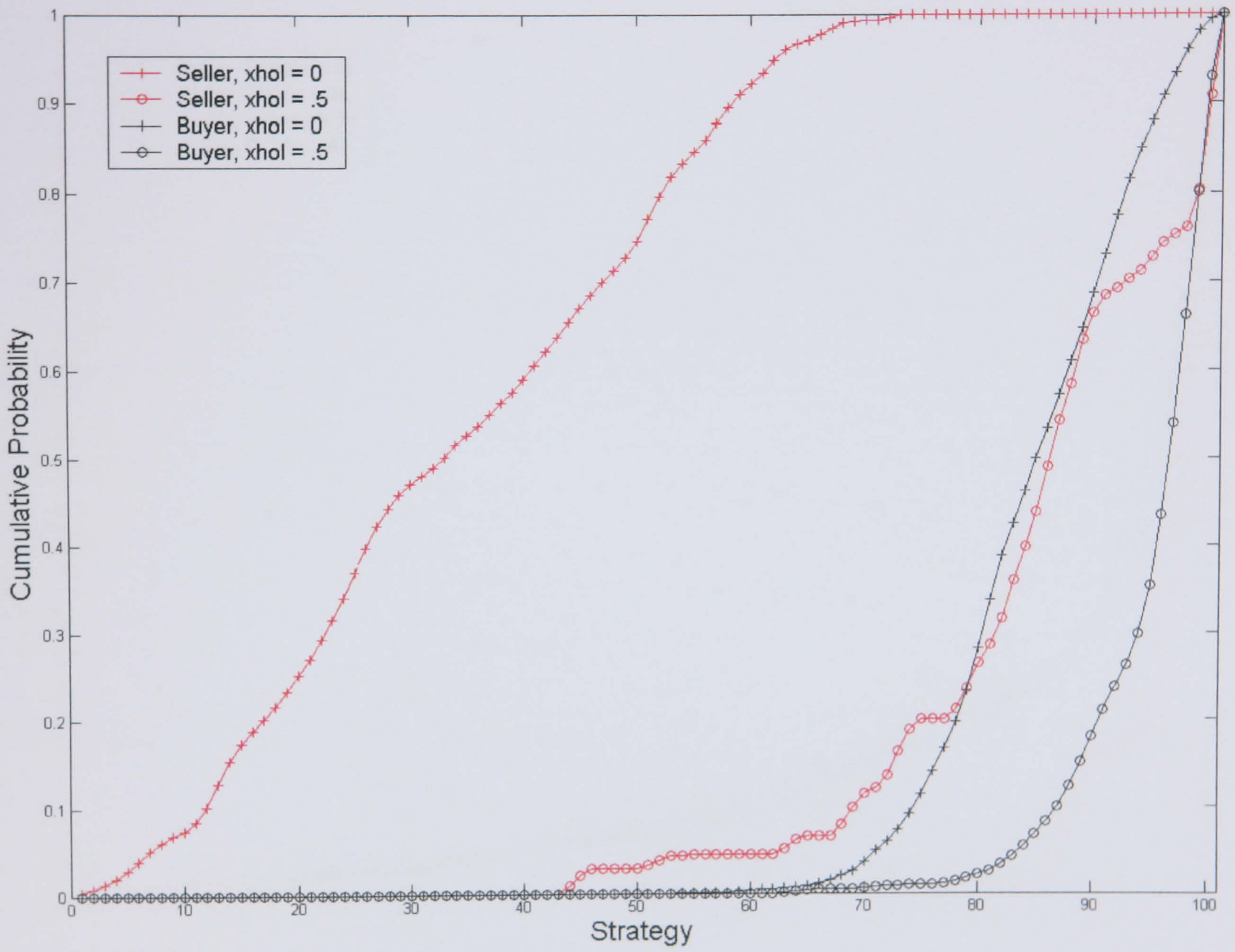

Figure 3-11: Change in cumulative distribution of strategies due to change from, $\Phi = 0$ to $\Phi = 50, m = 10$, private information

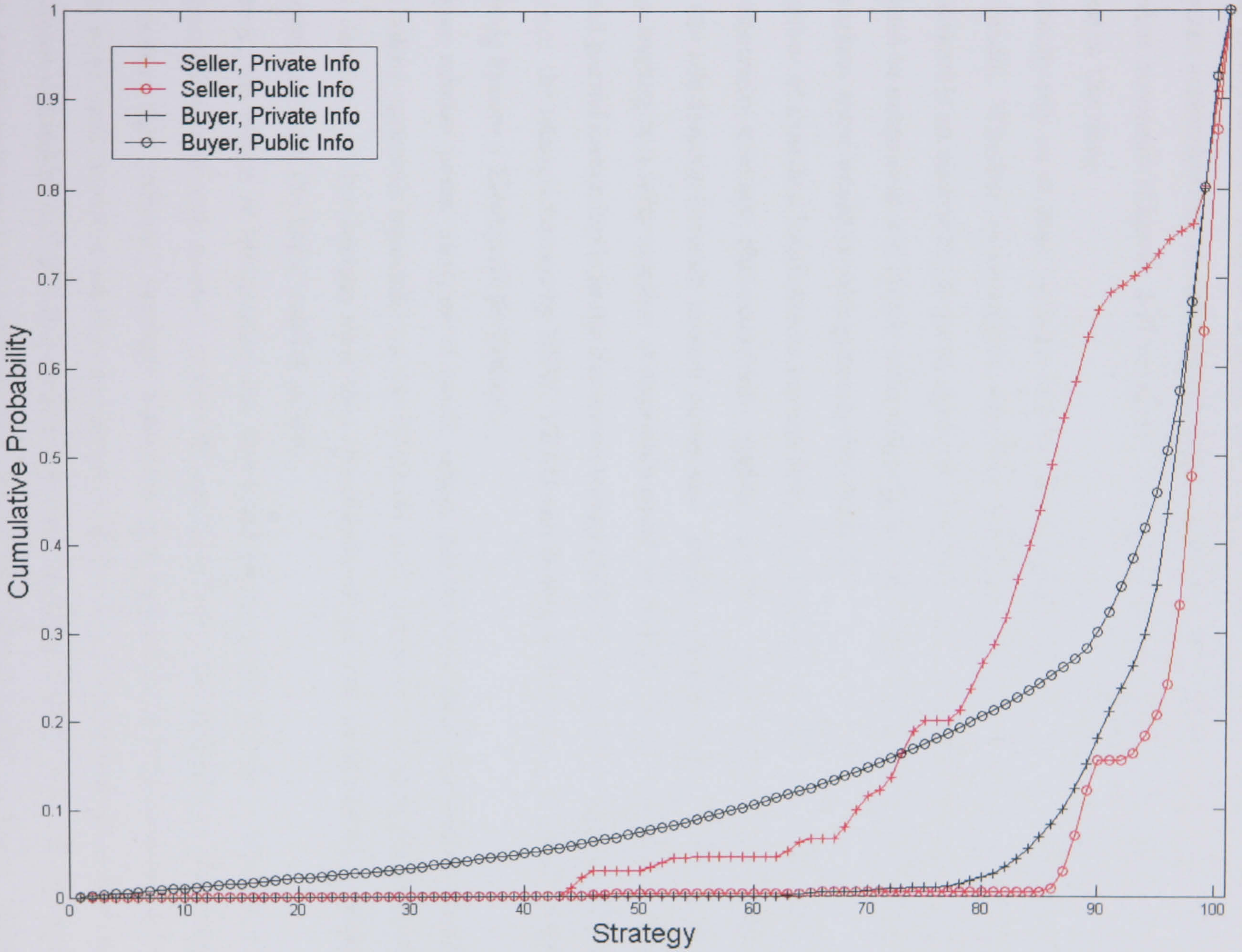

Figure 3-12: Change in cumulative distribution of strategies due to change from private to public information, $\Phi = 50$, $m = 10$.

With the right data, one could analyse empirically market prices and actual bids. The simulation approach allows in addition the inspection of the probability priors upon which bids are based. It was therefore possible to study how market rules (i.e. information) and structures (downstream concentration, crossholdings) influence the agents' *bidding rules* and not only their market outcomes (Figures 3-10 to 3-12). This is one of the methodological innovations introduced in the essay.

The results rely on at least two assumptions. First, they stem from the R&E reinforcement learning model. Whether an alternative algorithm represents better the trading behaviour in energy markets is an interesting research question. Secondly, the various simulation parameters were defined as exogenous and largely independently of each other. However, it is possible that in real markets these would be endogenously determined.

A number of practical implications emerge from the analysis. Returning to the European gas and electricity example, the simulations suggests that EU energy regulators have underestimated the relationship between market power and "small" crossholdings, so the screening of the latter leading to a large number of approvals could be flawed. Figure 3-13 illustrates how widespread partial ownership is in the European energy industry. Firms hold positions both nationally (e.g. the triangle formed by HEW, VEAG and Bewag in Germany) and internationally (e.g. Gaz de France / Electricité de France).

Tougher market power analyses of small, silent, partial ownership agreements should be required before approval, especially on the relatively more concentrated upstream part of the industry. Moreover, it has become clear that the amount of information available to traders is a key element to limit the firms' market power.

However, the effects of information and crossholdings on prices will be a function of the specific peculiarities of each market, in the EU and elsewhere. The difficulty in disentangling different factors that influence strategic behaviour in a capacity-constrained sealed bid-offer auction is what motivated the use of a simulation method. The above results should be understood as general insights, and are characterised by three features: Firstly, they raise new policy questions, which are relevant to other capacity-constrained double-sided auctions. Secondly, they are rationalised through the R&E social mimicry features. Finally, they provide a number of predictions that are susceptible of testing in the behavioural laboratory.

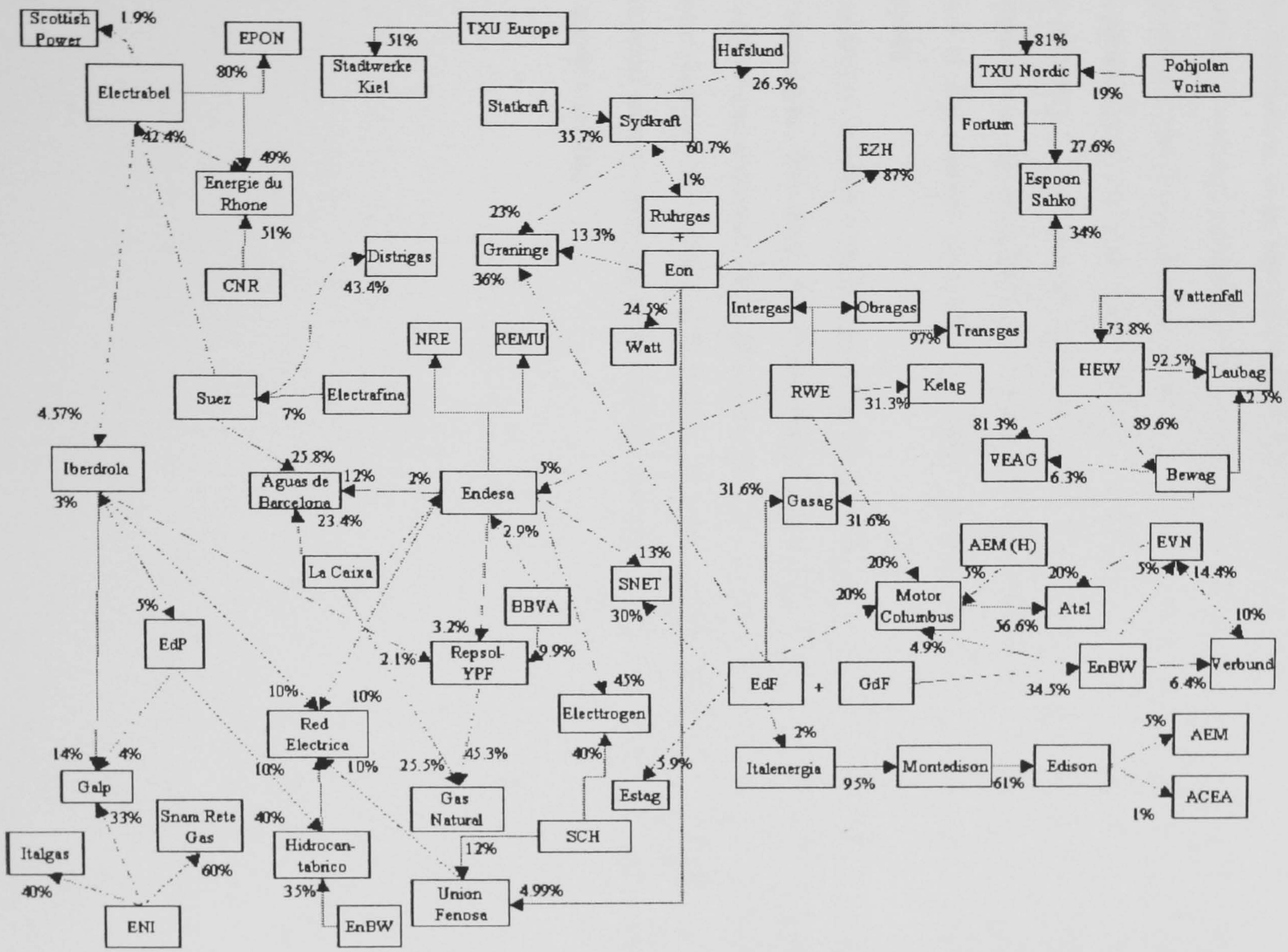

Figure 3-13: Cross-ownership in the European electricity industry (2001)

The relationship between electricity and natural gas is horizontal in that the two are close substitutes and sold through similar channels to the same end-users. However, they are also related vertically. Natural gas is often the fuel of choice in modern de-regulated electricity markets and hence, is an essential input for electricity generation.

Therefore, vertical integration is crucial to understanding competition in energy markets. Among others, the literature has characterised foreclosure mechanisms to exert vertical market power, prominently the "raising rivals' costs" argument, which might well apply to the European energy industry. This theory is based upon the vertically integrated firms' ability to price differentiate, e.g. through internalised trading. In voluntary markets, firms can decide whether to resort to the market or not and, if they do, choose the internal incentives that maximise their profit.

Mandatory markets could therefore limit the firms' ability to implement vertical market power strategies. However, the dichotomy between compulsory and voluntary trading mechanisms and its connection to how firms exert market power has received little scholarly attention. The next chapter covers part of that gap. A series of agent-based simulations characterise the coordination effects resulting from vertical incentives within a firm operating in a mandatory, multi-market setting.

Chapter 4

Incentive Breadth and Coordination in Vertically Related Energy Markets

4.1 Introduction

This essay[1] [2] studies the vertical interrelationships between gas and electricity markets. Vertical relationships are those that involve an exchange between sequential stages of the value chain. At the firm level, vertical interactions may involve either different strategic business units (SBUs) within the same firm or separate firms (Gulati et al., forthcoming).

In the energy industry, gas is an important input for electricity generation, and so wholesale natural gas and electricity markets are vertically interrelated. The same is true for wholesale and retail electricity markets (Stern, 1998). Vertical integration is widespread among European energy firms. Gas producers often own gas-fired power plants and many electricity firms consist of generation and retail SBUs (Midttun and Finon, 2004).[3]

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[1] Preliminary versions of this work were presented at the INFORMS-2004 (Denver) and European Doctoral Research (London) conferences and in research seminars at Gaz de France (Paris), Instituto de Empresa (Madrid), London Business School, Rotterdam School of Management and Unilever's Research Centre (Colworth, UK).

[2] This essay is co-authored by Albert Banal Estañol.

[3] Note that the discussion here is about separation between the buying and selling sides of the wholesale market and quite different from regulatory unbundling of transmission infrastructures which is also widespread in the energy industry.

Several streams of literature have studied the advantages as well as the disadvantages of vertical integration. Industrial economists have long argued that vertically related firms could strategically benefit from integrating.[4] Consider an intermediate market in which upstream and downstream firms interact. An integrated firm could gain market share and profits downstream by internalising production and refusing to sell (or selling at higher prices) to non-integrated downstream firms:

The firm's upstream opponents would exert more market power at the margin and increase prices, thereby raising the costs of non-integrated downstream firms. Higher costs would become a competitive disadvantage in the downstream market against the vertically integrated firm, resulting in lost market shares. Trading internalisation would then increase both upstream and downstream prices and lead to higher integrated firm profits.

Studies of vertical relationships in energy markets (e.g. Granitz and Klein, 1996; Bushnell et al., 2005) often explain their findings using this foreclosure argument. However, the "raising rivals' costs" or "foreclosure" logic depends crucially on the firm's ability to internalise transactions and / or price discriminate in favour of its downstream SBU. In practice, wholesale energy markets are often compulsory, so trading internalisation is not feasible. Moreover, the standard energy market mechanism is the uniform price auction, which seems to make price differentiation impossible at the outset. Thus, two of the main resting points of the raising rivals' costs logic are often not present in energy markets.

This essay shows that energy firms may benefit from vertical integration by using an alternative to foreclosure. The new mechanism is based on the presence of vertical incentives, which are widely used within energy firms, does not require internalisation or price discrimination and can be a way of circumventing regulatory constraints. One of the main contributions of this research is that although the new mechanism yields prices that are superficially equivalent to those of foreclosure, it operates in a fundamentally different manner.

The general reward system of an organisation plays a major role in the behavioural choices of its members. Bonuses tied to overall profits create incentives for cooperative behaviour both

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[4] Management scholars have also identified several motives for firms' to integrate vertically (Harrigan, 1984, 1986), including the reduction of transaction costs (Williamson, 1975; Mahoney, 1992), the reduction of corporate risk (Chatterjee et al., 1992), and the transmission of market information to the upstream stages of the value chain (Siggelkow and Levinthal, 2003).

between individuals (Zander and Wolfe, 1964; Wageman and Baker, 1997) and across departments within a firm (Petersen, 1992; Kretschmer and Puranam, 2004). For individuals, the more interdependent the task, the more interdependent should be the reward system (Wageman and Baker, 1997) because it results in a positive relationship between effectiveness of the integrative devices and organisational performance (Lawrence and Lorsch, 1967). For firms, the importance of cooperation between SBUs grows with their interdependence (Gulati and Singh, 1998) and the higher the inter-unit synergies, the more useful are the collaborative incentives (Kretschmer and Puranam, 2004). Collaborative incentives, however, not only encourage cooperation but may also enhance free riding. Indeed, rewards based on aggregate profits hinder the identification of individual performances. As a consequence, individuals have more incentives to shirk hoping that the others will compensate (Holmstrom, 1982; Petersen, 1992).[5]

Despite their importance, the existing literature provides no guidance as to how collaborative incentives should be given to sequential SBU's in vertically integrated energy firms. The simulations will show that coordination overcomes the potential disadvantages of broad collaborative incentives due to the large interdependences between energy markets.

The simulation setting consists of three sequential multiple-unit auctions representing a wholesale gas market, a wholesale electricity market and a retail electricity market. Although quite realistic, this complex trading environment presents a manifold of non-Pareto ranked equilibria (von der Fehr and Harbord, 1983).

A Roth and Erev (1995) reinforcement learning simulation uncovers a simple but powerful mechanism to exert vertical market power. Using collaborative incentives that link the reward to the performance of the different SBUs, vertically integrated firms achieve higher prices and higher profit. These observable outcomes are consistent with the foreclosure argument. Closer inspection, however, reveals that the downstream SBU behaves less competitively, increasing downstream prices instead of taking advantage of the rivals' higher costs. Moreover, the upstream SBU behaves more competitively and takes advantage of the higher downstream prices. Rather than foreclosure, the results are due to a financial netback effect connecting the different markets: downstream prices set the scope for the monetisation of upstream assets. This out-

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[5] Broad incentives could also obstruct learning since it is more difficult to identify the most successful business strategies.

come emerges also in the compulsory, uniform price auctions and is robust to different industry specifications.

The remaining of the essay is organised as follows. Section 4.2 outlines the agent-based simulation model. Section 4.3 presents the results, which are discussed in Section 4.4. A short discussion follows in 4.5.

4.2 The Computational Model

4.2.1 General Setting

The model incorporates key features of electricity and gas markets in the short-run. Consider three sequential, oligopolistic, energy markets, a "wholesale gas market", a "wholesale electricity market" and a "retail electricity market". Gas sold in the wholesale gas market is an input for the generation of the electricity traded in the wholesale electricity market that, in turn, is sold to end users in the retail market. In the gas market, there are A upstream "natural gas shippers" that sell gas to B "electricity generators". These generators buy gas to produce electricity and sell it in the electricity market to C "electricity retailers". These, in turn, re-sell the electricity in the end-user market.[6] Marginal costs are assumed to be constant throughout and normalised to 0 for simplicity. There are no transmission constraints or storage.

Firms are capacity constrained and total capacity is equal across tiers. Moreover, firms in each tier are identical. If one denotes market capacity as K^m, the individual capacity of a gas shipper is $K^g = \frac{K^m}{A}$, of an electricity generator is $K^e = \frac{K^m}{B}$ and of an electricity retailer is $K^r = \frac{K^m}{C}$.

4.2.2 Market Rules

Goods are traded repeatedly along a value chain (Figure 4-1). In a given round t, three uniform price auctions take place sequentially, at the retail, wholesale electricity and wholesale gas levels. In each market i, $i \in \{r, e, g\}$, trading occurs as follows. Suppliers submit simultaneously single price bids from $[0, \overline{P}^i(t)]$ at which they are willing to sell (up to) their capacity. An independent

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[6] Although relevant in the medium term, we do not deal with entry and exit of firms, variation in end-user demand or capacity expansion.

auctioneer determines a uniform market price ($P^i(t)$) by intersecting the *ad hoc* supply function with the corresponding inelastic demand curve, $Q^i(t)$. The independent auctioneer assigns full capacity, $q^i(t) = K^i$, to the m sellers that submitted bids below the market price; the remaining capacity, $q^i(t) = Q^i(t) - mK^i$, to the retailer that submitted a bid equal to the market price;[7] and zero sales, $q^i(t) = 0$, to the retailers that submitted bids above the retail market price. The market price and the individual quantities are communicated independently to each supplier.

At the retail level, the inelastic market demand $Q^r(t)$ is drawn, independently in each round, from a uniform distribution in $[\bar{Q}^r - \varepsilon,\ \bar{Q}^r + \varepsilon]$, where $\bar{Q}^r$ is the expected end-user demand and ε accounts for the small uncertainty typical in day-ahead electricity forecasting.[8] Possible retail prices are bounded in $[0, \Psi]$, with Ψ being the maximum "reasonable end-user price".[9] Retail commitments are honoured with purchases in the wholesale electricity market. The retailers' aggregated demand curve in the wholesale electricity market is therefore equal to the market demand at the retail level if the price is below the retail market price, $Q^e(t) = Q^r(t)$ if $P^e(t) \leq P^r(t)$, and zero otherwise, $Q^e(t) = 0$ if $P^e(t) > P^r(t)$. Accordingly, electricity generators submit bids bounded between $[0, P^r(t)]$. The generators' aggregated demand curve in the wholesale gas market is equal to the market demand at the retail level if the price is below the wholesale electricity market price, $Q^g(t) = Q^r(t)$ if $P^g(t) \leq P^e(t)$, and zero otherwise, $Q^g(t) = 0$ if $P^g(t) > P^e(t)$. Gas shippers submit bids bounded between $[0, P^e(t)]$.

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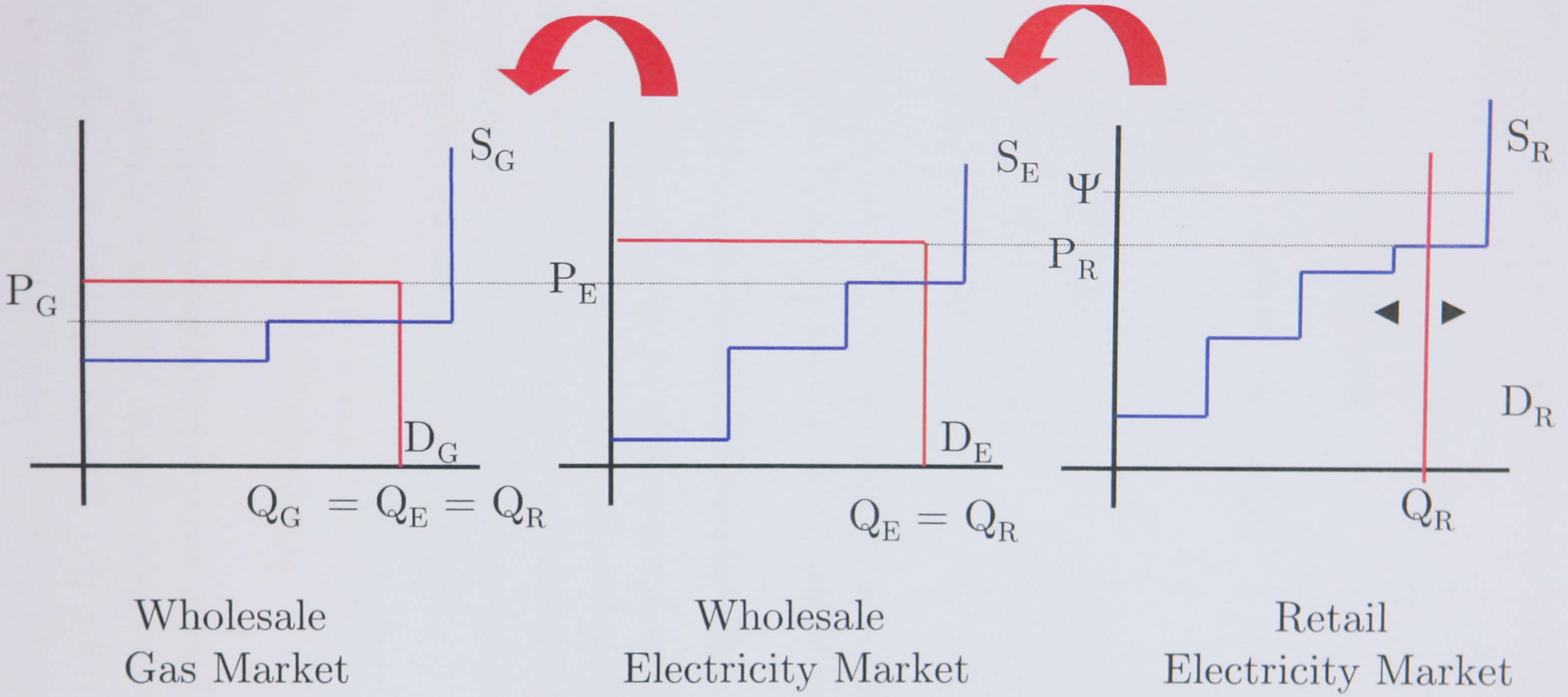
[7] In case of a tie, the selling firm is selected randomly.

[8] Similarly to real electricity markets, the model also includes some excess capacity, i.e. $\bar{Q}^r + \varepsilon < K^{rn}$.

[9] This upper price ceiling can be understood as a limit triggering regulatory intervention or the cost of alternative, expensive, peaking load fuels to which the system administrator could switch at short notice if gas prices exceeds Ψ.



Wholesale
Gas Market

Wholesale
Electricity Market

Retail
Electricity Market

Figure 4-1: Market clearing sequence

By construction, the end-user market demand in each round t determines the volumes traded in the wholesale markets,

$$Q^g(t) = Q^e(t) = Q^r(t).$$

Moreover, the three prices are vertically related,

$$P^g(t) \leq P^e(t) \leq P^r(t).$$

Profits for each firm type are

$$\begin{aligned} \pi_a^g(t) &= P^g(t)\ q_a^g(t) && \text{for } a = 1...A && (4.1)\\ \pi_b^e(t) &= [P^e(t) - P^g(t)]\, q_b^e(t) && \text{for } b = 1...B && (4.2)\\ \pi_c^r(t) &= [P^r(t) - P^e(t)]\ q_c^r(t) && \text{for } c = 1...C. && (4.3) \end{aligned}$$

There are apparently no other multi-tier simulations driven by netback principles in the energy modelling literature. This new method is the essay's main methodological contribution.

4.2.3 Vertical Integration and Reward Interdependence

In the basic model, it is assumed that a shipper (without loss of generality, $a = 1$) and a generator ($b = 1$) are vertically integrated in that they belong to the same organizational structure, i.e. the same firm. Trading is compulsory and firms are not allowed to price discriminate. However, the vertically integrated firm can influence its traders' decisions by giving them incentives that depend on the profits of their own unit but also on the other unit,

$$\begin{aligned} \Omega_1^g(t) &= (1-\alpha)\pi_1^g(t) + \alpha\pi_1^e(t) \text{ and} && (4.4)\\ \Omega_1^e(t) &= (1-\alpha)\pi_1^e(t) + \alpha\pi_1^g(t), && (4.5) \end{aligned}$$

where $\alpha = \{0, .01, .02, ..., .5\}$ parameterises the "reward interdependence" (Wageman and Baker, 1997) between the two vertically related SBUs. A small α represents narrow incentives, which become broader for growing α. Note that for $\alpha = 0$, $\Omega_1^g(t) = \pi_1^g(t)$ and $\Omega_1^e(t) = \pi_1^e(t)$, and SBUs trade as if they were independent. For tractability and realism, the model is restricted to the case in which SBUs are rewarded predominantly on the basis of their own performance. i.e. $\alpha \leq 0.5$.

Managers in the non-integrated firms do not have reward interdependences so their incentives are correlated to their own unit performance,

$$\Omega^i_j(t) = \pi^i_j(t) \text{ for either } i = \{g, e\} \text{ and } j \neq 1 \text{ or } i = r \text{ and any } j. \tag{4.6}$$

4.2.4 Bidding and Behavioural Learning

The feasible price offer domain for each firm is approximated by a discrete grid consisting of a fixed number of possible actions (independent of t). In each trading period, suppliers choose among S_i possible prices, equally spaced between the minimum and the maximum "reasonable" price offer, $[0, \overline{P}^i(t)]$, where $\overline{P}^r(t) = \Psi$, $\overline{P}^e(t) = P^r(t)$ and $\overline{P}^g(t) = P^e(t)$. Hence, the set of possible actions, A^i at a tier i in a period t is given by

$$A^i(t) = s * \left(\frac{\overline{P}^i(t)}{S_i}\right) \; for \; s = 1, ..., S_i. \tag{4.7}$$

Notice that in the wholesale markets, the sets of possible prices change over time. In all markets, actions with a lower "s" are more competitive or closer to the marginal costs.

The R&E application is similar to the one used in double sided crossholdings model. Each trader plays each possible action with a given likelihood or "propensity", $r^i_{j,s}$. The probability that an agent j plays an action s is given by its propensity divided by the sum of the propensities of all possible actions,

$$p^i_{j,s}(t) = \frac{r^i_{j,s}(t)}{\sum_{s=1}^{S^i} r^i_{j,s}(t)}. \tag{4.8}$$

Propensities for all actions are initialized to the firms' maximum profit, i.e. $r^i_{j,s}(1) = \Psi K^i$ for all s, so that all actions have the same initial probability, $p^i_{j,s}(1) = \frac{1}{S^i}$ for all s and i.

At the end of each round, traders reinforce the selected action, k, through an increase in its propensity by $\Omega^i_j(t)$. Moreover, actions that are similar, i.e. $k-1$ and $k+1$, are also reinforced, by $\Omega^i_j(t) * (1 - \delta)$ where $0 < \delta < 1$ ("persistent local experimentation"). All propensities are discounted by γ ("gradual forgetting") and actions whose probability falls below a certain threshold are removed from the space of choice ("extinction in finite time"). The pre-extinction propensities $r^{i\prime}_{j,s}$ are

$$r^{i\prime}_{j,s}(t) = \begin{cases} (1-\gamma)r^{i}_{j,s}(t-1) + \Omega^{i}_{j}(t) & \text{if } s = k \\ (1-\gamma)r^{i}_{j,s}(t-1) + (1-\delta)\,\Omega^{i}_{j}(t) & \text{if } s = k-1 \text{ or } s = k+1 \\ (1-\gamma)r^{i}_{j,s}(t-1) & \text{if } s \neq k-1,\ s \neq k \text{ and } s \neq k+1 \end{cases} \tag{4.9}$$

Then, the propensities are corrected by Roth and Erev's (1995) "extinction" feature,

$$r^{i}_{j,s}(t) = r^{i\prime}_{j,s}(t) I_{\{\frac{r^{i\prime}_{j,s}(t)}{\sum_{s=1}^{S^i} r^{i\prime}_{j,s}(t)} > \mu\}} \tag{4.10}$$

where I is an indicator function that takes value 1 if the condition is satisfied and 0 otherwise.

There are two differences between this application and that of the crossholdings essay. First, this model is of sequential single sided auctions and there is therefore no demand side reinforcement. Second, the set of considered strategies was previously constant but in this simulation varies depending on the applicable $\overline{P}^{i}(t)$.

4.2.5 Simulation Parameters

In the first instance, industry structure is simplified to consist of two gas shippers, three generators and four retailers (i.e. $A = 2$; $B = 3$; $C = 4$). Gas shippers will be referred to as G_1 and G_2, generators as E_1, E_2 and E_3 and retailers as R_1, R_2, R_3 and R_4. In the base case, the two vertically integrated entities are G_1 and E_1. Total capacity is set to $K^m = 300$, so that the individual capacity of a gas shipper is $K^g = 150$, of an electricity generator is $K^e = 100$ and of an electricity retailer is $K^r = 75$. Expected market demand is $\bar{Q}^r = 240$ and $\varepsilon = 5$, so that there is an expected excess capacity of 20% with about 5% uncertainty in the day-ahead forecasted demand, approximately of the magnitude observed in energy markets. The end-user "reasonable" price ceiling is set at $\Psi = 200$.

Fifty-one reward interdependence cases $\alpha = \{0, .01, .02, .03, ..., .50\}$ are studied and 50 simulation runs[10] consisting of 500 periods were carried out for each of them. The data presented

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[10] The fact that these simulations include one-sided auctions simplifies significantly the market clearing protocol. Due to that, the simulation is more efficient than that of chapter 3 and so that I can include more simulation runs.

consists of averages for the last 200 periods, for each run and each case. These represent long term stationary values[11] to which the three markets converge, based on the R&E reinforcement parameters.[12]

4.3 Results

4.3.1 Market Prices and Profits

Figures 4-2, 4-3 and 4-4 report the 95% mean confidence intervals of simulated prices in the three sequential markets when G_1 and E_1 are vertically integrated. They present the relationship between reward interdependence α (on the horizontal axis) and P^g, P^e and P^r (on the vertical axis), respectively. As shown by Figure 4-2, shippers coordinate on higher prices as α grows. No reward interdependences ($\alpha = 0$) result in an average gas price of approximately 59 monetary units, which increases to about 63 units for $\alpha = .50$. Figure 4-3 shows that wholesale electricity prices are also clearly influenced by α. When $\alpha = 0$, the simulation produces an average price of about 83 units, for $\alpha = .50$ it is about 93. Finally, Figure 4-4 presents retail price levels not varying systematically as a function of α. The structure of incentives in the vertically integrated firm does not influence P^r.

By construction, the expected absolute size of the resource rent shared by the three market tiers is constant ($= \Psi\bar{Q}^r$). What changes is the proportion accruing to each of them. Increasing P^g with constant production costs results in a higher proportion of the rent staying with the gas duopoly. Taking Figures 4-2, 4-3 and 4-4 together, P^e increases compensate to some extent the higher P^g, but that is not the case for P^r. Market prices seem to indicate that generators and, particularly, retailers are subject to shippers foreclosure emerging from reward interdependences between G_1 and E_1.

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[11] Augmented Dickey-Fuller (ADF) reject the null unit root hypotheses with $p < .01$.

[12] The R&E parameters used throughout are $\gamma = 0.01$, $\delta = 0.5$ and $\mu = 0.0005$.

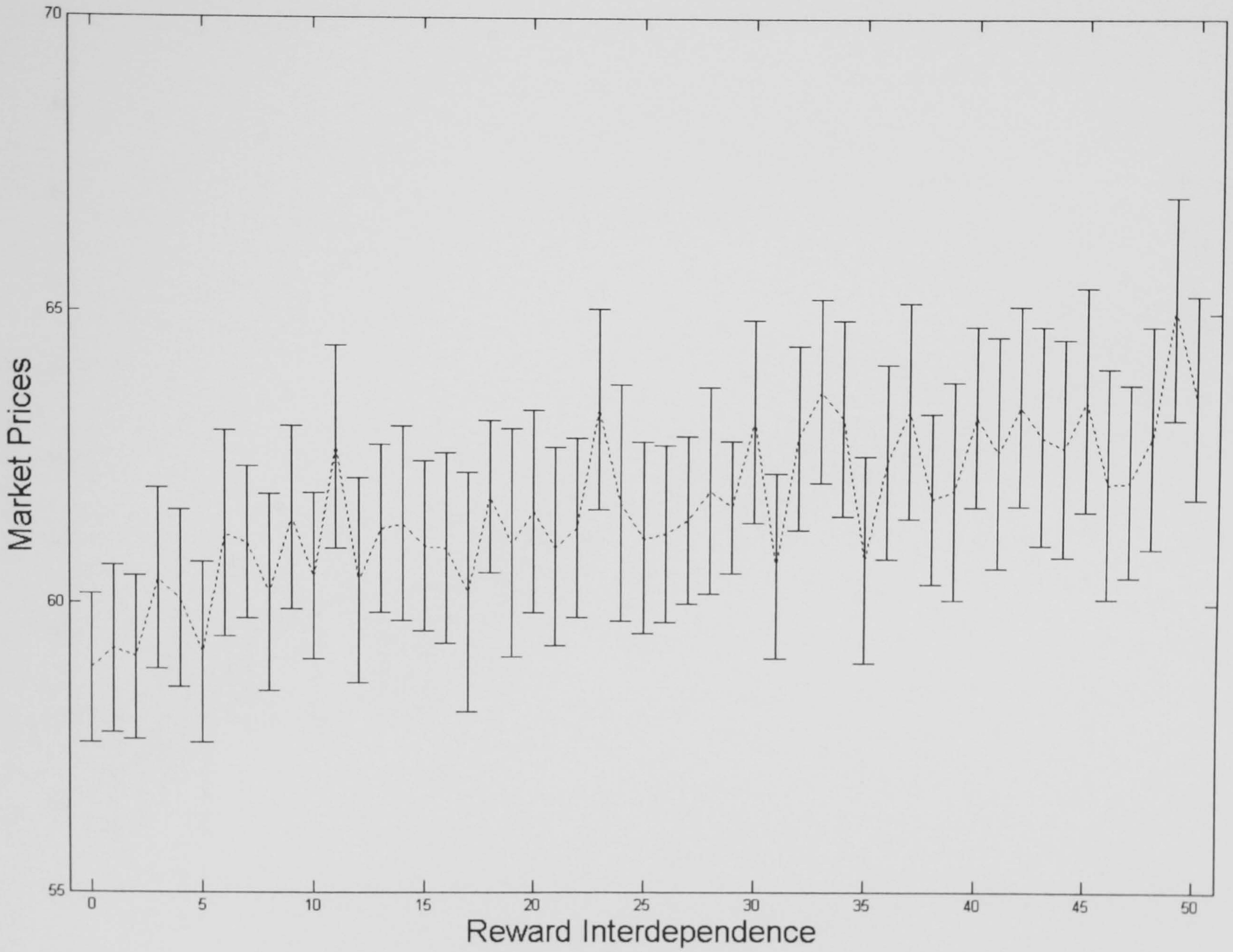


Figure 4-2: Natural gas prices, base case, $\alpha = 0$ to $\alpha = .5$

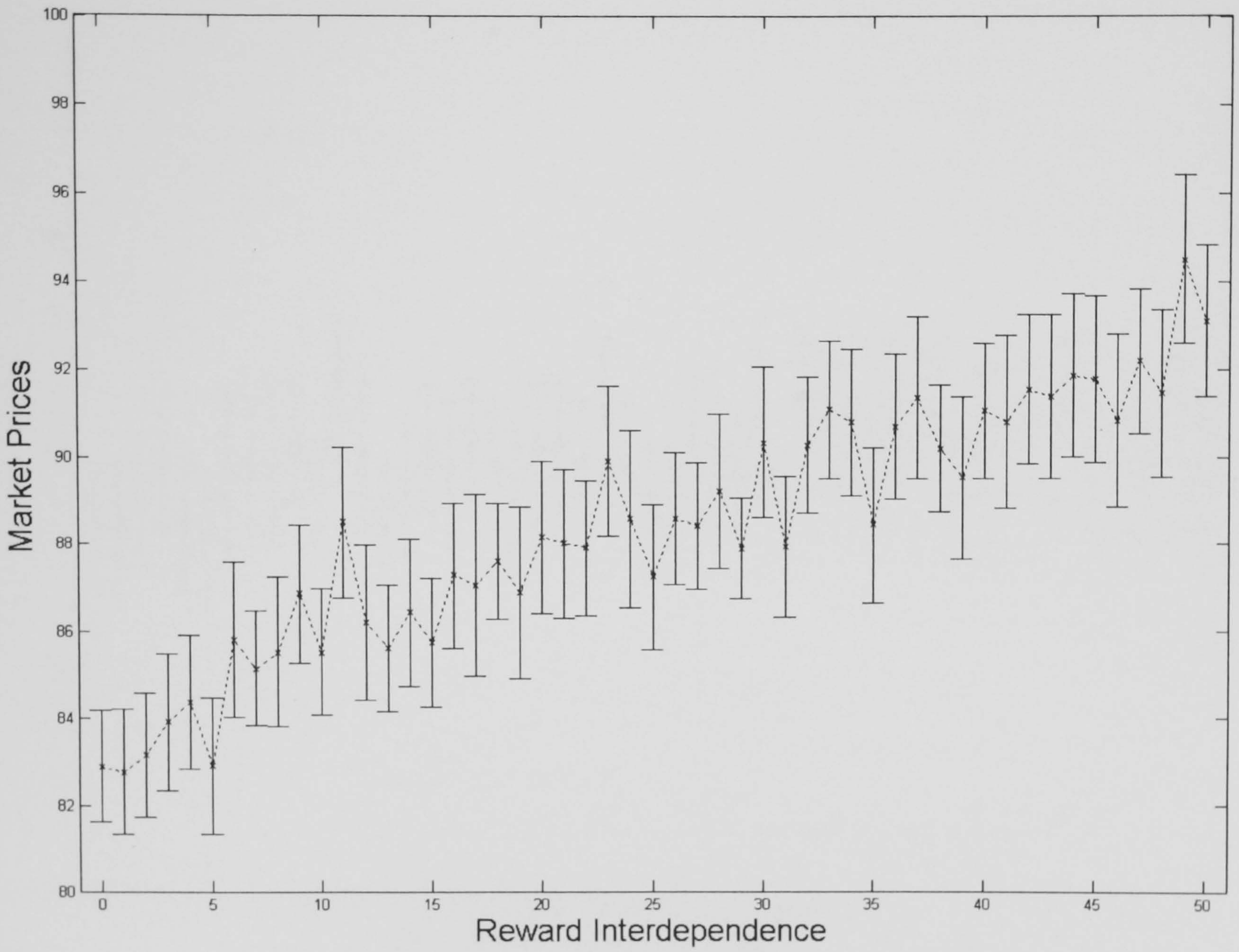


Figure 4-3: Wholesale electricity prices, base case, $\alpha = 0$ to $\alpha = .5$

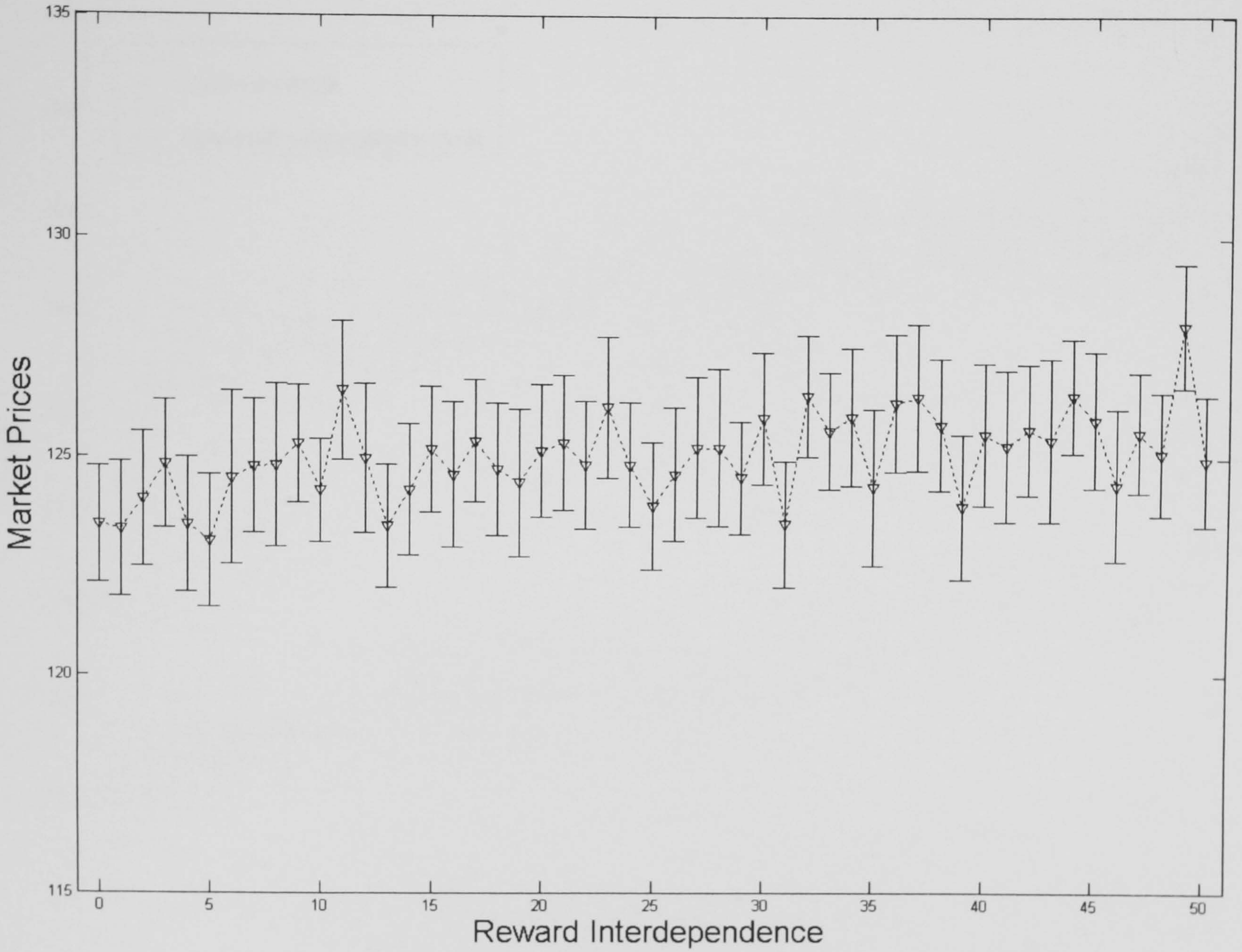


Figure 4-4: Retail prices, base case, $\alpha = 0$ to $\alpha = .5$

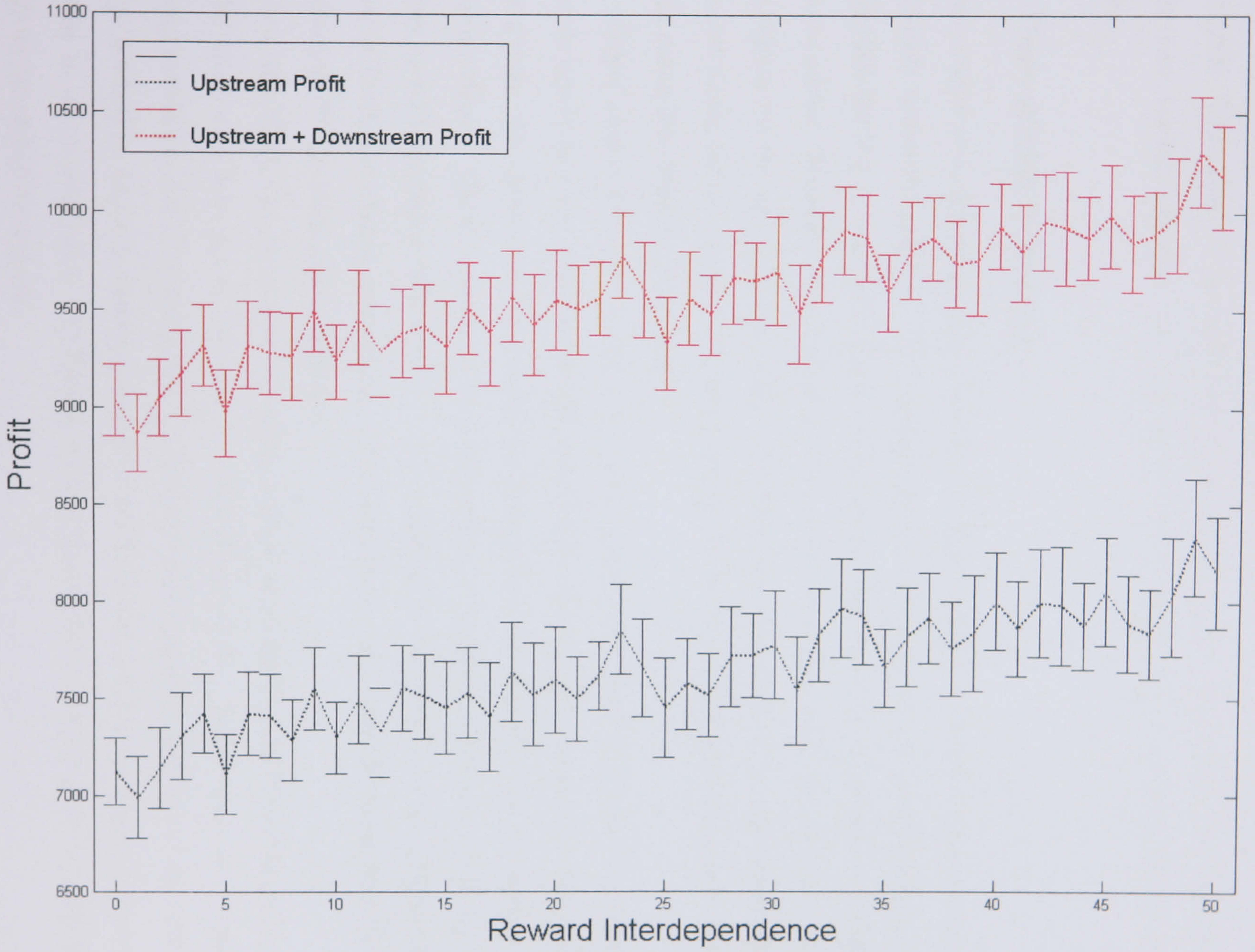


Figure 4-5: Profit vertically integrated firm , base case, $\alpha = 0$ to $\alpha = .5$

Moreover, α influences both the profits of the vertically integrated firm and its two SBUs (Figure 4-5). Broader vertical incentives increase the G_1's profit but decrease those of E_1. The resulting overall corporate profit $(\pi_1^g + \pi_1^e)$ is clearly increasing from about 9,000 monetary units to over 10,000. Thus, there is a positive relationship between vertical reward interdependence across the two strategic business units, the firm's overall profit and the concentration of profit upstream.

4.3.2 Price-setting Behaviour

The raising rivals' cost logic requires G_1 and E_1 to concede market power (i.e. increase market share) in their respective markets. In a uniform price auction, prices are determined only by those bids that are last on the merit order, and so being marginal seller is a necessary condition to influence prices. Therefore, the frequency with which each firm takes the marginal price-setting position on the supply merit order represents one dimension of its predisposition to exert market power (at the expense of market share). In the foreclosure logic, G_1 and E_1 would be setting prices less often for increasing α.

The vertical axes in Figures 4-6 and 4-7, provide averages over the frequencies with which each market player sets the price in the 200 end-of-simulation periods averaged across the 50 simulation runs. An increase in the reward interdependence between G_1 and E_1 creates two simultaneous effects. On the one hand, the proportion of trading periods in which G_1 sets prices goes down from about 50% when $\alpha = 0$ to around 41%, when $\alpha = 0.5$ (Figure 4-6). Consistent with the foreclosure predictions, reward interdependence provides incentives for the G_1 to influence P^g less often and benefit G_2.

On the other hand, the proportion of trading periods in which E_1 is price-setting increases from 33% when $\alpha = 0$ to about 50% for $\alpha = 0.5$ (Figure 4-7). Hence there is a positive relationship between α and E_1's predisposition to exert market power, which is ***at odds*** with the foreclosure prediction. Since E_1 bidding behaviour results in lower $\pi(E_1)$ but higher $\pi(G_1 + E_1)$, there seems to be an alternative mechanism to foreclosure that, operating via α, links E_1's behaviour to the overall firm profit.

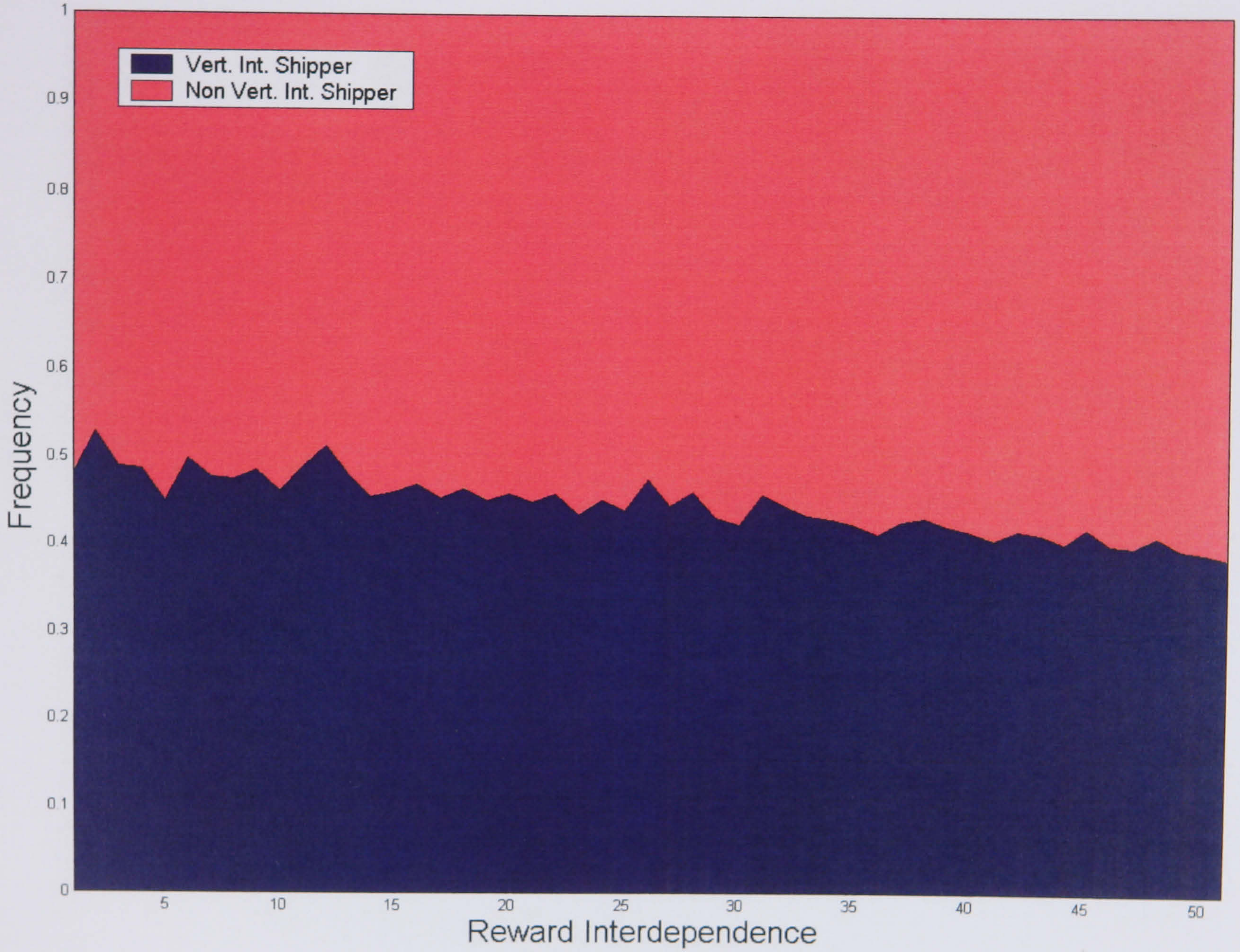


Figure 4-6: Shippers' price-setting frequencies, base case, $\alpha = 0$ to $\alpha = .5$

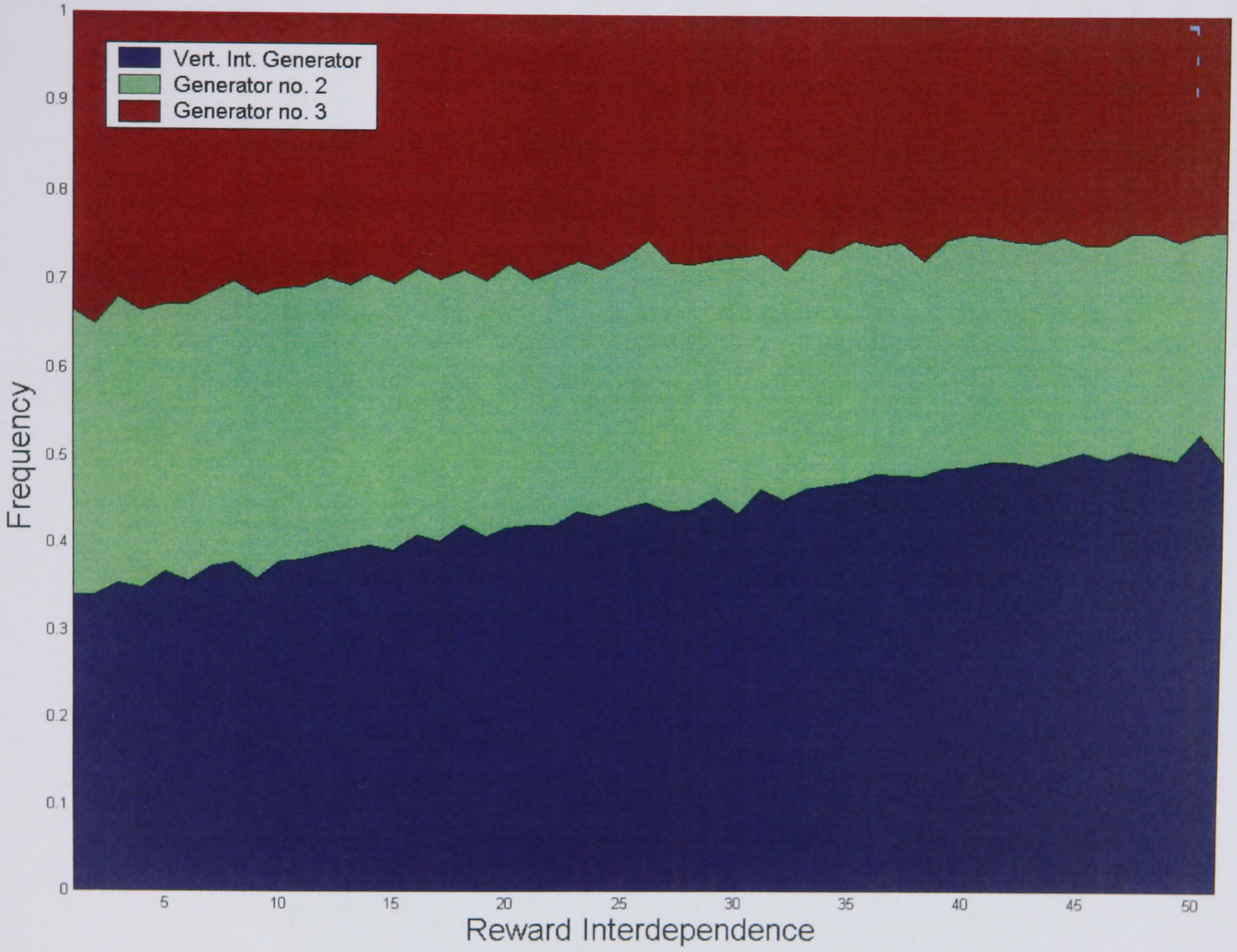


Figure 4-7: Generators' price-setting frequencies, base case, $\alpha = 0$ to $\alpha = .5$

4.3.3 Latent Intensity of Competition

Figures 4-8 and 4-9 characterise the S_i end-of-simulation individual latent probability distributions from which agents choose. The concentration of probabilities is largely invariant across a large number of periods once the market reaches convergence, so the distributions at $t = 500$ are an indication of the firms' long-term mixed strategies.

On the horizontal axes, strategies are identified with numbers ranging from 1 for the more competitive to 100 for the highest possible bid. Cumulative probabilities for the three tiers are calculated on the vertical axes for each element of the strategy space. The curves summarise the cumulative bidding probabilities for $\alpha = 0$ and $\alpha = 0.5$, averaged across the 50 simulation runs. In all cases, probabilities concentrated on lower (higher) strategies result on the agents behaving more (less) competitively. That is, curve movements to the "Northwest - NW" and "Southeast - SE" are indications of more and less competition, respectively. The figures offer a number of insights linking individual probability distributions to market outcomes:

(a) The shippers' distributions are very similar under $\alpha = 0$ but become different under $\alpha = 0.5$ (Figure 4-8). Reward interdependence incentives in the vertically integrated firm have the effect of making G_1 bids more competitive (NW movement). Moreover, G_2's prior is slightly less competitive (movement to SE). Gas firms behave as predicted by the foreclosure argument and concentrate market power on G_2.

(b) Probability distributions on the generator's side are similar for all firms under $\alpha = 0$ (Figure 4-9). However, when $\alpha = 0.5$, E_1 tends to exert more market power than that of its competitors, E_2 and E_3 (movement to the SE). This does not fit into the raising rivals' costs logic and suggests that the coordination mechanism is driven by reward interdependences and the ability of the generating SBU to benefit from higher natural gas prices.

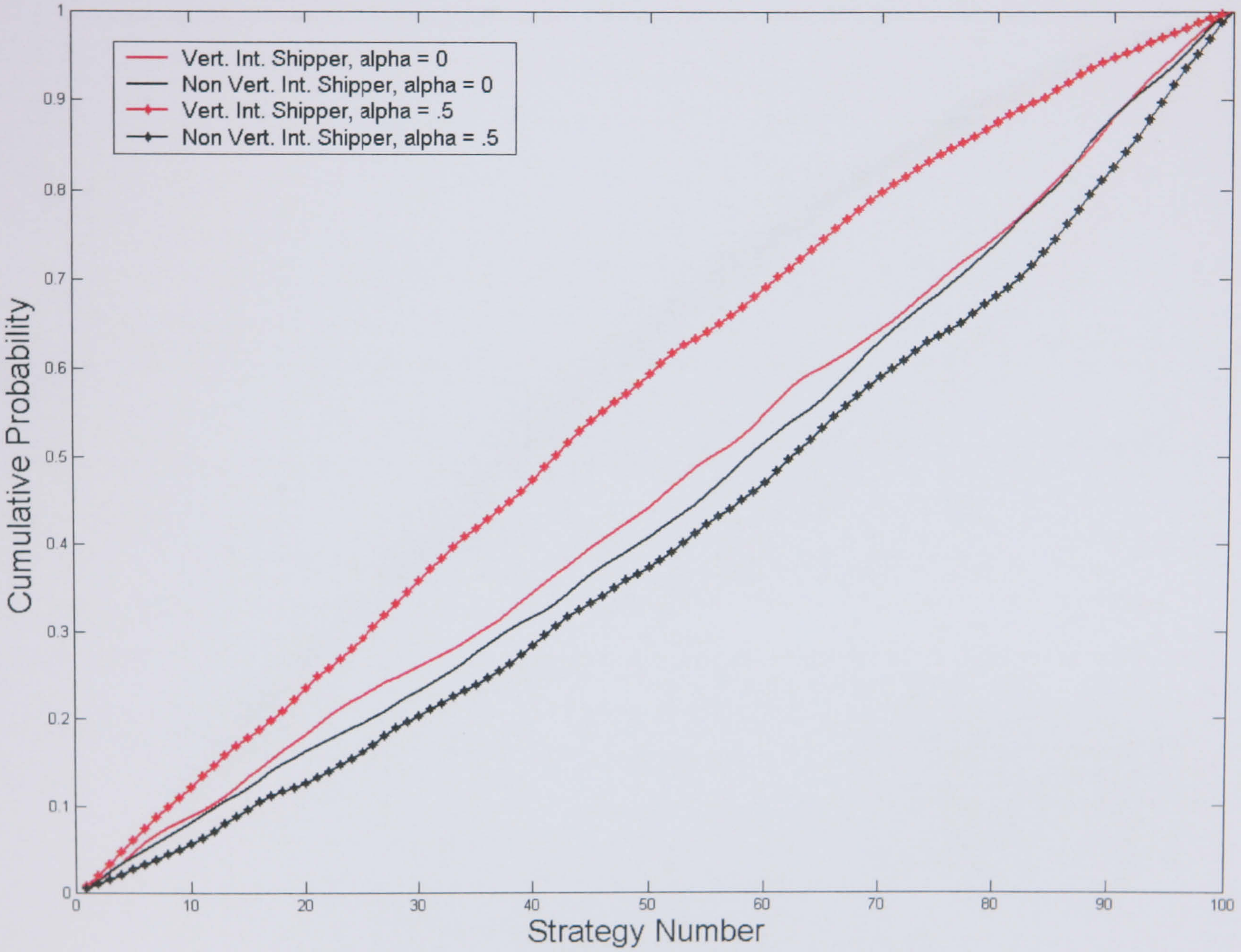


Figure 4-8: End of simulation distribution of strategies, shippers, $\alpha = 0$ and $\alpha = .5$, base case

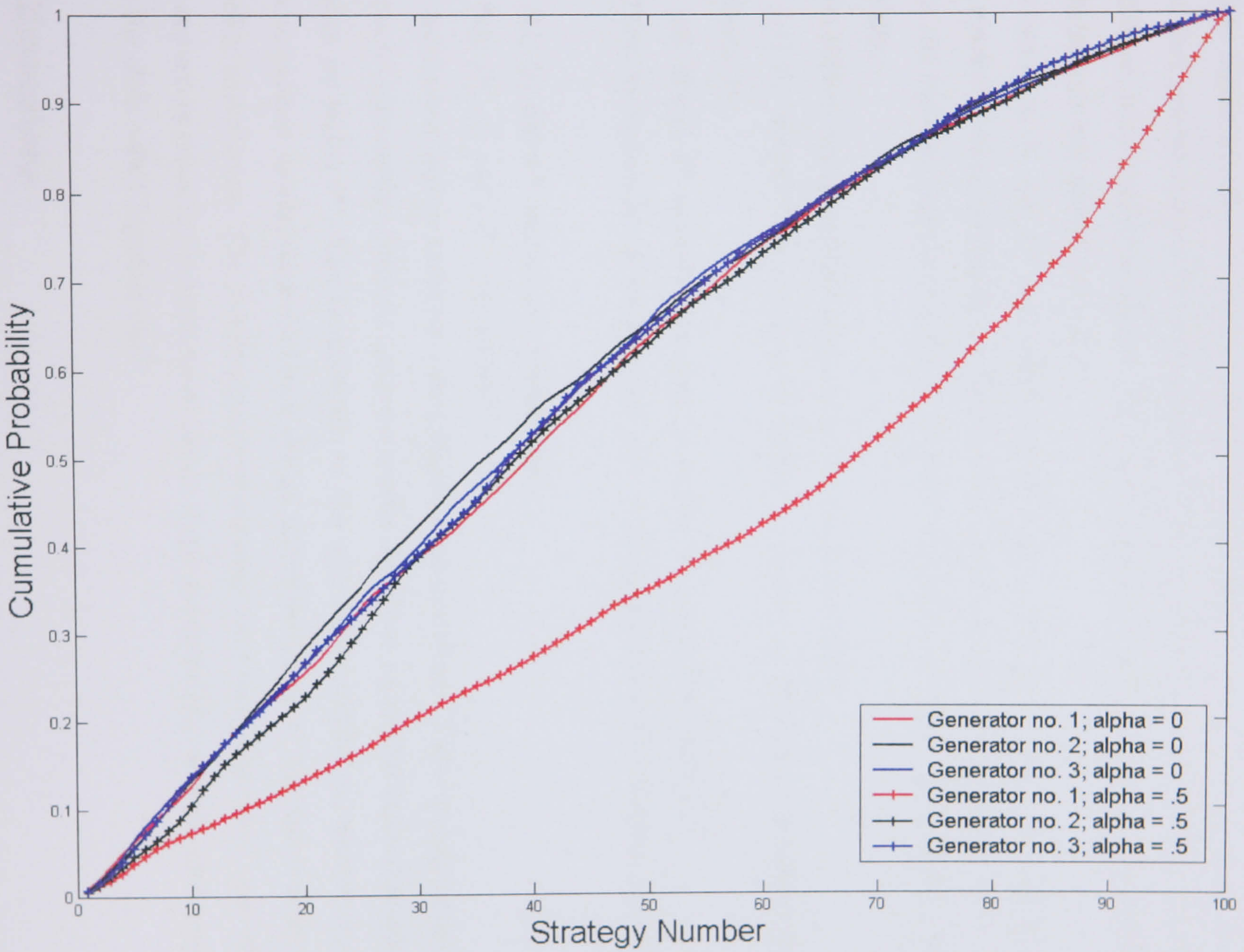


Figure 4-9: End of simulation distribution of strategies, generators, $\alpha = 0$ and $\alpha = .5$, base case

4.3.4 Linking Firm Learning to Behaviour and Market Outcomes

Through their dynamic trading interaction, firms learn to prioritise those bidding strategies that achieve higher payoffs and choose them more often. Each firm's price setting frequency is related to that prioritisation of the strategies and, once marginal supply and demand patterns are established, price regularities follow. The results suggest a link between α, firm learning, trading behaviour and market outcomes.

As α increases, E_1 sets P^e more often and manages to increase it markedly. Due to the netback market clearing procedure, a higher P^e provides more scope for higher P^g's. G_1 trades on the base-load more often which increases its market share and profitability. More synthetically:

(a) By bidding higher than its competitors, E_1 causes two effects

(a1) E_1 brings P^e up, being at the margin more often at the expense of market share, which reduces π_1^e;

(a2) Higher P^e increases the scope for higher P^g (since $P^g \in [0, P^e]$);

(b) Then, by remaining on the base-load part of the supply curve, G_1 increases its market share;

(b1) G_2 sets P^g exerts more market power;

(b2) P^g, π_1^g and $(\pi_1^g + \pi_1^e)$ increase.

The simulations' logic is therefore quite different from foreclosure. The vertically integrated firm learns to gain market share in upstream market and gives up market share downstream in exchange for higher P^e. The identification of this mechanism relating the market clearing sequence to vertical coordination via broad reward interdependences is this essay's main economic policy contribution. The coordination does not arise due to a raising rivals' costs effect. Rather, appears to relate to the interrelated nature of gas and electricity markets, made explicit through the often called "spark-spread".

4.4 Extensions

This section checks whether the results depend on the position of the vertically integrated SBUs in the value chain and on the market concentration levels.

	$\mathbf{P}^g$	$\mathbf{P}^e$	$\mathbf{P}^r$
$\alpha = 0$	59	83	124
$\alpha = .5$			
[1, 1, 0]	63	93	125
	+6.77%	+12.04%	+0.88%
[1, 0, 1]	67	95	144
	+15%	+14.45%	+16.12%
[0, 1, 1]	63	88	136
	6.77%	6.02%	9.67%

Table 4.1: Average Prices, A=2; B =3; C=4

4.4.1 Position of the Vertically Integrated Firm

New simulations analyse "reward interdependences" between between G_1 and E_1 plus those between E_1 and R_1, keeping constant all other parameters. For ease of exposition and comparison between cases, the case in which vertical generation occurs within the electricity industry (between generation and retail activities) is referred to as [0, 1, 1]. The basic situation in which the one shipper and one generator are integrated is [1, 1, 0] and where the shipper is integrated with the retailer, [1, 0, 1]. Table 4-1 and Figures 4-10 and 4-11 summarize results for $\alpha = 0$ and $\alpha = .5$ in these new simulations.

Integration between G_1 and E_1 [1,0,1]

Two interesting findings emerge from the simulations, complementing and extending the previous results:

Retail Prices Increase. P^r increases from about 124 for $\alpha = 0$ to 144 when $\alpha = .5$ (+16.12%), compared to a negligible change in the [1,1,0] simulation (+0.88%). Reward interdependence with G_1 induces R_1 to implement a less competitive–more collusive- mixed strategy through which the firm becomes price setting more often with P^r increasing steadily (Figure 4-10).

Wholesale Prices Increase. The P^r effect moves up in the value chain. It translates into higher P^e and P^g from about 83 to 95 (+14.45) and 59 to 67 (+15%), respectively. Reward interdependences hurt end users in this case. Although the E_1, E_2, E_3 probability priors and trading behaviour change little, G_1 becomes more competitive and facilitates the exertion of G_2 market power (upper panels, Figure 4-10). That effect results in a $P^e - P^g$ difference similar to

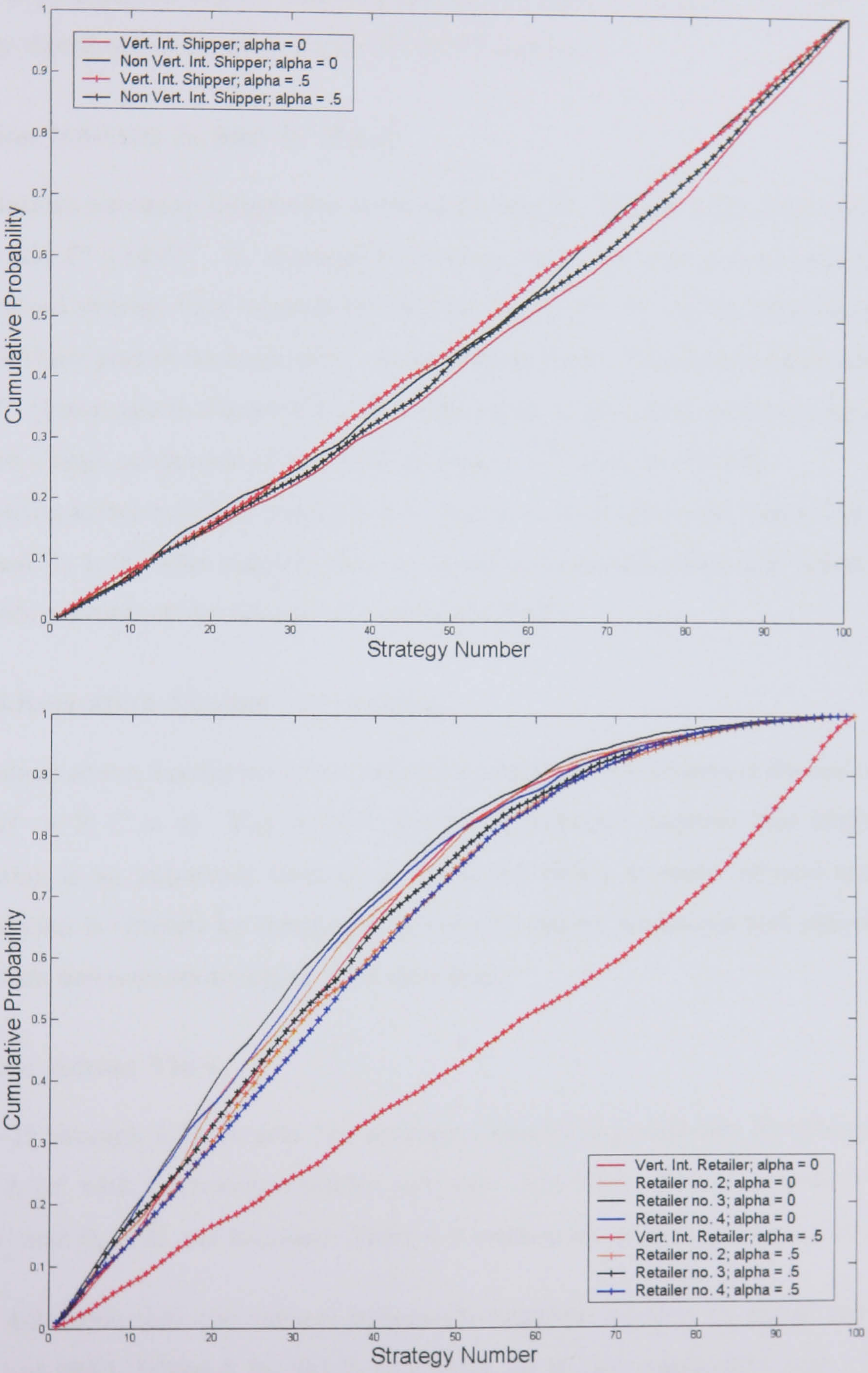


Figure 4-10: End of simulation distribution of strategies, shippers and retailers, $\alpha = 0$ and $\alpha = .5$, [101]

that of the [1,1,0] case. Moreover, by construction, higher P^r widens the $[0, P^r]$ range within which P^e is determined. With a constant number of bidding strategies, S_i, similar generators' probability distributions result in higher P^e as P^r increases.

Integration between E_1 and R_1 [0,1,1]

The simulations assuming integration between E_1 and R_1 (Figure 4-11) show increases in P^e (+6.02%) and P^r (+9.67). R_1 manages to leverage its overall revenue and implement a more collusive mixed strategy that expands the base for higher P^e. E_1, on the other hand, bids more often on the base part of the load curve – more competitively. That results in E_2 and E_3 setting (higher) P^e (lower panels, Figure 4-10). It is interesting to note how the non-integrated G_1 and G_2 capture a large proportion of that rent through a P^g increase of 6.77%.

Comparing across $\alpha = 0.50$ cases, [1, 0, 1] results in the highest end user prices followed by [0, 1, 1] and [1, 1, 0]. This suggests that the α effect on market prices also depends upon the supply chain position of the vertically coordinated SBUs.

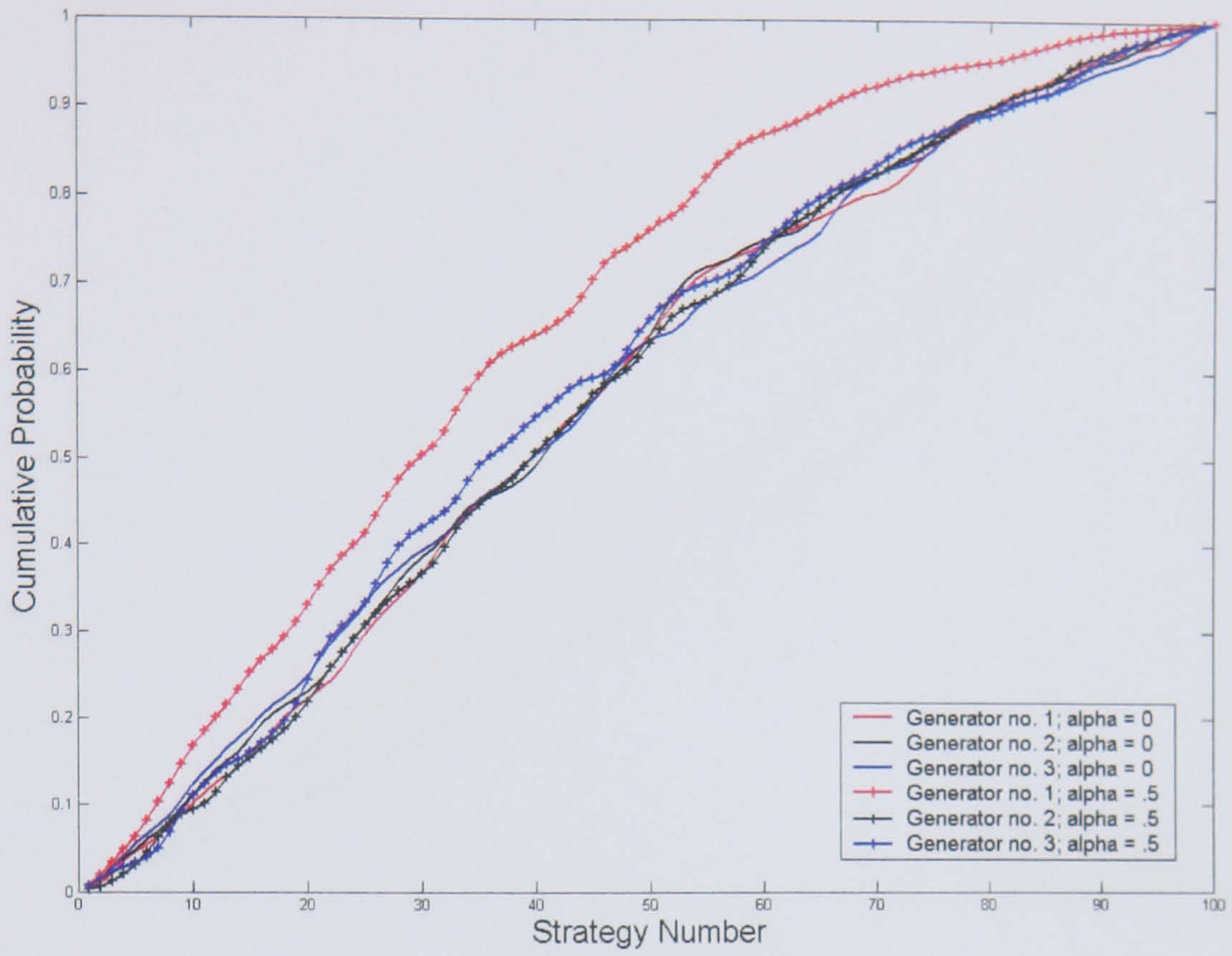
4.4.2 Alternative Market Structures

In the analysis above, market structure remained invariable and progressively less concentrated ($A = 2$; $B = 3$; $C = 4$). The vertical foreclosure literature suggests that higher upstream concentration is an important element of the firms' ability to exert vertical market power. This conclusion is checked by simulating symmetric market structures and also one in which concentration downstream is higher than upstream.

Symmetric Across Tiers

Figures 4-12 through 4-14 present the strategy cumulative probability distributions for $A = B = C = 2$, i.e. with a symmetric market structure. The three vertical integration cases, [1, 1, 0], [1, 0, 1] and [0, 1, 1], are included. Table 4-2 summarises market prices in this setting.

Table 4-2 shows that the vertical integration structure leading to higher end user prices is [1,0,1] (+4.89%), followed by [0,1,1] (+2.79%), as in the asymmetric case. The vertical integration structures involving R_1 lead to higher P^r. These results strengthen the chapter's



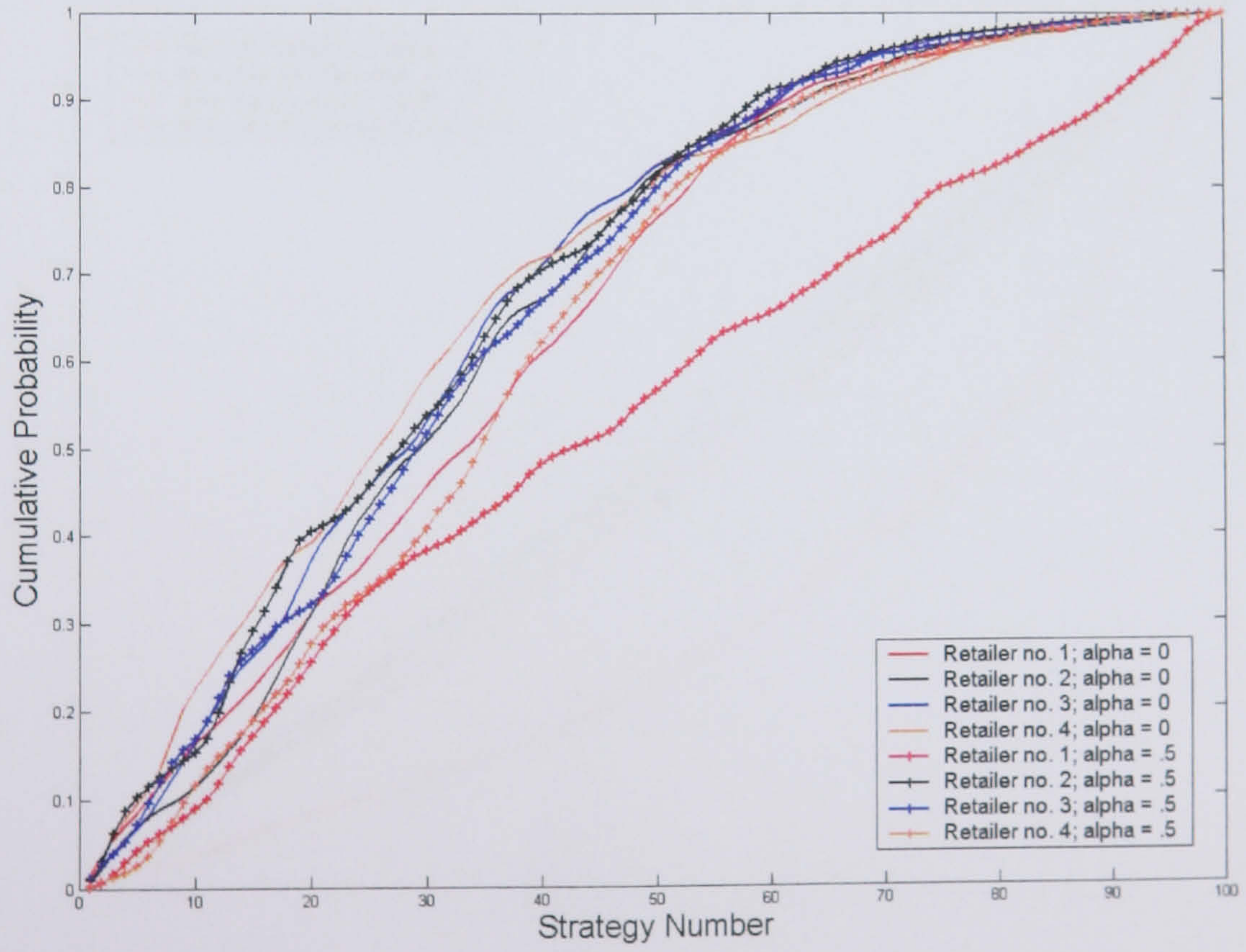


Figure 4-11: End of simulation distribution of strategies, generators and retailers, $\alpha = 0$ and $\alpha = .5$, [011]

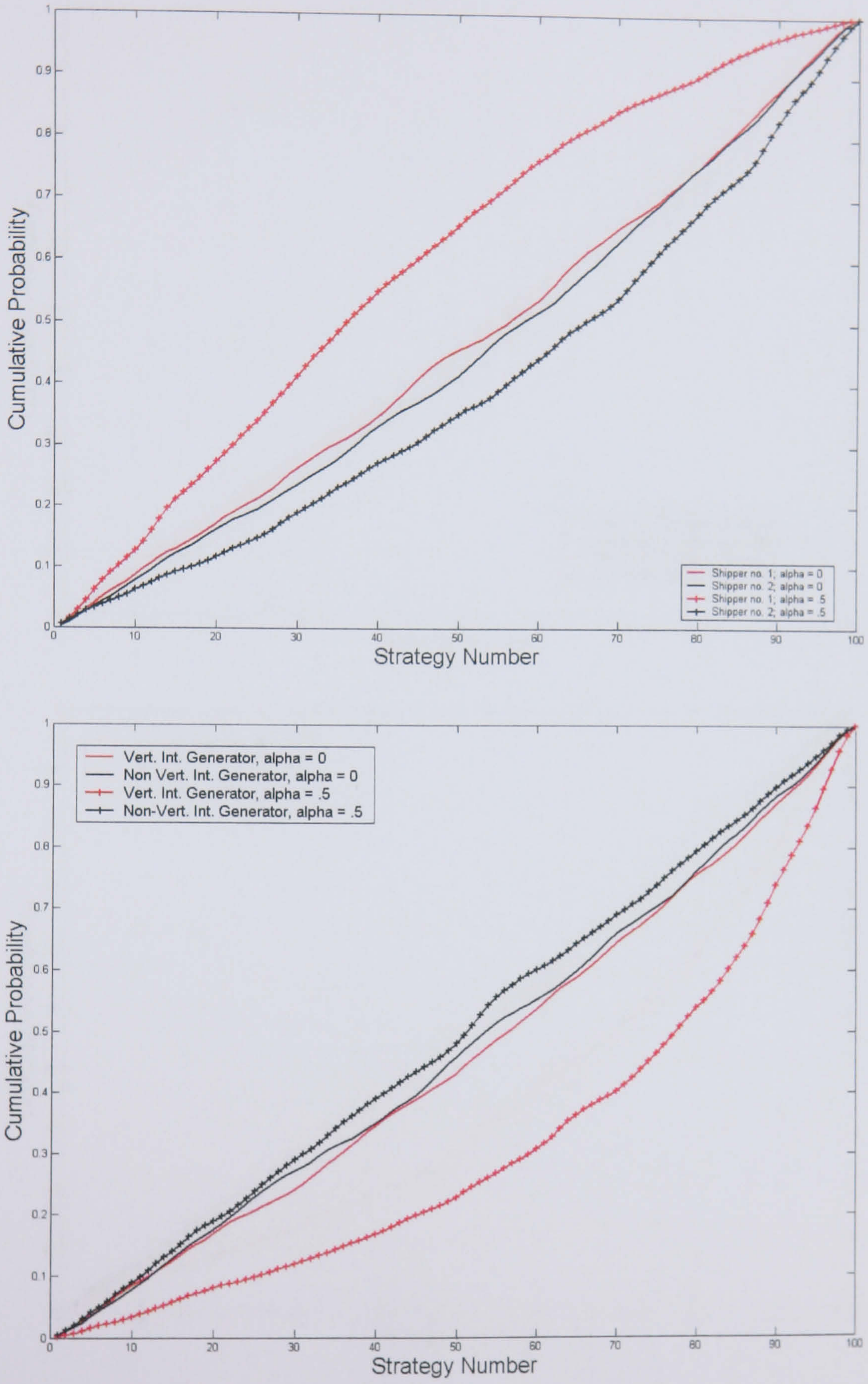


Figure 4-12: End of simulation distribution of strategies, shippers and generators, $\alpha = 0$ and $\alpha = .5$, [110], symmetric market structure

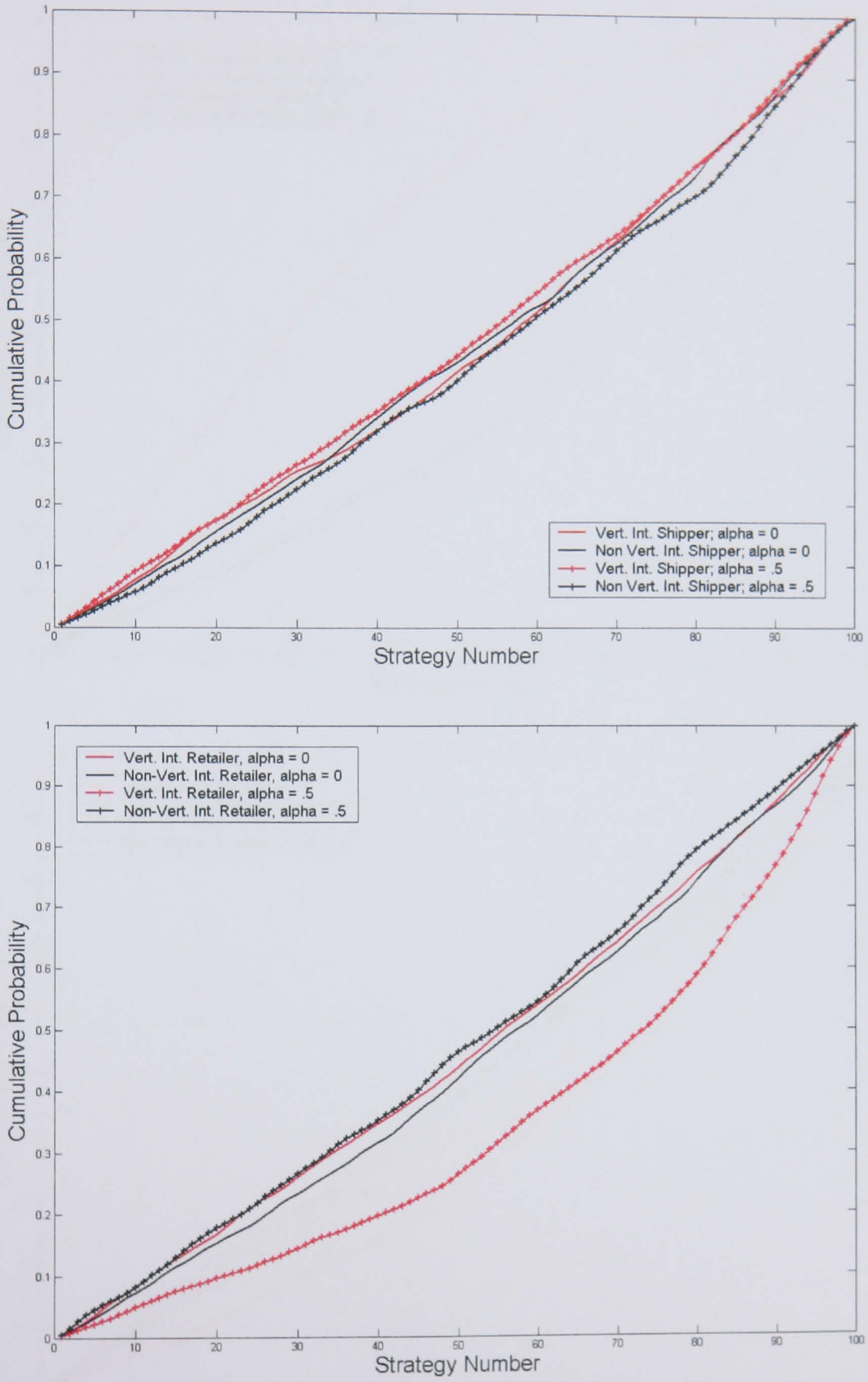


Figure 4-13: End of simulation distribution of strategies, shippers and retailers, $\alpha = 0$ and $\alpha = .5$, [101], symmetric market structure

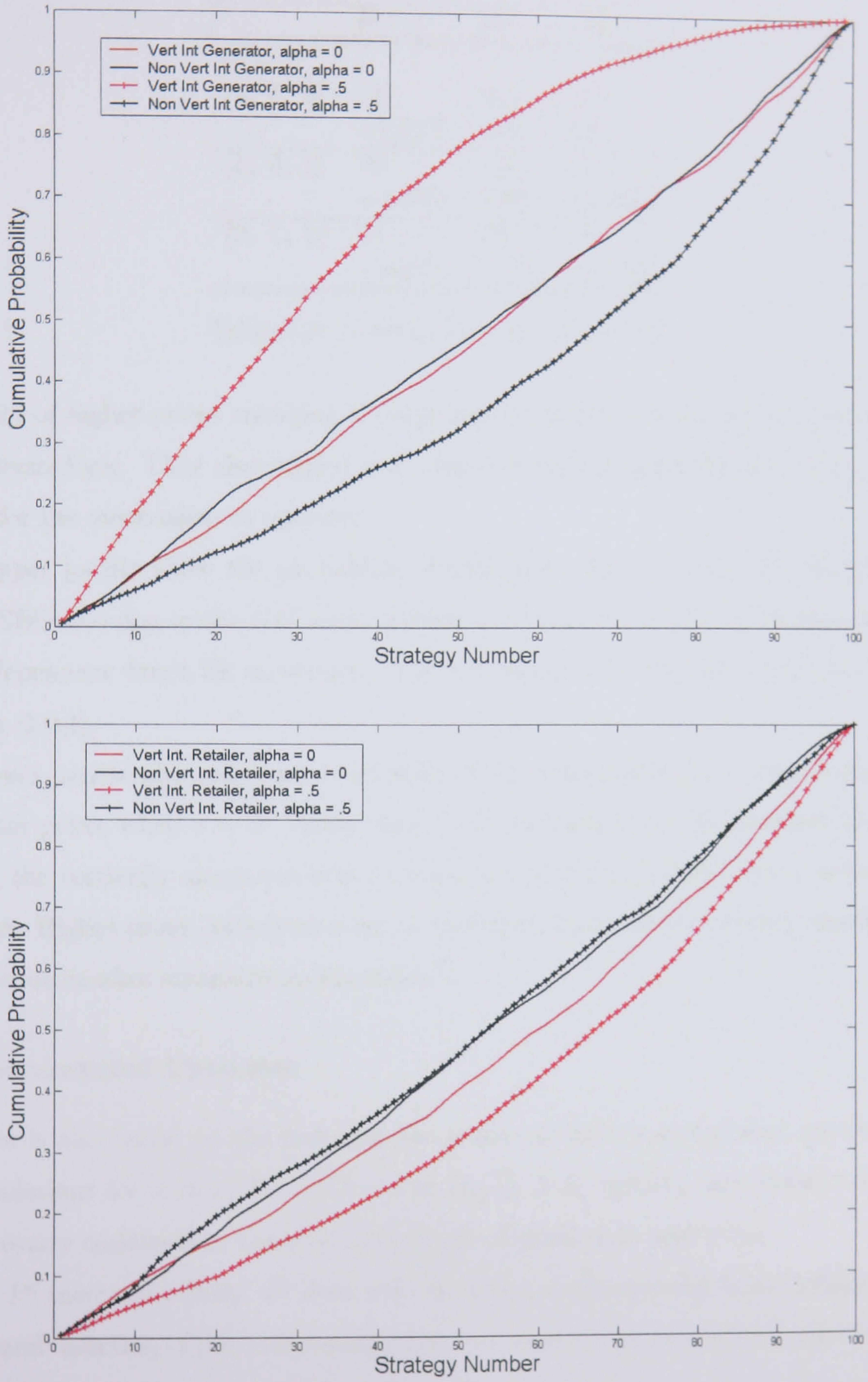


Figure 4-14: End of simulation distribution of strategies, generators and retailers, $\alpha = 0$ and $\alpha = .5$, [011], symmetric market structure

	$\mathbf{P}^g$	$\mathbf{P}^e$	$\mathbf{P}^r$
$\alpha = \mathbf{0}$			
	71	100	143
$\alpha = .\mathbf{5}$			
[1, 1, 0]	73	108	143
	+2.81%	+8%	0%
[1, 0, 1]	76	106	150
	+7.04%	+6%	+4.89%
[0, 1, 1]	68	95	147
	−4.22%	−5%	+2.79%

Table 4.2: Average Prices, A=B=C=2.

main insight of higher prices emerging through market sequence coordination, rather than via the foreclosure logic. They also suggest that market structure asymmetries are not a necessary condition for the mechanism to operate.

The upper panels show the probability distributions for the vertically integrated firms' upstream SBUs moving to the NW when α changes from $\alpha = 0$ to $\alpha = .5$, complemented again by the independent firm's SE movement. The results are very clear for [1,1,0] and [0,1,1] and smaller for [1,0,1].

The lower panels offer substantive evidence of the downstream firm positioning itself so as to set higher prices when $\alpha = .5$. While there is no variation in the independent firm's bidding strategies, the vertically integrated firm's cumulative probability distribution moves to the SE throughout. Higher prices with increasing α, therefore, hinge on the market clearing sequence rather than on market structure asymmetries.[13]

More Concentrated Upstream

Foreclosure is also based on the fact that the market is more concentrated upstream. A new set of simulations for $A = 3; B = 2; C = 4$ in the [1, 1, 0] vertical case assess whether this is also a necessary condition in the alternative logic (Figures 4-15 and 4-16).

While P^e increases clearly, P^g does not. However, α changes the firms' bidding behaviour in the general direction of previous results. The existence of this new market power mechanism,

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[13] Results under symmetrical $A = B = C = 3$ and $A = B = C = 4$ assumptions were qualitatively equivalent to those of $A = B = C = 2$.

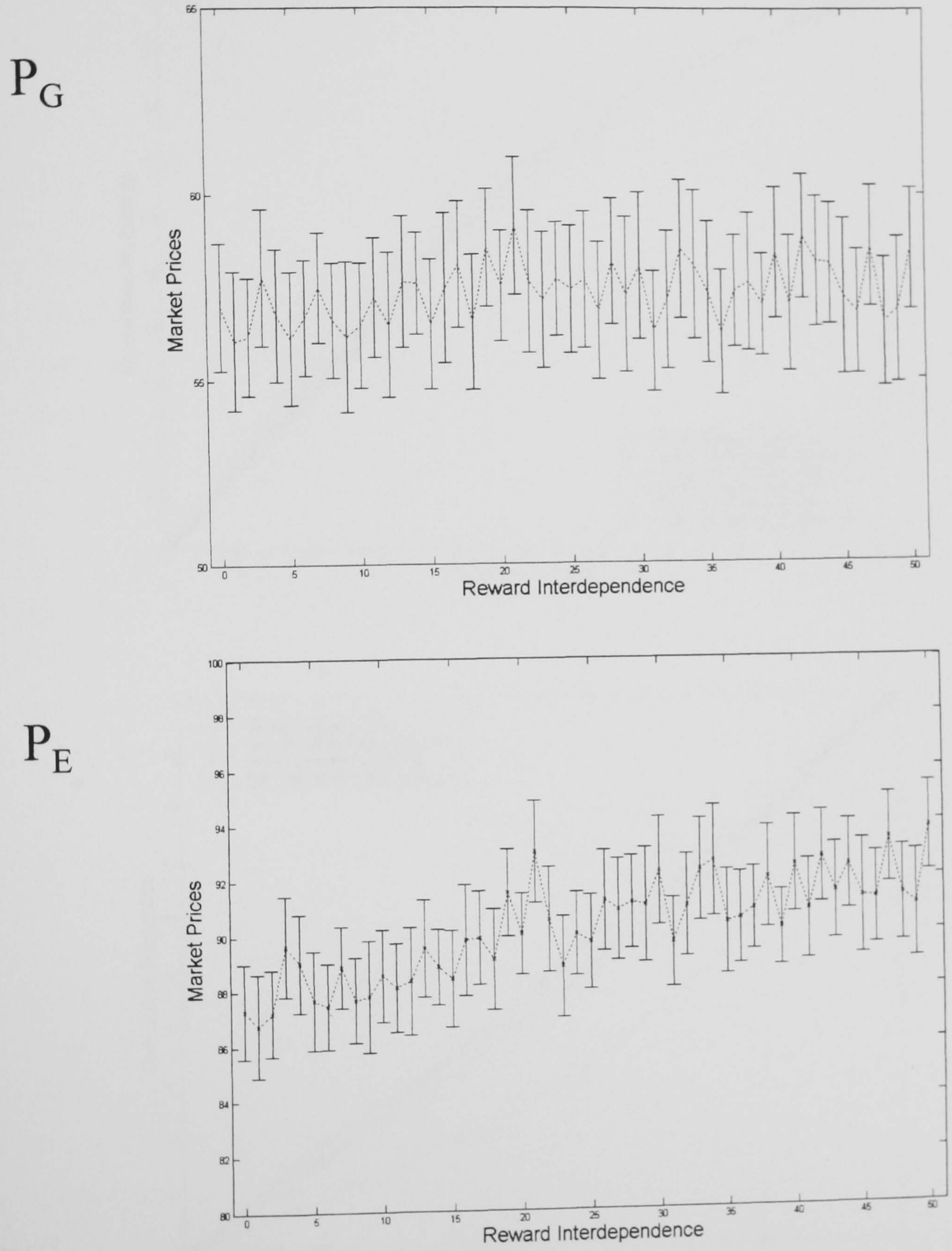

Figure 4-15: P_G and P_E for 3x2x4 Industry Structure

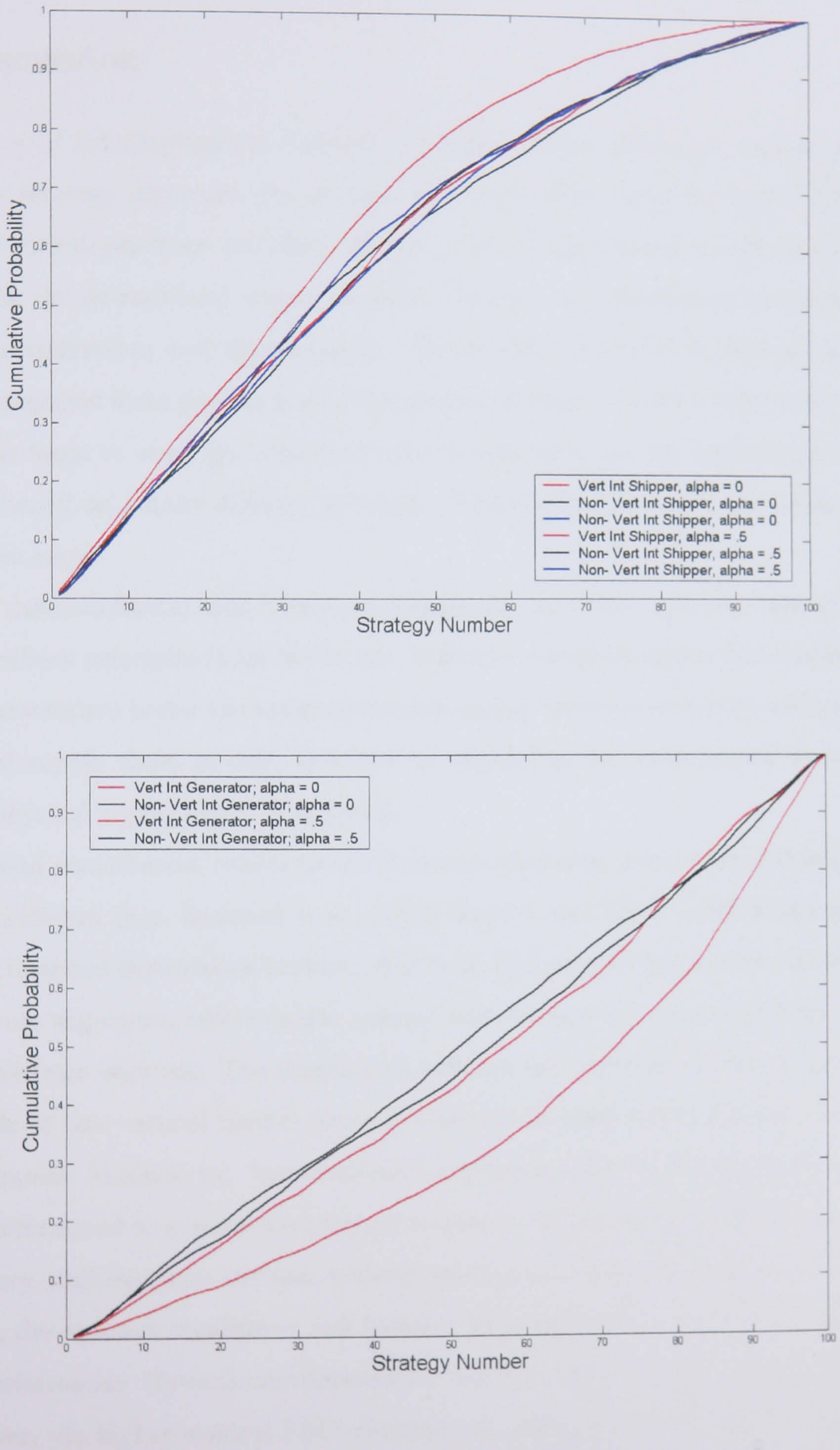

Figure 4-16: Generators, $\alpha = 0$ and $\alpha = .5$ for 3x2x4 Industry Structure

hence, seems to be robust to situations in which downstream markets are more concentrated.

4.5 Discussion

The existence of interdependence between vertically related SBUs has become a bedrock in the business strategy literature, yet we know relatively little about the underlying forces that create these interdependence and their effects. A set of agent-based simulations identifies one such effect in the de-regulated energy industry. Reward interdependences between SBUs lead to trading coordination and higher prices. Under tight reward interdependence structures, vertically integrated firms give up profits downstream in order to increase the scope for upstream profits. This leads to strategic behaviour that superficially has the appearance of foreclosure but that is based on a quite different principle. This essay adds to the preceding literature in at least three ways.

On the methodological side, there are apparently no other multi-tier energy simulations driven by netback principles in the literature. Industry wisdom suggests that this type of market clearing characterises better the reciprocal relationships between electricity and gas prices than conventional supply chain models, and so it is surprising that conventional economic models follow the physical supply chain formulation.

The second contribution relates to the literature on the sources of vertical market power in the energy industry (e.g. Bushnell et al., 2005; Granitz and Klein, 1996; Kühn and Machado, 2004). The financial dependence between electricity and natural gas markets is not captured in the foreclosure argument, where causal pricing relationships are sequential from the upstream to the downstream segment. The simulations unveil a new mechanism that suggests a solution to the puzzle of how vertical market power is observed in some energy markets where it should not really appear. Netback, i.e. "spark spread", pricing means that wholesale gas and electricity prices are determined in a down-to-upstream sequence. Hence, vertical market power can occur in compulsory, uniform price auction, without trading internalisation and price discrimination.

Thirdly, the research identifies a link between internal incentive structures, SBU behaviour and firm performance. Reward interdependence has been shown to be an instrument leading to market power, via higher vertical SBU coordination. Ways in which reward interdependences can be articulated include direct bonuses and stock options, and casual evidence indicates that these are widespread in the energy industry. It is interesting to note that such reward interdependence contracts are internal to the firm and, hence, normally fall outside the scope for regulatory intervention. To my knowledge, no regulatory body has investigated the energy price implications of those contracts. Whether firms use them explicitly as a way of aligning their interests to those of their SBU employees is an interesting question for future empirical work.

Chapter 5

Concluding Remarks

The European Union (EU) electricity and natural gas Directives have triggered a general liberalisation process expected to reduce end-user prices. Some firms have responded with market power strategies. In particular, the two ways in which electricity and natural gas markets interact (gas-for-power and retail bundling) produce many opportunities for market power interlinkages between the different parts of the industry. The overall objective of this thesis was therefore to unveil new interrelation market power mechanisms in energy industries. With this objective, it was structured in the form of three interrelated but self-contained essays.

The first essay consisted of an econometric study of the interrelationships between the two main European wholesale gas markets. The findings showed that a complex relationship between them emerges once their interconnector status is taken into account. There was an interconnector capacity threshold above which the two markets split, so that the relationship between local price differentials and capacity deployment was increasing and convex. The spot prices' dynamic structure was characterised by leader-follower dynamics and "convergence to mean" in levels, with the most developed hub taking a leading role. The functional form including a hybrid arbitrage/market power relationship is new in the literature.

The EU energy liberalisation is leading to the introduction of sophisticated financial trading arrangements. Prices in the new energy hubs are volatile and often characterised by regime switching and strategic learning. It therefore seemed natural to use time series analysis to study the dynamic behaviour of energy prices and how these are influenced by industry developments on both sides of the English Channel.

The interrelations that emerged in the study and the EU natural gas market evolution are likely to influence each other. For example, in the near future, it will be interesting to analyse how new UK-Continent pipelines influence the two regions. Moreover, experts forecast an almost immediate decline in the UK continental shelf gas reserves which should have an effect on the interconnector flows. Future research will presumably cast light on these and other issues.

The second essay introduced a series of agent-based simulations to inform the relationships between information transparency, crossholdings and market prices. The results suggested that the functional form of the crossholdings to prices relationship is not linear but better defined by (concave) threshold specification. Moreover, they indicated that, while transparency leads to higher prices, its influence is decreasing on the degree of downstream competition. The functional form linking crossholdings to market prices had not been identified in previous studies.

The third essay focused on the vertical integration between spot gas and electricity markets. Under high vertical reward interdependences, prices behaved as predicted in the foreclosure literature, but the firms' trading behaviour was different. The simulations illustrated a "netback" link across markets. Downstream prices set the scope for the monetisation of upstream assets. Vertically integrated firms benefited from this mechanism, losing market share and profits downstream but gaining overall through an increase in upstream prices. This effect emerged also in compulsory, uniform price auctions, was robust to a wide range of parameter specifications and is a substantial contribution to the industrial economics literature.

The Roth-Erev (1995) algorithm has achieved substantial support in a number of studies, but an interesting open question is whether the simulation conclusions are robust to alternative, more sophisticated, behavioural rules. Further, the auction protocols have been used extensively in the energy modelling literature. However, they restrict sellers to make a single per unit offer for all of its (limited) capacity. Thus, it is not possible for them to submit low offers for most capacity, and a high offer for a small number of capacity units, i.e. "hockey sticks" in the industry jargon. Experience weighted attraction models (Camerer and Ho, 1999) on the behavioural side and Supply Function Equilibria bidding (Klemperer and Meyer, 1989) could add insights to the behavioural and auction protocols.

In spite of their stylisation, though, the simulations led to a number of policy implications. The main one is that some European regulators' benign view of small crossholdings and vertical integrations might be misguided. The simulations suggested that tougher market power analyses of vertical and small horizontal mergers should be required before approval, due to the sequential and very concentrated nature of energy markets.

The simulations also suggested that public information aids coordination between competing firms. One practical illustration of this effect is provided by the Spanish electricity pool. In its first months of operations, all bidding information was provided within 24 hours, so that firms could learn how to trade in the new market. However, the delay was quickly extended to one and later three months. The regulator explained that the delays were imposed to reduce collusion in this very concentrated market (Centeno et al., 2003).

Nevertheless, the effects of information, crossholdings and vertical integration on prices will be a function of the specific peculiarities of each market, not only in the EU but also elsewhere. Disentangling the different factors that influence strategic behaviour in interrelated markets justifies the use of relatively novel agent-based methods. In this sense, simulations complement rather than substitute theorizing and field research. They can suggest possibilities to inspire new theory and indicate interesting kinds of data to collect.

The present thesis aimed at providing insights about market structures and mechanisms, to raise policy questions, and provide predictions that were susceptible of testing in the behavioural laboratory. Further, the agent-based models presented here illustrate a general theme that has emerged in the literature. Connections at one level of analysis drive connections at other levels. The firms' incentives (i.e. reward interdependences) and structure (crossholdings) shape the firms latent behavioural rules which, in turn, influence trading, market prices and profits.

The liberalisation of European electricity and natural gas markets continues. Many questions remain unanswered and the academic debate around those is still in full swing. This thesis aimed at contributing to that body of research through new methodologies and insights on the economics of inter-related energy markets.

Appendix A

Computer Codes

A.1 Crossholdings Simulation

```
% Outline
   configuration_matrices
   for crossown = crossownmin : crossownmax
   for T = 1 : Tmax
   for t = 2 : tmax
   definition_strategies_sellers
   definition_strategies_buyers
   market_clearing
   quantity_assignment
   rotherev_reinforcement_sellers
   rotherev_reinforcement_buyers
   end
   end
   end
   end
   % The sub-files are listed below:
   for u = 1 : umax
   strat_upstream (u) = (u - 1) * (tariff / (umax - 1));
```

```
end
for n = 1 : nmax
prob_seller (:, n) = propensity_seller (:, n, t - 1, T) / sum (propensity_seller (:, n, t - 1, T));
if public_info == 1
for u = 1: umax
prob_seller (u, :) = 0.10;
end
end
cum_prob_seller (:, 1) = cumsum (prob_seller (:, n));
u = 1;
r = rand;
while r > cum_prob_seller (u, 1) & u < umax
u = u + 1;
end
strat_seller (n) = strat_upstream(u);
strat_no_seller (n) = u;
end
for v = 1 : vmax
strat_downstream (v) = (v - 1) * (tariff / (vmax - 1));
end
for m = 1 : mmax
prob_buyer (:, m) = propensity_buyer (:, m, t - 1, T) / sum (propensity_buyer (:, m, t - 1, T));
if public_info == 1
for v = 1 : vmax
prob_buyer (v, :) = sum (prob_buyer (v, :))/mmax;
end
end
cum_prob_buyer (:, 1) = cumsum (prob_buyer (:, m));
```

```
v = 1;
r = rand;
while r > cum_prob_buyer (v, 1)
v = v + 1;
end
strat_buyer (m) = strat_downstream(v);
strat_no_buyer (m) = v;
end
zeros_seller = zeros (1, nmax);
zeros_buyer = zeros (1, mmax);
sellers_matrix = sortrows ([index_seller; strat_seller; capacity_seller; zeros_seller; zeros_seller]', 2);
sellers_matrix (:, 4) = cumsum (sellers_matrix (:, 3));
buyers_matrix = flipud ( sortrows ([index_buyer; strat_buyer; capacity_buyer; zeros_buyer; zeros_buyer]', 2));
buyers_matrix (:, 4) = cumsum (buyers_matrix (:, 3));
if buyers_matrix (1, 2) < sellers_matrix (1, 2)
market_price (t, T, crossown) = market_price (t - 1, T, crossown);
market_quantity (t, T, crossown) = market_quantity (t - 1, T, crossown);
else
n = 1;
m = 1;
while buyers_matrix (m, 2) >= sellers_matrix (n, 2) & ( (m < mmax) | (n < nmax) )
if buyers_matrix (m, 4) > sellers_matrix (n, 4) & (n < nmax)
market_price (t, T, crossown) = mean (buyers_matrix (m, 2), sellers_matrix (n, 2));
market_quantity (t, T, crossown) = min (buyers_matrix (n, 4), sellers_matrix (n, 4));
n = n + 1;
flag = 1
elseif buyers_matrix (m, 4) < sellers_matrix (n, 4) & (m < mmax)
market_price (t, T, crossown) = mean (buyers_matrix (m, 2), sellers_matrix (n, 2));
```

```
market_quantity (t, T, crossown) = min (buyers_matrix (n, 4), sellers_matrix (n, 4));
m = m + 1;
flag = 2
else
market_price (t, T, crossown) = mean (buyers_matrix (m + 1, 2), sellers_matrix (n + 1,
2));
market_quantity (t, T, crossown) = max ( buyers_matrix (n + 1, 4), sellers_matrix (n +
1, 4) );
n = n + 1;
m = m + 1;
flag = 3
end
end
end
n = 1;
while market_quantity (t, T, crossown) >= sellers_matrix (n, 4) & n < nmax
sellers_matrix (n, 5) = sellers_matrix (n, 3);
n = n + 1 ;
end
if n == 1
sellers_matrix (n, 5) = market_quantity (t, T, crossown);
else sellers_matrix (n, 5) = market_quantity (t, T, crossown) - sellers_matrix (n - 1, 4);
end
m = 1;
while market_quantity (t, T, crossown) >= buyers_matrix (m, 4) & m < mmax
buyers_matrix (m, 5) = buyers_matrix (m, 3);
m = m + 1 ;
end
if m == 1
buyers_matrix (m, 5) = market_quantity (t, T, crossown);
```

```
else buyers_matrix (m, 5) = market_quantity (t, T, crossown) - buyers_matrix (m - 1, 4);
end
for m = 1 : mmax
buyers_matrix = sortrows (buyers_matrix, 1);
sales_buyers (m, t) = buyers_matrix (m, 5) * (retail_price - market_price (t, T, crossown));
if strat_no_buyer(m) == 1
propensity_buyer (1, m, t, T) = propensity_buyer (1, m, t - 1, T) * (1 - gamma) + sales_buyers (m, t) ;
propensity_buyer (2, m, t, T) = propensity_buyer (2, m, t - 1, T) * (1 - gamma) + ( (1-epsilon) * sales_buyers (m, t) ) ;
propensity_buyer (3:vmax, m, t, T) = propensity_buyer (3:umax, m, t - 1, T) * (1 - gamma) ;
elseif strat_no_buyer(m) == vmax
propensity_buyer (vmax, m, t, T) = propensity_buyer (vmax, m, t - 1, T) * (1 - gamma) + sales_buyers (m, t) ;
propensity_buyer (vmax-1, m, t, T) = propensity_buyer (vmax - 1, m, t - 1, T) * (1 - gamma) + ( (1 - epsilon) * sales_buyers (m, t) ) ;
propensity_buyer (1: (vmax - 2), m, t, T) = propensity_buyer ((1 : vmax - 2), m, t - 1, T) * (1 - gamma) ;
else
propensity_buyer (:, m, t, T) = propensity_buyer (:, m, t - 1, T) * (1 - gamma) ;
propensity_buyer (strat_no_buyer(m), m, t, T) = propensity_buyer (strat_no_buyer(m), m, t - 1, T) * (1 - gamma) + sales_buyers (m, t) ;
propensity_buyer (strat_no_buyer(m) - 1, m, t, T) = propensity_buyer (strat_no_buyer(m) - 1, m, t - 1, T) * (1 - gamma) + ( (1 - epsilon) * sales_buyers (m, t) ) ;
propensity_buyer (strat_no_buyer(m) + 1, m, t, T) = propensity_buyer (strat_no_buyer(m) + 1, m, t - 1, T) * (1 - gamma) + ( (1 - epsilon) * sales_buyers (m, t) ) ;
end
for v = 1 : vmax
if prob_buyer (v, m) < mu
```

```
    propensity_buyer (v, m, t, T) = 0;
    end
    end
    end
    for n = 1 : nmax
    sellers_matrix = sortrows (sellers_matrix, 1);
    sales_sellers (n, t) = sellers_matrix (n, 5) .* market_price (t, T, crossown) ;
    sales_sellers (1, t) = ( sellers_matrix (1, 5) + ( (crossown - 1) * sellers_matrix (2, 5) ) )
.* market_price (t, T, crossown) ;
    sales_sellers (2, t) = ( sellers_matrix (2, 5) + ( (crossown - 1) * sellers_matrix (1, 5) ) )
.* market_price (t, T, crossown) ;
    if strat_no_seller(n) == 1
    propensity_seller (1, n, t, T) = propensity_seller (1, n, t - 1, T) * (1 - gamma) +
sales_sellers (n, t) ;
    propensity_seller (2, n, t, T) = propensity_seller (2, n, t - 1, T)*(1 - gamma) + ((1 -
epsilon) * sales_sellers (n, t) ) ;
    propensity_seller (3:umax, n, t, T) = propensity_seller (3:umax, n, t - 1, T)*(1 - gamma)
;
    elseif strat_no_seller(n) == umax
    propensity_seller (umax, n, t, T) = propensity_seller (umax, n, t - 1, T)*(1 - gamma) +
sales_sellers (n, t);
    propensity_seller (umax-1, n, t, T) = propensity_seller (umax - 1, n, t-1, T)*(1 - gamma)
+ ((1 - epsilon) * sales_sellers (n, t) );
    propensity_seller (1:(umax-2), n, t, T) = propensity_seller ((1 : umax - 2), n, t - 1, T)*(1
- gamma) ;
    else
    propensity_seller (:, n, t, T) = propensity_seller (:, n, t - 1, T) * (1 - gamma) ;
    propensity_seller (strat_no_seller(n), n, t, T) = propensity_seller (strat_no_seller(n), n,
t - 1, T)*(1 - gamma) + sales_sellers (n, t) ;
    propensity_seller (strat_no_seller(n) - 1, n, t, T) = propensity_seller (strat_no_seller(n)
```

```
- 1, n, t - 1, T)*(1 - gamma) + ((1 - epsilon) * sales_sellers (n, t) ) ;
    propensity_seller (strat_no_seller(n) + 1, n, t, T) = propensity_seller (strat_no_seller(n)
+ 1, n, t - 1, T)*(1 - gamma) + ((1 - epsilon) * sales_sellers (n, t) ) ;
    end
    prob_seller (:, n) = propensity_seller (:, n, t. T) / sum (propensity_seller (:. n. t. T));
    for u = 1 : umax
    if prob_seller (u, n) < mu
    propensity_seller (u, n, t, T) = 0;
    end
    end
    end
```

A.2 Vertical Incentives Simulation

```
configuration_matrices;
    if internal == 1
    alphamin = 51;
    alphamax = 51;
    else
    alphamin = 1;
    alphamax = 51;
    end
    strategies_retail
    for alpha = alphamin:alphamax
    for T = 1:Tmax
    t = 1;
    suppliers_random_choice
    market_clearing_retail
    strategies_downstream
    generators_random_choice
```

```
market_clearing_downstream
internalise_capacities
strategies_upstream
shippers_random_choice
market_clearing_upstream
incentives
for t = 2:tmax
suppliers_choice
market_clearing_retail
strategies_downstream
generators_choice
market_clearing_downstream
internalise_capacities
strategies_upstream
shippers_choice
market_clearing_upstream
incentives
reinforcement_suppliers
reinforcement_generators
reinforcement_shippers
end
end
toc
for k = 1: kmax
strat_retail (k) = k*tariff/kmax;
end
propensity_supplier(:,c,t-1,T)=propensity_supplier(:,c,2,T). We need two
for c = 1: cmax
prob_supplier (:, c, T, alpha) = propensity_supplier (:, c, 1, T) / sum (propensity_supplier (:, c, 1, T));
```

```
cum_prob_supplier = cumsum (prob_supplier (:, c, T, alpha));
k = 1;
r = rand;
while r > cum_prob_supplier (k)
k=k+1;
end
strat_supplier (c) = strat_retail (k);
strat_no_supplier (c) = k;
end
zero = zeros (1,cmax);
suppliers_matrix = sortrows ([index_supplier; strat_supplier; capacity_supplier; zero; zero]', 2);
suppliers_matrix(:,4) = cumsum(suppliers_matrix(:,3)) ;
if inelastic == 0
bids_expand = zeros(1,cmax+2);
cum_cap_expand = zeros(1,cmax+1);
bids_expand(2:cmax+1) = suppliers_matrix(:,2);
cum_cap_expand(2:cmax+1) = suppliers_matrix(:,4);
bids_expand(cmax+2) = 10000;
c=2;
while bids_expand(c + 1) < (intercept + slope * cum_cap_expand(c))
suppliers_matrix(c - 1,5) = suppliers_matrix(c - 1,3);
c = c + 1; % and we look at the next supplier
end
if bids_expand(c) < (intercept + slope * cum_cap_expand(c))
quantity_retail(t,T) = cum_cap_expand(c);
else
quantity_retail(t,T) = round( ( bids_expand(c) - intercept ) / slope ) ;
end
price_retail(t,T,alpha) = bids_expand(c);
```

```
suppliers_matrix(c - 1,5) = quantity_retail (t,T) - cum_cap_expand(c - 1) ;
marginal_supplier (t, T, alpha) = suppliers_matrix (c - 1, 1);
else % inelastic demand (simlar structure than the other markets (downstream and upstream)
c = 1;
unc_demand = rand;
demand = mean_demand - (5 * uncertainty) + round((uncertainty * unc_demand * 10));
while suppliers_matrix(c,4) < demand % while the cumulative is lower than the demand then keep assigning
suppliers_matrix(c,5) = suppliers_matrix(c,3);
c = c + 1;
end
if c == 1
suppliers_matrix(1,5) = demand ;
else
suppliers_matrix(c,5) = demand - suppliers_matrix(c-1,4) ;
end
price_retail(t,T,alpha) = suppliers_matrix (c , 2);
quantity_retail(t,T) = demand;
marginal_supplier (t, T, alpha) = suppliers_matrix (c, 1); % Here the last supplier is s (if elastic is c-1)
end
suppliers_matrix = sortrows (suppliers_matrix, 1); % We reorder here
for j = 1: jmax
strat_downstream(j) = j* price_retail(t,T,alpha) /jmax;
end
for b= 1: bmax
prob_generator (:, b, T, alpha) = propensity_generator (:, b, 1, T) / sum (propensity_generator (:, b, 1, T));
cum_prob_generator = cumsum (prob_generator (:, b, T, alpha));
```

```
j=1;
r = rand;
while r > cum_prob_generator (j)
j=j+1;
end
strat_generator (b) = strat_downstream(j) ;
strat_no_generator (b) = j;
end
zero = zeros (1,bmax);
generators_matrix = sortrows ([index_generator; strat_generator; capacity_generator;
zero; zero]', 2);
generators_matrix(:,4) = cumsum(generators_matrix(:,3)) ;
b=1;
while generators_matrix(b,4) < quantity_retail(t,T)
generators_matrix(b,5) = generators_matrix(b,3);
b = b + 1;
end
if b == 1
generators_matrix(1,5) = quantity_retail (t,T) ;
else
generators_matrix(b,5) = quantity_retail (t,T) - generators_matrix(b-1,4) ;
end
price_downstream(t,T,alpha) = generators_matrix (b , 2);
marginal_generator (t, T, alpha) = generators_matrix (b, 1);
generators_matrix = sortrows (generators_matrix, 1); % We reorder here
if internal == 1
capacity_int_shipper_withold = min( generators_matrix(1,5) , capacity_shipper(1,1) );
else
capacity_int_shipper_withold = 0; % If they do not internalise then we have no capcity
withold
```

```
end
capacity_shipper_adjusted(1,1) = capacity_shipper(1.1) - capacity_int_shipper_withold:
quantity_traded_upstream(t,T) = quantity_retail(t,T) - capacity_int_shipper_withold:
for m=1:mmax
strat_upstream(m)= m* price_downstream(t,T,alpha) /mmax;
end
for a = 1:amax
prob_shipper (:, a, T, alpha) = propensity_shipper (:, a, 1, T) / sum (propensity_shipper (:, a, 1, T));
cum_prob_shipper = cumsum (prob_shipper (:, a, T. alpha));
m = 1;
r = rand;
while r > cum_prob_shipper (m)
m=m+1;
end
strat_shipper (a) = strat_upstream(m);
strat_no_shipper (a) = m; %this is the real order of shippers
end
zero = zeros (1,amax);
shippers_matrix = sortrows ([index_shipper; strat_shipper; capacity_shipper_adjusted; zero; zero]', 2);
shippers_matrix(:,4) = cumsum(shippers_matrix(:,3)) ;
a = 1;
while shippers_matrix(a,4) < quantity_traded_upstream(t,T)
shippers_matrix(a,5) = shippers_matrix(a,3);
a = a + 1;
end
if a == 1
shippers_matrix(1,5) = quantity_traded_upstream (t.T) :
else
```

```
    shippers_matrix(a,5) = quantity_traded_upstream (t,T) - shippers_matrix(a-1.4) ;
    end
    price_upstream(t,T,alpha) = shippers_matrix (a , 2);
    marginal_shipper (t, T, alpha) = shippers_matrix (a, 1);
    shippers_matrix = sortrows (shippers_matrix, 1);
    shippers_matrix (1,5) = shippers_matrix (1,5) + capacity_int_shipper_withold;
    integrated_shipper_profits (t, T, alpha) = price_upstream (t,T,alpha)* shippers_matrix
(1,5) ;
    integrated_generator_profits (t, T, alpha) = ( price_downstream (t.T,alpha) - price_upstream
(t,T,alpha) )* generators_matrix (1,5);
    integrated_supplier_profits (t, T, alpha) = ( price_retail (t,T,alpha) - price_downstream
(t,T,alpha) )* suppliers_matrix (1,5);
    shippers_incentives (1,t,T) = (1 - (ver_mer(1))*(0.01*alpha - 0.01) ) * integrated_shipper_profits
(t, T, alpha) + ver_mer(1)*ver_mer(2)*(0.01*alpha - 0.01) * integrated_generator_profits (t,
T, alpha)+ ver_mer(1) * ver_mer(3)*(0.01*alpha - 0.01) * integrated_supplier_profits (t, T,
alpha);
    shippers_incentives (2:amax, t, T) = price_upstream (t,T,alpha)* shippers_matrix (2:amax,5);
    generators_incentives (1,t,T) = (1 - (ver_mer(2))*(0.01*alpha - 0.01) ) * integrated_generator_profits
(t, T, alpha) + ver_mer(2)*ver_mer(1)*(0.01*alpha - 0.01) * integrated_shipper_profits (t,
T, alpha)+ ver_mer(2) * ver_mer(3)*(0.01*alpha - 0.01) * integrated_supplier_profits (t. T.
alpha); ;
    generators_incentives (2:bmax, t, T) = (price_downstream (t,T,alpha) - price_upstream
(t,T,alpha) )* generators_matrix (2:bmax,5);
    suppliers_incentives (1,t,T) = (1 - (ver_mer(3))*(0.01*alpha - 0.01) ) * integrated_supplier_profits
(t, T, alpha) + ver_mer(3)*ver_mer(1)*(0.01*alpha - 0.01) * integrated_shipper_profits (t,
T, alpha)+ ver_mer(3)*ver_mer(2)*(0.01*alpha - 0.01) * integrated_generator_profits (t, T,
alpha);
    suppliers_incentives (2:cmax, t, T) = (price_retail (t,T,alpha)-price_downstream (t,T.alpha))
* suppliers_matrix (2:cmax,5);
    for c = 1: cmax
```

```
prob_supplier (:, c, T, alpha) = propensity_supplier (:, c, t-1, T) / sum (propensity_supplier (:, c, t-1, T));
cum_prob_supplier = cumsum (prob_supplier (:, c, T, alpha));
k = 1;
r = rand;
while r > cum_prob_supplier (k)
k=k+1;
end
strat_supplier (c) = strat_retail (k);
strat_no_supplier (c) = k;
end
for b= 1: bmax
prob_generator (:, b, T, alpha) = propensity_generator (:, b, t-1, T) / sum (propensity_generator (:, b, t-1, T));
cum_prob_generator = cumsum (prob_generator (:, b, T, alpha));
j=1;
r = rand;
while r > cum_prob_generator (j)
j=j+1;
end
strat_generator (b) = strat_downstream(j) ;
strat_no_generator (b) = j;
end
for a = 1:amax % Here, a=1 means the shipper index 1.
prob_shipper (:, a, T, alpha) = propensity_shipper (:, a, t-1, T) / sum (propensity_shipper (:, a, t-1, T));
cum_prob_shipper = cumsum (prob_shipper (:, a, T, alpha));
m = 1;
r = rand;
while r > cum_prob_shipper (m)
```

```
    m=m+1;
    end
    strat_shipper (a) = strat_upstream(m);
    strat_no_shipper (a) = m; %this is the real order of shippers
    end
    for c=1:cmax
    if suppliers_incentives (c,t,T) > suppliers_incentives (c, t-1,T)
    if strat_no_supplier(c) == 1
    propensity_supplier (1, c, t, T) = propensity_supplier (1, c, t-1, T)*(1-gamma) + epsilon
;
    propensity_supplier (2, c, t, T) = propensity_supplier (2, c, t-1, T)*(1-gamma) + delta ;
    propensity_supplier (3:kmax, c, t, T) = propensity_supplier (3:kmax, c, t-1, T)*(1-gamma)
;
    elseif strat_no_supplier(c) == kmax
    propensity_supplier (kmax, c, t, T) = propensity_supplier (kmax, c, t-1, T)*(1-gamma) +
epsilon ;
    propensity_supplier (kmax-1, c, t, T) = propensity_supplier (kmax-1, c, t-1, T)*(1-gamma)
+ delta ;
    propensity_supplier (1:(kmax-2), c, t, T) = propensity_supplier ((1:kmax-2), c, t-1, T)*(1-
gamma) ;
    else
    propensity_supplier (:, c, t, T) = propensity_supplier (:, c, t-1, T)*(1-gamma) ;
    propensity_supplier (strat_no_supplier(c), c, t, T) = propensity_supplier (strat_no_supplier(c),
c, t-1, T)*(1-gamma) + epsilon ;
    propensity_supplier (strat_no_supplier(c)-1, c, t, T) = propensity_supplier (strat_no_supplier(c)-
1, c, t-1, T)*(1-gamma) + delta ;
    propensity_supplier (strat_no_supplier(c)+1, c, t, T) = propensity_supplier (strat_no_supplier(c)+1,
c, t-1, T)*(1-gamma) + delta ;
    end
    else
```

```
propensity_supplier (:, c, t, T) = propensity_supplier (:, c, t-1, T)*(1-gamma);
end
support_prob_supplier(1,:)= propensity_supplier (:, c, t, T)' / sum (propensity_supplier (:, c, t, T)); %this is the same as the probability that a strategy k will be played (we compute prob in the next period)
for k = 1:kmax
if support_prob_supplier(1,k) < mu
propensity_supplier (k, c, t, T) = 0;
end
end
end
for b=1:bmax
if generators_incentives (b,t,T) > generators_incentives (b, t-1,T)
if strat_no_generator(b) == 1
propensity_generator (1, b, t, T) = propensity_generator (1, b, t-1, T)*(1-gamma) + epsilon ;
propensity_generator (2, b, t, T) = propensity_generator (2, b, t-1, T)*(1-gamma) + delta ;
propensity_generator (3:jmax, b, t, T) = propensity_generator (3:jmax, b, t-1, T)*(1-gamma) ;
elseif strat_no_generator(b) == jmax
propensity_generator (jmax, b, t, T) = propensity_generator (jmax, b, t-1, T)*(1-gamma) + epsilon ;
propensity_generator (jmax-1, b, t, T) = propensity_generator (jmax-1, b, t-1, T)*(1-gamma) + delta ;
propensity_generator (1:(jmax-2), b, t, T) = propensity_generator ((1:jmax-2), b, t-1, T)*(1-gamma) ;
else
propensity_generator (:, b, t, T) = propensity_generator (:, b, t-1, T)*(1-gamma) ;
propensity_generator (strat_no_generator(b), b, t, T) = propensity_generator (strat_no_generator(b),
```

```
b, t-1, T)*(1-gamma) + epsilon ;
    propensity_generator (strat_no_generator(b)-1, b, t, T) = propensity_generator (strat_no_generator(b)-
1, b, t-1, T)*(1-gamma) + delta ;
    propensity_generator (strat_no_generator(b)+1, b, t, T) = propensity_generator (strat_no_generator(b
b, t-1, T)*(1-gamma) + delta ;
    end
    else
    propensity_generator (:, b, t, T) = propensity_generator (:, b, t-1, T)*(1-gamma);
    end
    support_prob_generator(1,:) = propensity_generator (:, b, t, T)' / sum (propensity_generator
(:, b, t, T));
    for j = 1:jmax
    if support_prob_generator(1,j) < mu
    propensity_generator (j, b, t, T) = 0;
    end
    end
    end
    for a=1:amax
    if shippers_incentives (a,t,T) > shippers_incentives (a, t-1,T)
    if strat_no_shipper(a) == 1
    propensity_shipper (1, a, t, T) = propensity_shipper (1, a, t-1, T)*(1-gamma) + epsilon ;
    propensity_shipper (2, a, t, T) = propensity_shipper (2, a, t-1, T)*(1-gamma) + delta ;
    propensity_shipper (3:mmax, a, t, T) = propensity_shipper (3:mmax, a, t-1, T)*(1-gamma)
;
    elseif strat_no_shipper(a) == mmax
    propensity_shipper (mmax, a, t, T) = propensity_shipper (mmax, a, t-1, T)*(1-gamma)
+ epsilon ;
    propensity_shipper (mmax-1, a, t, T) = propensity_shipper (mmax-1, a, t-1, T)*(1-
gamma) + delta ;
```

```
    propensity_shipper (1:(mmax-2), a, t, T) = propensity_shipper ((1:mmax-2). a, t-1. T)*(1-
gamma) ;
    else
    propensity_shipper (:, a, t, T) = propensity_shipper (:, a. t-1. T)*(1-gamma) :
    propensity_shipper (strat_no_shipper(a), a, t, T) = propensity_shipper (strat_no_shipper(a).
a, t-1, T)*(1-gamma) + epsilon ;
    propensity_shipper (strat_no_shipper(a)-1, a, t, T) = propensity_shipper (strat_no_shipper(a)-
1, a, t-1, T)*(1-gamma) + delta ;
    propensity_shipper (strat_no_shipper(a)+1, a, t, T) = propensity_shipper (strat_no_shipper(a)+1.
a, t-1, T)*(1-gamma) + delta ;
    end
    else
    propensity_shipper (:, a, t, T) = propensity_shipper (:, a, t-1, T)*(1-gamma);
    end
    support_prob_shipper(1,:) = propensity_shipper (:, a, t, T)' / sum (propensity_shipper
(:, a, t, T));
    for m = 1:mmax
    if support_prob_shipper(1,m) < mu
    propensity_shipper (m, a, t, T) = 0;
    end
    end
    end
```

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