

THE IMPACTS OF MANUFACTURERS' CAPACITY AND PRICING DECISIONS  
ON DYNAMIC RANDOM-ACCESS MEMORY MARKET

by

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B.S., Industrial Engineering, Boğaziçi University, 2016

Submitted to the Institute for Graduate Studies in  
Science and Engineering in partial fulfillment of  
the requirements for the degree of  
Master of Science

Graduate Program in Industrial Engineering  
Boğaziçi University

2018

## ACKNOWLEDGEMENTS

First and furthermore, I would like to thank my thesis supervisor Assoc. Prof. *Gönenç Yücel*. From the very beginning of my thesis, he supported my ideas and guided me with his wisdom when I got lost in details. I am grateful to him for his optimism and encouragement, not only throughout this research, but during my undergraduate and graduate studies.

I want to thank Assist. Prof. *Enis Kayış* and Assist. Prof. *Mustafa Gökçe Baydaoğan* for being a part of my thesis committee and their valuable comments.

I want to thank each and every member of Industrial Engineering faculty for their support for six years. I have gained incredible experience as a student of this department.

I want to thank *Mustafa Gökçe Baydaoğan* specially for his kindness and never-ending support to me as his student and assistant. I have learnt so many valuable things from him in the last five years and he continues to share his knowledge with me and his students each and every day.

I would like to show my gratitude to Prof. *Taner Bilgiç* for his supports and for exchanging ideas with me from the beginning of this research. I want to thank him also for his endless support from the very first day of my undergraduate study as my advisor.

I wish to thank Prof. *Yaman Barlas*, for introducing the simulation field to me and igniting my interest and love for system science. I am also grateful to him for my place in SESDYN lab, where I can discover my abilities and improve myself each and every day.

I want to specially thank to each member of SESDYN research group for taking care of me and their friendships. I would like to thank *Berk Görgülü* for his patience for my never-ending questions and for helping me with his excellent programming skills every time I needed. However, I want to specially thank him for being a true friend and brother to me in the last two years. I wish to express my gratitude to *Oylum Şeker* for setting a great example of how to be an excellent teaching assistant. I am grateful for her support, sense of justice and excellent advises.

Additionally, being a friend *Nefel Tellioğlu* and *Gizem Aktaş* is a great honour to me. I want to thank both of them for being there for me, when I most needed. I would like to thank *Pınar Dursun* for always guiding me to right direction and her sensitive heart.

Finally, I want to thank both of my parents, *Şenay* and *Oktaç Dursun*, for their endless support. It is perfect to know that there are always two people who will be there for you.

## ABSTRACT

# THE IMPACTS OF MANUFACTURERS' CAPACITY AND PRICING DECISIONS ON DYNAMIC RANDOM-ACCESS MEMORY MARKET

Dynamic Random-Access Memory (DRAM) market is a capital-intensive oligopolistic market with less than ten major players. Capacity investment decisions of manufacturers affect the demand-supply balance in the market and determine the price level. Pricing decisions affect the overall demand and distribution of demand amongst the DRAM manufacturers. These players adapt their decisions over years by learning from the market dynamics. The aim of this research is to investigate how different capacity investment and pricing decisions of manufacturers affect the price dynamics under different scenarios such as random demand fluctuations between DRAM generations, supply and demand shocks. Coordinative and adaptive strategies of manufacturers are also considered in this research. Agent-based modelling and simulation is a convenient tool to model a system with multiple autonomous interacting players with adaptive capabilities. This study shows that in case of an under-capacity investment coordination, the price in the market increases. However, if one of the manufacturers defects from the coordination, others must defect from the agreement to prevent the loss of market share. Supply and demand shocks create bullwhip effect in the price levels, however the market recovers from a shock after a few product generations. The stationary or random behaviour of demand between generations does not affect the price level in the market significantly in the most of the experiments. Finally, adaptive pricing decisions based on price differentiations may help manufacturers to gain or protect market share in some special cases such as supply shocks. However in most of the cases, the effects of capacity decisions dominate the effects of pricing decisions.

## ÖZET

# ÜRETİCİLERİN KAPASİTE VE FİYATLANDIRMA KARARLARININ DİNAMİK RASTGELE-ERİŞİMLİ BELLEK PİYASASI ÜZERİNE ETKİLERİ

Dinamik Rastgele-Erişimli Bellek (DREB) piyasası ondan az sayıda büyük oyuncusu ile oligopol bir piyasa özelliği göstermektedir. Bu piyasa kapital yoğunluktur ve üreticilerin kapasite kararları arz-talep dengesi ile piyasadaki fiyat dinamiklerini önemli ölçüde etkilemektedir. Fiyat kararları ise talep miktarını ve talebin üreticiler arasında dağılımını değiştirmektedir. Bu oyuncuların kararları yıllar boyunca piyasa dinamiklerinden edindikleri bilgilere göre değişkenlik göstermektedir. Bu çalışmanın amacı üreticilerin farklı kapasite ve fiyatlandırma kararlarının arz, talep şoku ve ürün kuşakları arası rassal hareket eden talep gibi farklı senaryolar altında fiyat dinamiklerini nasıl etkileyeceğini anlamaktır. Üreticilerin işbirlikçi ve rekabetçi stratejileri de bu çalışmada göz önünde bulundurulmuştur. Etmen tabanlı modelleme ve benzetim uyum sağlama yetenekleri olan etkileşen bu çoklu bağımsız oyuncuları modellemek için uygun bir araçtır. Sonuç olarak, anlaşmalı bir şekilde kapasite yatırımını az yapan üreticiler, fiyat seviyesini yükseltmektedirler. Fakat sadece bir üreticinin bile işbirliğinden çekilmesi diğer üreticileri pazar payı kaybetmemek adına anlaşmadan çekilmeye zorlamaktadır. Arz ve talep şokları fiyatlar üzerinde kamçı etkisi yaratmasına karşın piyasa birkaç ürün kuşağından sonra kendini toparlayabilmektedir. Ürün kuşakları arası talebin rassal ya da durgun olması genel olarak fiyat seviyelerini etkilememektedir. Son olarak, uyum sağlayan fiyatlandırma kararları üreticilere pazar paylarını korumak ya da pazar payı kazanmak konusunda yarar sağlayabilse de çoğu durumda sonuçlar üzerinde kapasite kararları fiyatlandırma kararlarına baskın gelmektedir.

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## LIST OF SYMBOLS

\$	United States Dollars
a	Symmetrical market share distribution experiment setting
$Age_p$	Time since launch of a product p
$AvgDemandFrcst_{i,p}$	Average demand forecast of firm i for product p
b	Asymmetrical market share distribution experiment setting
$Backlog_t$	Number of products backlogged for period t
c	Index represents a production cycle
$capacity_{i,p}$	Capacity installed by firm i for product p
I	Demand shock with an increase in demand experiment setting
i	Index representing the manufacturers in the market
$Inventory_{i,t}$	Total inventory on hand of firm i at time t
j	Index representing the manufacturers in the markets
D	Demand shock with a decrease in demand experiment setting
$Demand_t$	Total demand in the market at time t
$demand_{i,t}$	Demand faced by firm i at time t
$DemandForecast_{i,p,t}$	Demand forecast of firm i for product p for time t
$SharedDemand_t$	The demand amount to be shared according to sales price
$DesiredSalesPrice_t$	Desired sales price of a firm i at time t
$Deviation_{j,t}$	Multiplicative deviation of sales price of firm j from the mean sales price
$EntryTime_{i,p}$	Entry time of firm i for product p
$MarketShare_{i,t}$	Market share of a firm i at time t
$NormalizedDev_{j,t}$	The normalized deviation of firm j at time t
p	Index representing product p
$Price_t$	Price of a unit product at time t
$Price^*$	Reference price level
$PriceEffect_t$	Effect of demand on price at time t
$Production_{i,t}$	Total production made by firm i at time t

<i>ProfitMargin</i>	The coefficient determines to sales price as a function of unit cost
<i>RealizedDemand<sub>t</sub></i>	Total demand realized in the market at time t
<i>TotalRealDemand<sub>i,p</sub></i>	Total demand realized by firm i for product p
<i>Sales<sub>i,t</sub></i>	Total sold products at time t by firm i
<i>SalesPrice<sub>i,t</sub></i>	Sales price of a firm i at time t
<i>Supply<sub>t</sub></i>	Total products in the market at time t
<i>t</i>	Index representing one month long time period
<i>UnitProdCost<sub>i,t</sub></i>	Unit production cost of a firm i at time t
<i>UnsatisfiedDmnd<sub>t</sub></i>	Unsatisfied demand at period t
<i>UnutilizedCap<sub>i,t</sub></i>	Unutilized capacity of firm i for period t
$\alpha$	Significance level for statistical t-tests
$\beta$	Exponent for cost function
$\Theta$	Exponent for price function

## LIST OF ACRONYMS/ABBREVIATIONS

ABM	Agent-based Modelling
Asymm	Asymmetric
Dist.	Distribution
diff.	Different
Df	Degree of freedom
DRAM	Dynamic Random-Access Memory
DXI	DRAM Output Value Index
IoT	Internet of Things
LPDDR4	A type of dynamic random-access memory
No.	Number
PC	Personal Computer
Signif.	Significantly
Symm	Symmetric
USD	United States Dollars

## 1. INTRODUCTION

Random-Access Memory (RAM) is a memory type which is used to store data temporarily on a computing device when the device is on. Dynamic Random-Access Memory (DRAM) is a type of random-access memory where each bit of data is stored in a separate capacitor. As a type of RAM, usage of the DRAM is very common in modern computers and the computing performance of a computer, such as a server, personal computer (PC) or smartphone, is highly dependent on the DRAM capacity. Improvements in technology and data-driven systems lead an increase in demand for more computational power. Importance of DRAM as a computer component is escalated for many parties. These parties can be exemplified as business, academy, home users and the companies which provides server or data services. Price levels and product availability in the market has a significant influence on all of these stakeholders. In the past years, market encountered with unexpected price rise and drops. Understanding the dynamics of price fluctuations and product shortage in the market is crucial because of this wide influence area.

DRAM market shows the characteristics of an oligopolistic market with less than 10 players. Four of these players, listed with their market shares in parentheses, are Samsung (44.9 %), SK Hynix (27.9%), Micron Group (22.6%), and Nanya (2.8%) [6]. Small players in the market have tendency to lose market share in recent years. At the beginning of this research, Winbond had 1.1% and Powerchip had 0.8% market share, however during the one-year period Winbond's market share declined to 0.8% and Powerchip's market share declined to 0.5%.

DRAM industry is a capital-intensive industry with a stochastic demand and supply [1]. The market is controlled by four major players and due to this fact, capacity and production decisions of these players directly affect market supply levels and price. Besides that, the oligopolistic, capital and technology intensive structure of the market creates entry barriers to the market.

DRAM market is a commoditized market where product differentiation is hard and customer loyalty is low [7]. Product life-cycle is short [1]; according to the Moore's Law, the number of transistors in a computer chip doubles in every two years [7]. A sample DRAM product life-cycle can be seen in Figure 1.1.

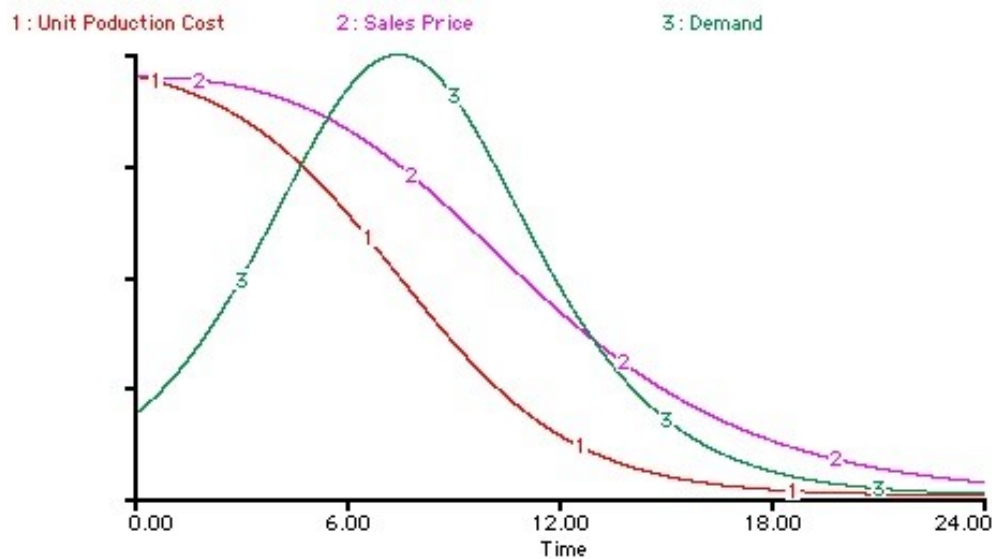


Figure 1.1. A sample product life-cycle in DRAM market [1].

On the other hand, lead time of launching a new product in the market is high due to the research and development process [7]. Firms that can launch a product earlier than their rivals to obtain a competitive advantage in terms of cost and benefit from larger profits [8]. For instance, the market leader Samsung charges lower prices to increase the number of sold quantity and obtain more market share [7]. The other players in the market must also drop their prices to compete with Samsung, however, they cannot obtain as much profit as Samsung since they cannot lower their costs and therefore prices to Samsung's level [7].

Another consequence of delayed entry to the market is the possibility of losing market share to a competitor who entered the market earlier [9]. The type of products launched by top DRAM manufacturers and their entry times to the market with these products are demonstrated by DRAM Process Node Roadmap for Manufacturers in Figure 1.2 [2].

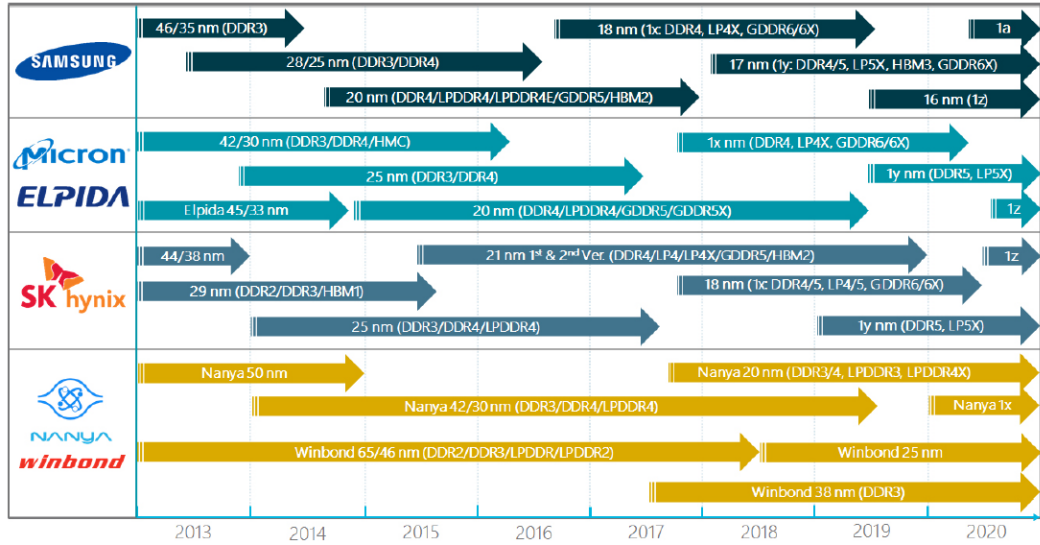


Figure 1.2. DRAM process node roadmap of manufacturers [2].

Before the launch of a new product generation, each manufacturer should take a capacity investment decision. The level of capacity investment can be decided according to various objective functions. The objective of a manufacturer can be gaining more market share to eliminate their competitors from the market or increasing profit.

Different objectives lead manufacturers to build different investment strategies which results in a capacity game between competitors. Capacity games in the market affect market price considerably. If firms install relatively higher capacity than competitors, they can lower their costs. If they invest less capacity than the average anticipated demand, they can raise the price in order to obtain more profit margin. The effects of capacity on price can be seen in Figure 1.3.

The causal relations are represented by an arrow in this figure. The direction of the arrow symbolizes the direction of causality. The positive causality is represented by a plus (+) sign, which means an increase (decrease) in the effecting variable creates an increase (decrease) in the value of effected variable. The negative causality is represented by a minus (-) sign, which means an increase (decrease) in the effecting variable creates a decrease (increase) in the value of the effected variable.

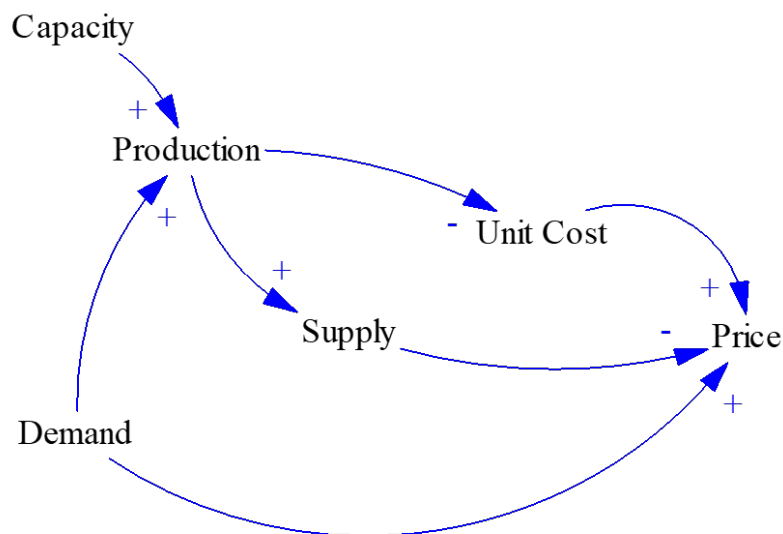


Figure 1.3. The effects of capacity decisions on price.

Firms that enter the market earlier decrease their production costs significantly [1]. There are two sides of cost competition, a low-cost firm can decrease the market price significantly so the other players cannot afford to sell from that price and leave the market or receive a lower market share. Another perspective is that low-cost firms can sell their products at a higher price and obtain larger profits than their competitors; so in the future periods, they can invest higher capacities than their competitors.

Demand-supply balance is another factor that affect price dynamics in the market. As the demand increases in the market, both the price in the market and firms willingness to produce will increase. The more a firm produces, the more it decreases its unit production costs. Decrease in unit production cost may be reflected on the sales price and the manufacturers with lower costs can satisfy a larger part of market demand. As firms produce more, the goods become abundant in the market. Then customers are not willing to pay more for that product. Increasing supply of products leads market price to decrease and reduces the profit margin of the firms. The effects of demand and production amount on price again can be seen in Figure 1.3.

Producing comparatively less than average market demand is another problematic issue. From the customer point of view, in case of a shortage of products, it becomes hard to find that product and even the price of available products is higher than general. Even though firms may raise the price by producing less than the demand, there is always a risk of loss of customers' goodwill and market share. When a firm loses market share, it is hard for that firm to gain that share. All in all, the capacity decision is an important matter for all DRAM manufacturers, which must be handled with detailed planning. The consequences of capacity investment decisions will not affect only the manufacturers themselves but also affect all echelons of the market.

Besides the planned capacity decisions of the manufacturers, exogenous events can affect the DRAM market dynamics such as supply or demand shocks. A supply shock indicates the unpredicted shortage in stocks. A demand shock indicates a sudden change in demand in terms of quantity or product type. Supply shocks can be caused by accidents, natural disasters or terrorism. Due to this kind of disasters, the production facilities may not be able to operate, supply network may get damaged or stocks may disappear.

The demand and supply shocks are commonly encountered problems in the DRAM market. On September 4<sup>th</sup>, 2013 a fire at Hynix's Chinese Fab 1 and 2 destroyed most of its production capacity and lead to increase in DRAM prices [10]. On the other hand, capacity shocks may be related to change of demand in the market. Due to the increase in mobile phone production, the most of the capacity of DRAM manufacturers dedicated for mobile phones, which lead to a capacity shock in PC DRAM market [11]. Samsung dedicated more DRAM capacity to LPDDR4 (DRAM for mobile phones) since mobile phone market is more profitable than PC market [11, 12]. There is also an increasing demand in the market. Activities such as gaming, data mining, IoT increased in recent years, which will increase the demand of DRAMs. Besides those, capital expenditure growth of top three suppliers was moderate in 2017. As a result of increasing demand-supply ratio, the market price increased even more causing the customers suffer from high prices.

DRAMeXchange created an index called DXI which is an index to measure the DRAM output value and to help to track DRAM prices and output trend. "DXI is calculated by multiplying mainstream DRAM chips with their respective spot prices" [13].

The fluctuations in DRAM prices can be tracked from DXI values and DXI values from 2008-2016 can be seen in Figure 1.4. Mostly as a result of a supply and demand levels in the market, a boom or bust is observed in prices once in a two or three year period. In this Figure 1.4, the boom and bust periods can be seen from price index. Between 2005 to early 2008 capacity utilization of firms were nearly one-hundred-percent and the market prices are relatively higher than other periods.

When manufacturers install comparatively more capacity from 2008 to mid 2009 period, capacity utilization has dropped to eighty-percent levels and prices decreased due to low demand compared to capacity investment [14]. Between 2013-2016 years price index increases again however, after mid-2015 there is a significant drop in price index. Customers are affected negatively from periods when an price increase is observed. Periods with lower prices affect manufacturers negatively.

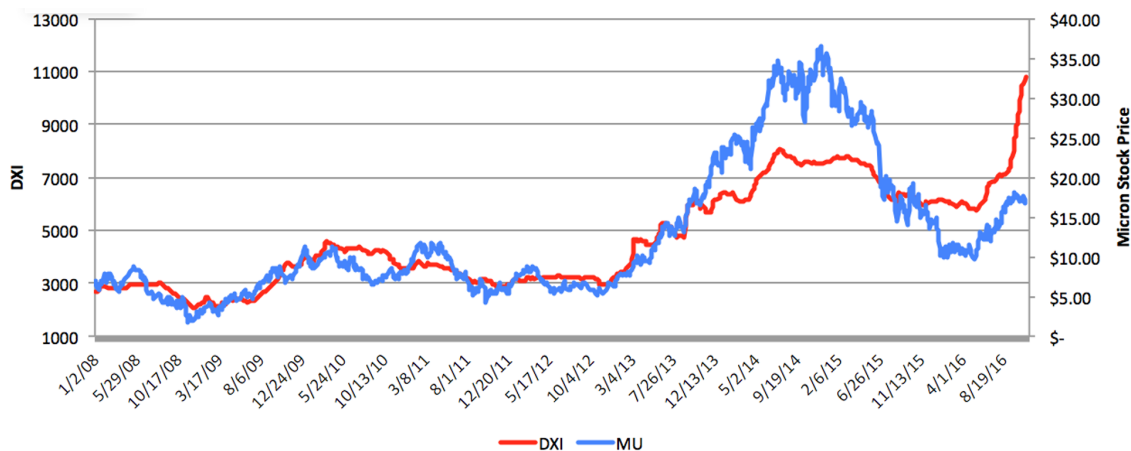


Figure 1.4. DXI data from 2008 to 2016 [3].

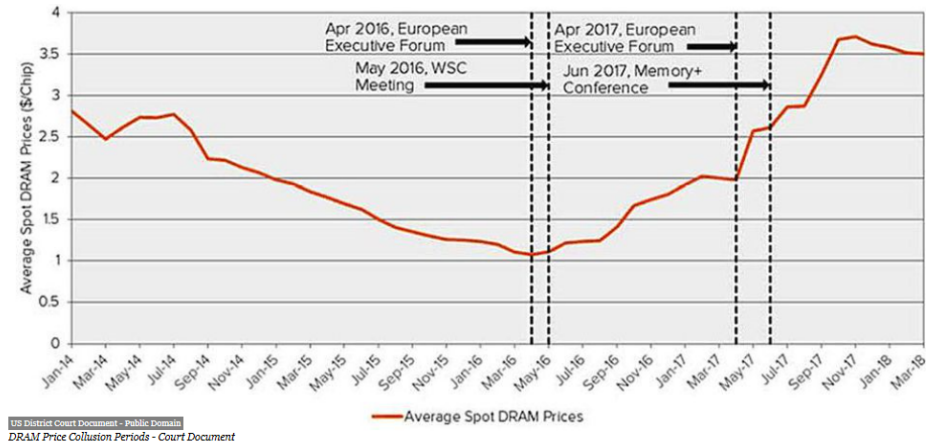


Figure 1.5. Average spot DRAM prices in 2014-2018 [4, 5].

Recently, from the beginning of 2017, market observes relatively higher prices than 2013-2016 period and there is a positive trend in average DRAM prices until mid-2018 which can be seen in Figure 1.5. Supply and demand levels can affect the market price, however, in a market without a supply or demand shock, it is not expected to see major changes in price levels with manufacturers who take independent capacity decisions. Even though, demand and supply shocks are blamed for the rise in price levels, especially for 2017-2018 period, in April 2018 a class action suit filed against the top three DRAM manufacturers: Samsung, Micron and Hynix with the claim of installing low capacity to inflate prices and obtain more profit in the market [4]. This lawsuit against top manufacturers is an indication of a coordination game in the market.

### 1.1. Problem Description

High price levels in the market is a severe issue from customers' point of view. A sudden price increase damages the customers' welfare. A sudden price drop damages the manufacturers' welfare by decreasing their profits. Understanding the mechanisms behind the change in price levels is an important problem. Capacity, production and pricing decisions of manufacturers are key components of main market dynamics. This research aims to investigate how different capacity investment and pricing decisions

of manufacturers affect the price dynamics under different scenarios such as random demand change between DRAM generations, supply and demand shocks. Adaptive coordinative and competitive strategies of manufacturers are also considered as a part of scenario analyses.

One of the important factors that affect price dynamics is the total capacity level in the market because it affects the future production ability in the market. Decisions of manufacturers are vital in determining these dynamics. A manufacturer may decide on capacity investment level with different mechanisms. A manufacturer may choose to invest purely depending on its demand forecast in order to sell more products and obtain more market share and revenue. Another way to select a capacity investment level is due to a profit maximization objective function. If the manufacturer wants to gain more profit, it does not only consider the demand satisfaction but also considers raising the price. In order to raise price, a manufacturer may invest less capacity than anticipated demand at the cost of loss sales.

If all manufacturers in the market act independently in their decisions, what kind of price dynamics can be expected in the market is one of the questions investigated in this research. However, manufacturers do not have to act independently. They may consider the acts of their rivals. A manufacturer may embrace a competing strategy against its rivals or choose to coordinate with them. A coordinative strategy may aim to increase the price in the market by investing less capacity than demand forecast within an agreement with competitors.

Besides using capacity as a strategic variable, the pricing mechanism can also be used as a strategic tool to compete with other firms. A competitive strategy may aim to decrease price levels to gain more market share or to eliminate some of the high cost competitors from the market. This research investigates how price dynamics in the DRAM market are affected by competitive and coordinative behaviours of manufacturers by capacity and pricing decisions. A general market structure is conceptualized for DRAM market in order to set the system boundaries.

## 1.2. Market Structure Conceptualization

The market has an oligopolistic structure with four to five major players. The capital-intensive characteristic of the market creates entry barriers to market. The investment and production decisions are the main determinants of the market dynamics. Products from same generation and specifications do not differentiate, so customers are sensitive to price differences between firms. They can easily switch to a firm with lower cost supplying the same product.

Supply and demand shocks are commonly seen in the market. Shocks disturb the demand-supply balance and alter the price levels. Unexpected and sudden changes in price levels have an influence on both manufacturers and customers. Manufacturers can be harmed by unexpected low price levels, customer can be harmed by escalating prices.

Adaptation is the key to the success in business. Manufacturers adjust their capacity, production and pricing decisions according to their experiences and market environment over time. Interactions between manufacturers exist in different forms. There are signs of competitive strategies applied by top manufacturers to gain market share from rival firms. There are also signs of coordinative behaviour in the market to increase price levels. The most straightforward way to raise price levels is investing less capacity to the market. Even in a 100% utilization case, the products will be scarce in the market and manufacturers can charge higher prices. However, these strategies may also cause loss of customer's goodwill and decrease in the overall demand level.

Pricing is another strategic variable in the market. The more experienced firms in production can decrease their unit costs more than their competitors. They can charge lower prices for the same product and gain more customers from the other manufacturers.

### 1.3. Literature Review

The analytical mathematical models for price-production quantity games are common in the literature to solve production-pricing games [15–17]. In 1838 Cournot [18], built a mathematical game-theoretical model depending on production quantity decision of manufacturers in an oligopoly [19]. In Cournot’s model, manufacturers determine production quantity independently and when they enter into market, the price is determined by demand-supply balance in the market. On the other hand, in 1883 Bertrand [20] claimed price as a competitive strategy in an oligopolistic market [21]. The equilibrium points of these two games differ from each other under duopolistic settings.

Krebs and Scheinkman [19] worked on Cournot and Bertrand games under certain assumptions and showed that in some special cases such as where most of the cost comes from demand realization Bertrand-like games end up with Cournot equilibrium. In 1952, Stackelberg introduced a leader-follower game for quantity competition [22].

There are extensions on economic oligopolistic non-coordinative game theoretical models, however the most of the cases focus on either production or price as strategic variable, but not both. Most of the studies do not consider capacity as a strategic competitive tool but as a constraint.

De Borger and Van Dender [16] studied duopolistic interactions between facilities that supply perfect substitutes and compared the results with monopolistic settings. In this research, facilities took sequential decisions on capacities and prices. As a result of this study, the price levels for Bertrand model of duopolistic settings were found between the price levels of socially optimal and monopolistic market settings. The number of manufacturers were limited with two in this study. However, in De Borger and Van Dender’s study, there was only one capacity decision formulation which is profit maximization and it was not adaptive. The problem was solved only for two players.

Chuang *et al.* [15] presented a non-coordinative game theory model with Cournot oligopolistic settings in electricity market. The model was solved with different competitive scenarios for generation expansion planning: independently profit maximizing, maximizing profit in a cartel and Cournot duopoly competition as a single player was against the joint of the other players. Similar to De Borger and Van Dender [16], the Cournot outcomes fell between social welfare optimization and cartel profit maximization settings. In the study of Chung *et al.* the capacity planning part was based on profit maximization, however the production part was not investigated in the model.

Gardete [14] studied specifically on competition between the manufacturers in the DRAM market. The study was based on information sharing among competitors. He mostly focused on market information (demand and cost) sharing between players of a duopolistic market. Analytical solutions according to Cournot competition shows that both customers and manufacturers got benefit from sharing demand information between competitors, additionally capacity and production signals of a competitor can be used to predict the market demand in a duopoly [14].

All of these studies searched an equilibrium point as a result of consecutive games. The change in price levels or other output of interest until the reaching an equilibrium point was not the focus of these researches. Besides that, the decision formulations did not change in time, even though the sequential decision mechanisms were utilized. Finally, most of these studies were bounded by duopolistic settings, the dynamics of market with more than two players were not investigated.

#### 1.4. Methodology

The analytical solution methods or optimization methodology have some limitations and assumptions as all methodologies. As the number of players increase, the complexity of a problem increases. As the degree of equations increase, it becomes hard even impossible to solve the equation. Handling non-linear relations is another factor that increases mathematical complexity. In order to extend these kinds of as-

assumptions and limitations, simulation methodology has significant advantages, even though it does not offer an optimal or exact solution. The source of this difference depends on the structure of these two methodologies.

On one hand, simulation models, especially system simulation, is mainly descriptive. A descriptive tool tries to describe the current state of a situation. On the other hand, optimization models are prescriptive models. A prescriptive tool tries to offer a solution to a problem. The aim of this study is to examine the price dynamics in the market rather than finding an equilibrium point, if there exists any equilibrium. A simulation model provides an opportunity to create a simplified model for the system in interest and observe the pattern of dynamics in time.

Agent-based modelling (ABM) and simulation approach is another modelling methodology used for studying game theoretical models [23], which is also the selected modelling methodology for this study. Agent-based modelling is a simulation technique, where the model is composed of autonomous and interacting entities called agents. Agents are the key components of the ABM approach. An agent is an independent identity which can make decisions with their pre-defined rules and by evaluating the environment. The environment is the main medium of interactions between agents. The behaviour of each agent can be set by agent specific rules and parameters.

A multi-agent heterogeneous problem can be easily modelled with ABM methodology. As a simulation approach, ABM has certain advantages when modelling with multiple players. Each player can act consecutively and interact with other players. Agents can learn and adapt themselves according to their interactions with other agents or changes in the environment [24, 25].

Choice of the methodology is highly relevant to the characteristics of the real system. Each independent player in the market can be represented by an agent in the simulation model. Since these agents interact with each other and the environment they can learn and update their perception references. In analytical solution methodologies,

the behavioural rules of players cannot be changed or adapted during the consecutive time periods. However, adaptability is a key feature of agents in an ABM model. Adaptive behaviour of manufacturers can be easily modelled with ABM methodology.

As modelling environment NetLogo is used in this research. NetLogo is a multi-agent, Java based, open-source programming environment authored by Uri Wilensky, developed at the The Center for Connected Learning and Computer-Based Modeling, Northwestern University [26].

## 2. OVERVIEW OF THE MODEL

In order to understand the dynamics in the DRAM market, a general conceptual model is built to represent a capital-intensive, oligopolistic market similar to DRAM market. This model is utilized to understand how different conditions in the market affect the overall system single-handedly. These conditions may be the sudden shocks in the market or capacity and pricing decisions of manufacturers. After understanding the individual impacts in this generalized market model, how different factors affect the system together is the question of interest in order to investigate DRAM market specifically. The possible reasons of change in market dynamics can be detected by the experiments on the generalized model, then an experiment specific to DRAM market can be designed.

In this conceptual model, manufacturers and customers are the key components of the modelled system. They affect the main variables such as production amounts and price in the system. There are five manufacturers in this specific model. In an oligopolistic setting, each manufacturer takes independent decisions such as capacity investment or production. It is hard to capture their independent decisions from the perspective of a single decision maker. Because of this, behaviour of each individual player are modelled separately. Customers are modelled as a single entity in this problem, modelling the separate characteristics of each customer is not valid for the objective of the problem in interest.

It is a mathematically complex problem with more than two players in the market. Each manufacturer is an autonomous entity which also learns and adapts itself according to the environment. The core behaviours of manufacturers are mainly dependent both on other agents decisions and their own decisions. This kind of interactions creates temporal feedback loops. For example, demand in the market is considered as endogenous, which means while the demand affects the price, it is also affected by the price. Manufacturers are the determinants of market price with their capacity, pro-

duction and pricing decisions. Then the price affects the total demand in the market. Additionally, in the long run deviations from expected demand affects the capacity installation decisions of manufacturers.

There are some perception change delays and action delays in the model. When manufacturers take a capacity instalment decision, they cannot start production immediately. Their technological capabilities are the determinants of their entry time to the market. Change in perception of firms are also due to time delay because firms anchor their perceptions on many measurements and it takes time to adjust their perceptions according to new measurements [27]. This kind of delay structures exist in economical market models, as well as in this model.

In this model, some of the behavioural functions are non-linear. For instance, the cost function of manufacturers is a non-linear decay function because in real life the unit production cost does not always decrease in same amount with number of produced units. As another example, effect of demand-supply imbalance to market price is represented by non-linear functions, because price does not increase at the same rate as the demand-supply ratio increases. During modelling phase, the manufacturers must have adaptive capabilities in order to respond to the changes in demand, price and total supply in the market.

As a strategy, firms may choose to set a different price from their competitors. The manufacturers with more production experience can lower their unit production costs at a significant level. The demand in the market is sensitive to price. If manufacturers set a lower price than their competitors, they can get more market share by gaining competitors' demand. This is a strategy to increase market share at the cost of decreasing profit margin. However in the long run, with more production they can decrease their unit costs even more and then may choose to increase their profit margin to obtain more profit. Each firm can determine a price based on its unit production cost with a profit margin. After setting a sales price, some portion of demand of high price firms are shared amongst the low price firms.

## 2.1. Assumptions

In these section the underlying assumptions used during the modelling phase will be explained.

- Product life-cycle is assumed to be on average 24 months.
- Products first occur as product-ideas in the market. If a firm starts to produce that idea, a product launch happens. Then the demand for product starts to be generated by the model.
- This research investigates the interactions between manufacturers within a product generation. The interactions between generations are removed from the model in order to avoid complexity.
  - (i) When a firm installs capacity for a future product generation; it stops manufacturing of the current generation.
  - (i) A firm produces one type of product generation at a time.
  - (i) Each firm chooses to produce the same product same product generation to launch into market. Firms take the capacity investment decisions at the same time.
- There is a delay between capacity decision and starting production of a product generation. During this delay, a manufacturer does not produce any product.
- It is assumed that all manufacturers can see the demand pattern created by a product-idea equally and perfectly.
- If a manufacturers cannot satisfy some portion of its realized demand, that portion is satisfied by another manufacturer. In next time period that portion of demand is distributed to the manufacturer who satisfied the demand.

The base demand pattern generated for this model is shown in Figure 2.1, this demand pattern is generated by an innovation adoption model, which is similar to Roger's [28] adoption dynamics and adopter categorization study. This demand pattern is constant for each product generation. This pattern can also be multiplied by a random number to generate different demand levels for different product generations. The demand is calculated based on this demand pattern every period and it is updated according to price levels in the market. Then the total demand is distributed among the manufacturers according to their market shares in each period. Market share is the ratio of a firm's total sales quantity to total sales quantity of all firms.

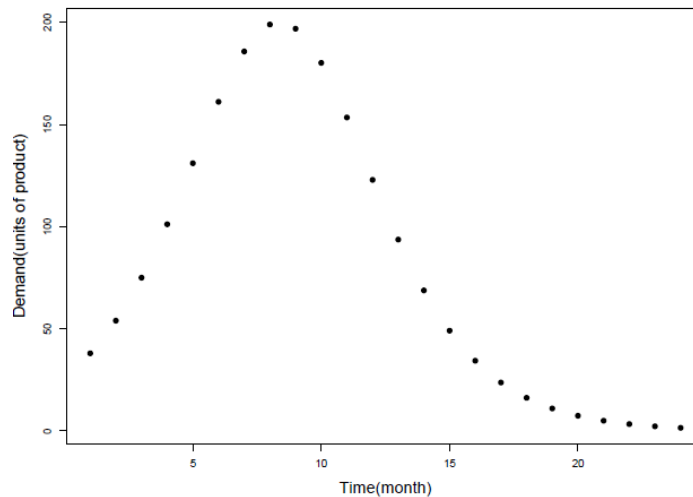


Figure 2.1. Base demand pattern.

## 2.2. Definitions

In this part the indices and variables used in the notations will be explained. The list of indices can be found in Table 2.1. The main variables, their explanations and units can be seen in Table 2.2. The time unit in the model is one month. A cycle or production cycle is defined as the time from the launch of a product generation until the capacity investment decision for the next product generation.

Table 2.1. Index definitions.

<b>Index</b>	<b>Definition</b>	<b>Range</b>
$i, j$ (aliases)	Manufacturers	$\in \{1, \dots, 10\}$
$c$	Cycle	$\in \{1, \dots, 20\}$
$t$	Time(months)	$\in \{1, \dots, 480\}$
$p$	Product generation	$\in \{1, \dots, c\}$

Table 2.2. Demand related variable definitions.

<b>Variable Name</b>	<b>Unit</b>	<b>Definition</b>
$Sales_{i,t}$	Product	Total sold products at time t by firm i
$Demand_t$	Product	Total demand in the market at time t
$demand_{i,t}$	Product	Demand faced by firm i at time t
$capacity_{i,p}$	Product per period	Capacity installed by firm i for product p
$Price_t$	\$/Product	Price of a unit product at time t
$SalesPrice_{i,t}$	\$/Product	Sales price of a firm i at time t
$DesiredSalesPrice_t$	\$/Product	Desired sales price of a firm i at time t
$UnitProdCost_{i,t}$	\$/Product	Unit production cost of a firm i at time t
$PriceEffect_t$	Unitless	Effect of demand on price at time t
$Backlog_t$	Product	Number of products backlogged for period t
$RealizedDemand_t$	Product	Total demand realized in the market at time t
$TotalRealDemand_{i,p}$	Product	Total demand realized by firm i for product p
$MarketShare_{i,t}$	Unitless	Market share of a firm i at time t
$Production_{i,t}$	Product	Total production made by firm i at time t
$Inventory_{i,t}$	Product	Total inventory on hand of firm i at time t
$EntryTime_{i,p}$	Month	Entry time of firm i for product p
$DemandForecast_{i,p,t}$	Product	Demand forecast of firm i for product p for time t
$AvgDemandFrcst_{i,p}$	Product	Average demand forecast of firm i for product p
$UnsatisfiedDmnd_t$	Product	Unsatisfied demand at period t
$UnutilizedCap_{i,t}$	Product	Unutilized capacity of firm i for period t
$Age_p$	Month	Time since launch of a product p
$Supply_t$	Product	Total products in the market at time t

### 3. DESCRIPTION OF THE MODEL

Manufacturers are the main agents in the model who take and apply decisions. Product ideas and products are entities in the model. Product ideas are the generations of products which have completed research and development studies. The future demand of these product ideas are anticipated. They are not tangible products, but they are like planned product projects. Products are the tangible goods in the market. A product is created from a product idea when a firm installs a capacity for that idea. Manufacturers decide the level of capacity investment at every 24-month period according to the most recent product idea in the market. Installed capacity decision mainly depends on the forecasted demand of that product idea, capacity signals of competitors in the market (in terms of quantity and timing) and market share of the firm. Demand forecast of each product idea is in a form of 24-month array and it is public to every firm. The information provided to all firms is symmetric in the market. Manufacturers only update their demand forecast according to their total realized/forecasted demand ratio from the last product generation.

Then after manufacturers launch a product, they choose a production level at every period until the next capacity installation. This time period between launch of a product to next capacity investment decision is defined as a (production) cycle in this research. A production period is defined as a month period  $t$ . At each production period  $t$ , demand is generated for that product and this demand is shared amongst the manufacturer firms according to their market shares.

If a firm cannot satisfy its realized demand, the demand will be satisfied by another firm with enough inventory on hand. In the next period the demand is shared according to updated market shares. It means if a manufacturer cannot satisfy the demand encountered, it may lose its market share to another firm. Half of the unsatisfied demand at the end of a production period is backlogged to the next production period. Before a new capacity investment decision, the profiles and statistics used in

decision making processes are updated according to information gathered from the last production cycle. The pseudocode for main procedures of the model is shown in Figure 3.1.

### 3.1. Capacity Installation

In this section the capacity investment decision process of manufacturers will be explained in detail.

After 24 months from firms last capacity investment decision, each manufacturer must take another capacity investment decision for a new product generation at the same time. Manufacturers use informations obtained from their own experiences from the market during a capacity installation period. These informations are demand signals sent by product idea, their market shares, the capacity signals sent by each of their competitors, technology adoption rates and the forecast correction factors. All of these informations and profiles are updated at the end of a production cycle before the capacity installation. Market shares of firms are updated according to total sales quantity of firms. The technology adoption rate is an attribute that specifies the entering time of firms into the market with the new idea. If firms face a different demand than what they forecasted during a production cycle, they adjust their demand forecast for next product generation by forecast correction factor. The adjustment process can be seen in Equation 3.23. The details of this correction will be explained in 3.3. Update of Profiles and Signals section.

Each firm sends capacity signals to its competitors depending on their known market demand share and technology adoption rate to the competitors. The competitor firms cannot know the exact market share and technology adoption rate of a firm, however can follow these attributes with a time delay. A firm collects these capacity investment signals from its competitors to obtain a general forecast of future capacity investment in the market.

```

Setup Create manufacturers and initial product idea for next product generation;
if  $TimeSinceLastCapacityInstallation \geq 24$  then
  Do each step for each  $manufacturer_i$ 
    Step 1: Make a demand forecast for next product generation;
    Step 2: Send capacity signals to competitors based on market share and demand forecast;
    Step 3: Take a capacity investment decision based on profit maximization or average of demand forecast;
  end if
for each production period  $t$  for a product  $p$  do
  Generate  $Demand_t$  for product  $p$ ;
  Do each step for  $manufacturer_i$  with  $capacity_{i,p} > 0$  and  $EntryTime_p \leq t$ 
    Step 1: Take a production decision according to  $DemandForecast_{i,p,t}$ ;
    Step 2: Calculate  $UnitProdCost_{i,t}$ 
    Step 3: Calculate  $Price_t$ ;
  Distribute  $Demand_t$  to manufacturers as  $demand_{i,t}$ ;
  Step 4: Satisfy the  $demand_{i,t}$ ;
  Calculate the amount of unsatisfied demand
  if  $\exists manufacturer_i$  with  $Inventory_{i,t} > 0$  then
    Step 5: Satisfy the excess demand;
  end if
  Backlog the half of the unsatisfied demand;
end for
Update statistics;

```

Figure 3.1. Pseudocode for main procedure.

There are two types of capacity decision process for manufacturers. They decide the level of capacity to be installed according to their capacity profiles. The capacity profile of a manufacturer can be either demand-oriented or profit maximizing for a product generation. If a manufacturer's capacity profile is demand-oriented, its capacity installation level is equal to average of demand forecast for the next production period. If the capacity profile is profit-maximizing, the manufacturer uses an algorithm to anticipate the future profits. Each firm takes into consideration a reference sales price, predicted unit production cost and capacity instalment cost as inputs of a profit function and simulates it for the following 24 months with different capacity levels. The range of these capacity levels are from zero to maximum demand forecast within 24-month period. As a reasonable assumption, a firm's capacity instalment level does not exceed the maximum demand level in the market. Then each manufacturer runs a simulation for the next 24 months production cycle and estimate their profits for each time period for each feasible capacity level. At the end of simulation, the monthly profits are summed up for each capacity level. Manufacturers choose the capacity level that maximizes their summed estimated profit over next 24 months. This simulation takes place in R software environment at every capacity decision period and the output is returned to agent based simulation model. The pseudocode for profit maximizing capacity installation algorithm can be seen in Figure 3.2.

**Setup** For a manufacturer  $j$   
*ProfitMargin* = 1.2, *Sales* <sub>$j,1$</sub>  = 0 Product, *UnitProdCost*<sub>1</sub> = 30 USD  
*SalesPrice*<sub>1</sub> = 30 USD , *UnitCapacityCost* = 10 USD  
*Demand* <sub>$t'$</sub> , *MarketShare* <sub>$j$</sub> ,  $\sum_{i=1; i \neq j}^N \textit{capacity}_i$  and *demand* <sub>$t',j$</sub>  is given for  $\forall t'$ ;  
**for** *capacity* <sub>$j$</sub>  = 0 to  $\max_{\forall t'} \{ \textit{demand}_{t',j} \}$  **do**  
    **Estimate**  
    **for**  $t' = t$  to  $t + 24$  for product  $p$  **do**  
        Calculate *demand* <sub>$j,t'$</sub>  by using Equation 3.1;  
        Calculate possible *Sales* <sub>$j,t'$</sub>  by using Equation 3.7;  
        Calculate *Price* <sub>$t'$</sub>  by using Equations 3.3 and 3.5;  
        Update total demand for period  $t'$  by using Equation 3.2;  
        Calculate *Profit* <sub>$t'$</sub>  by using Equation 3.10;  
        Update *UnitCost* <sub>$t'$</sub>  by using Equation 3.6;  
        Update *SalesPrice* <sub>$t'$</sub>  by using Equations 3.7 and 3.8;  
        Update *RealizedDemand* <sub>$t'+1$</sub>  by using Equation 3.2;  
    **end for**  
**end for**  
Choose the *capacity* <sub>$j$</sub>  which maximizes  $\sum_{t'=t}^{t+24} \textit{Profit}_{j,t'}$  to invest;

Figure 3.2. Pseudocode for capacity installation by profit maximization.

$$demand_{j,t} = RealizedDemand_t * MarketShare_j \quad (3.1)$$

$$RealizedDemand_{t+1} = Demand_{t+1} * (-0.2 * \frac{Price_t}{Price_{t-1}} + 1.2) + Backlog_t \quad (3.2)$$

$$PriceEffect_t = \max\left\{\left(\frac{RealizedDemand_t}{\sum_{i=1; i \neq j}^N capacity_i + capacity_j}\right)^{0.5}, 1\right\} \quad (3.3)$$

$$Sales_{j,t} = \min\{demand_{j,t}, capacity_j\} \quad (3.4)$$

$$Price_t = SalesPrice_t * PriceEffect_t \quad (3.5)$$

$$UnitProdCost_{j,t+1} = \left(\sum_{t'=1}^t Sales_{i,t'}\right)^{0.5} * UnitProdCost_1 \quad (3.6)$$

$$DesiredSalesPrice_{j,t} = UnitProdCost_{j,t} * ProfitMargin \quad (3.7)$$

$$SalesPrice_{j,t+1} = SalesPrice_{j,t} + \frac{DesiredSalesPrice_{j,t} - SalesPrice_{j,t}}{2} \quad (3.8)$$

$$Backlog_{t+1} = \max\left\{0, \frac{Demand_t - (Sales_{i,t} + \sum_{i=1; i \neq j}^N capacity_i)}{2}\right\} \quad (3.9)$$

$$Profit_{j,t} = (Price_t - UnitProdCost_t) * Sales_{i,t} - UnitCapacityCost * capacity_j \quad (3.10)$$

This part will explain the each of equations used in profit maximization algorithm in detail. Total demand forecast in the market is known to all firms symmetrically. However the realized demand will be different than this value which is forecasted by Equation 3.2. The price level will affect the demand value in the market. Since the manufacturers do not know the reference price value in the customer's mind, it uses the price level of previous period to forecast this effect. The formulation for effect of price on demand is derived similar to a downward sloping inverse demand function. Then the backlogged demand from previous period, which is the half of the unsatisfied demand, is summed up to obtain total realized demand in the market. The prediction of backlogged demand can be seen in Equation 3.9.

In Equation 3.1, the *manufacturer<sub>j</sub>* computes its future anticipated demand according to its market share. Sales quantity of a firm will be the maximum of the demand received or the installed capacity level which is indicated in Equation 3.4. In this context, sales and production are equivalent terms to each other, since during a two year forecast process the calculations of firms may not be so accurate to anticipate inventory levels. Unit production cost of the firm declines by the square root of total sales (production) quantity at each production period, shown in Equation 3.6. Sales price will not be updated immediately but after a time delay. The delay in sales price update according to unit production cost is represented by Equations 3.7 and 3.8. The overall price in the market is forecasted by the multiplication of sales price and effect of demand/capacity ratio on price, which can be seen in Equations 3.3 and 3.5. After these predictions, the firm predicts the profit for period  $t$  by Equation 3.10.

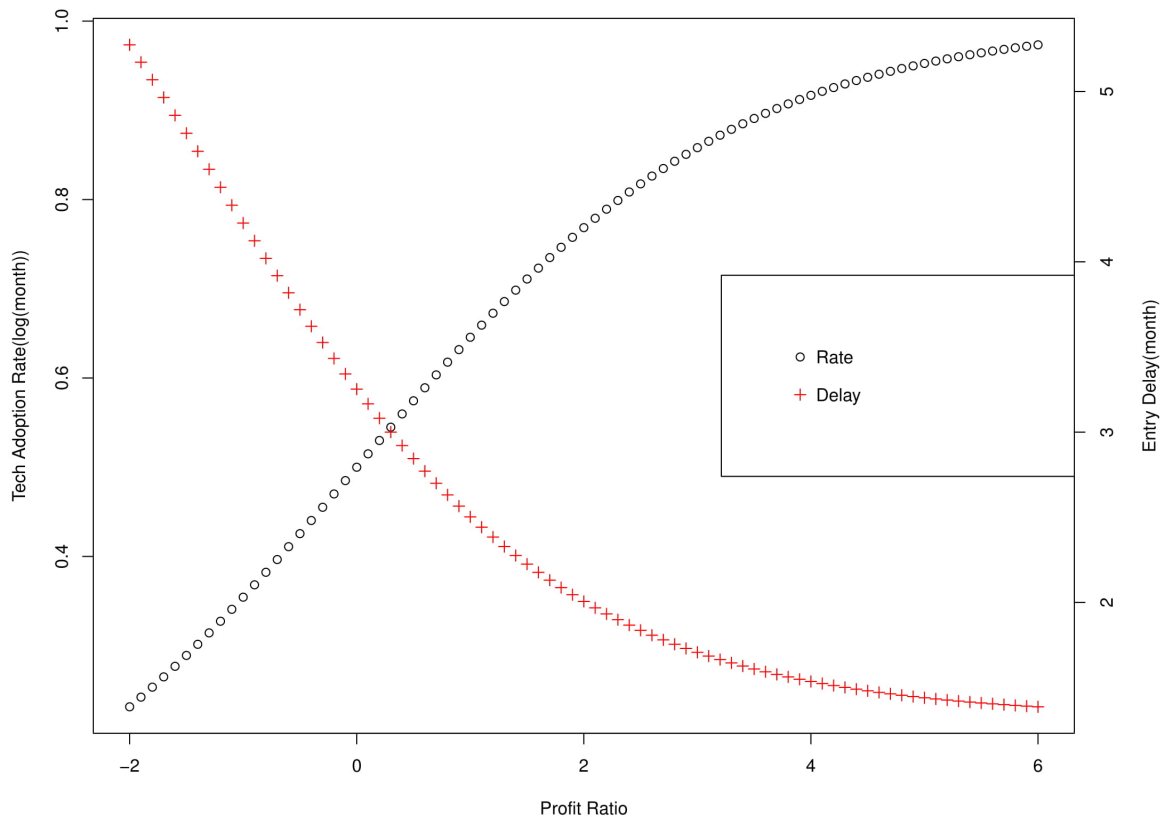


Figure 3.3. Change of entry delay and technology adoption rate due to profit ratio.

As an extension to this profit maximizing algorithm, there is a correction part for capacity installation quantity. If a firm installs a capacity amount lower than the minimum demand will be faced in the market, it sets its installation quantity to this minimum demand. Otherwise, firms may end to install nearly zero capacity in the market. It may be a decision to take in real-life. However, for the simplification purposes, it is avoided to a firm skip a production cycle.

Even though a manufacturer determines the capacity instalment quantity in a single period, it cannot launch the product directly into the market. There is an entry delay for all firms for each product. Entry delay of firms depends on the technology adoption rate of a firm. Technology adoption rate is an indicator of how a firm can adopt the new production technology. A firm's technological capability depends on the investment in the research and development studies, therefore it depends on the profit obtained by the firm. The technology adoption rate is a function of profit obtained from previous product launch to a reference profit\* value. The reference value is updated at every period with a weighted formula. Change in technology adoption rate and entry delay of firm due to profit ratio can be seen in Figure 3.3.

### **3.2. Production**

In this section, production decision of manufacturers will be explained in detail. Before the production cycle, the firm starts calculation of profit obtained for that product by subtracting the total capacity instalment cost. Profit of each production month is added to this value until the next capacity installation. The overall procedure for production process is represented by the pseudocode in Figure 3.4.

Demand of a product is created at the beginning of each period. This demand depends on the demand pattern of the product idea and the price in the market. Demand in the model is endogenous. It is affected by the price in the market. When a product is created from a product idea, product generates demand by multiplying this demand pattern with an effect function. This is a function of the ratio of market price

```

Do each step for manufactureri with capacityi,p > 0 and EntryTimep ≤ t
if TimeSinceLastCapacityInstallation < 24 then
  Step 1: Update DemandForecasti,p,t;
  Step 2: Produce according to Equation 3.4;
  Step 3: Calculate unutilized capacity;
  if UnutilizedCap ≥ 0 AND Inventoryt ≤ Inventory* then
    Step 4: Produce extra units according to Equation 3.15;
  end if
  Step 5: Satisfy demandi,t;
  Step 6:
  if Inventoryi,t ≥ 0 then
    Step 6: Satisfy the portion of UnsatisfiedDmndt which is less than or
    equal to Inventoryi,t;
  end if
  Transfer the half of the remaining unsatisfied demand as backlog to next period;
end if

```

Figure 3.4. Pseudocode for production from a manufacturer's point of view.

to a reference price\*. This multiplicative effect function of price on demand is derived similar to a downward sloping inverse demand function. The calculation of realized demand can be seen in Equation 3.11. The reference price is necessary to compare the price with some value when determining the magnitude of the effect of price on demand. This reference value is not constant but updated according to recent prices in the market with Equation 3.12.

$$RealizedDemand_t = Demand_t * (-0.2Price_t/Price^* + 1.2) \quad (3.11)$$

$$Price^* = 0.8 * Price^* + 0.2 * Price_{t-1} \quad (3.12)$$

A firm starts the production of a certain product type when the timer hits to its entry time. Entry time is calculated as the time when firms made the capacity decision plus the entry delay of a firm which is determined by technology adoption rate. Firms produce according to demand information they have received during capacity planning phase before they face the real demand. After each production cycle, they update the demand forecast of next period according to the error in the previous period's demand forecast. They do not always utilize their capacity 100%, unless their forecasted demand is greater than or equal to their installed capacity. The calculation of production quantity can be seen in Equation 3.13.

$$Production_{i,t} = \min\{capacity_{i,p}, demand_{i,t}\} \quad (3.13)$$

$$UnutilizedCap_{i,t} = capacity_{i,p} - Production_{i,t} \quad (3.14)$$

After the production of forecasted demand, if there are some remaining unutilized capacity, manufacturers also produce extra inventory to satisfy the excess demand in the next period. Unutilized capacity is calculated by Equation 3.14. The amount of production depends on the age of product in interest and the ratio of inventory on hand to a reference inventory value. If the inventory on hand is greater than the reference inventory level, they stop producing extra units.

$$Inventory_{i,t} = \min\{UnutilizedCap_t, AvgDemandFrcst_{i,p}/Age_p\} \quad (3.15)$$

The market demand is shared among the producers proportionally to their market share. If a manufacturer cannot satisfy the demand in that period due to shortage, demand is received by another manufacturer, with inventory on hand. If some amount of demand cannot be satisfied by any manufacturer in the market, the half of the remaining demand is backlogged in a common pool. This backlogged demand will be added the next period's market demand and distributed to manufacturers according to their market shares again.

Production costs and sales price have downward trend where the production quantity has an upward trend according to Gardete [14]. Under this assumption a cost function is designed with two components. The cost depends on both the total production of a firm until this product generation and the total production quantity of product generation in interest. As a firm's total output increases, its technological ability to produce next generation of products increases. Thus, the unit production cost decreases. However, also production amount of a particular generation is an important factor to decrease the unit production cost of that product generation. The second part of the cost function is based on just the sales of the current product generation. As the firms produce more output the unit production cost declines, which also affects the market price of a product in the market. Unit production cost is calculated by Equation 3.16.  $\beta$  value is set to 0.2 in the model settings after sensitivity analysis.

$$UnitProdCost_{i,t} = 0.5 * \left( \frac{UnitProdCost_1}{\left(\sum_{t'=1}^{t-EntryTime_{i,p}} Sales_{i,t'}\right)^\beta} + \frac{UnitProdCost_1}{\left(\sum_{t'=EntryTime_{i,p}}^t Sales_{i,t'}\right)^\beta} \right) \quad (3.16)$$

Price is determined in the market by two different settings: where all manufacturers charges the same price and where each manufacturer charges a different price for their products. The base setting is where all firms offer the same price. This price is determined according to maximum unit production cost in the market. The motivation behind the selection of the maximum cost in the market is to increase profit margin.

A manufacturer's minimum sales-price can be its unit cost. In this model, there is at least a 20% profit margin on the cost. The highest price a manufacturer can offer to market is the highest price of its competitors. A low cost firm can increase its profit margin by setting the highest price in the market.

The market price of a product is also affected by the demand/supply ratio. When supply amount exceeds the demand amount, the market price of a product decreases. Likewise, when demand exceeds the supply, the market price of a product increases. Sterman [27] has a general price and an effect formulation for demand-supply imbalance. The market price of a product is determined by the function shown in Equation 3.17, which is similar to Sterman's formulation.  $\theta$  value is set to 0.3 as a result of sensitivity analysis. Price formulation is depend on the maximum unit production cost of manufacturers, the profit margin they have selected and the demand/supply ratio.

$$Price_t = \max_{\forall i} \{UnitProdCost_{i,t}\} * ProfitMargin * \left(\frac{Demand_t}{Supply_t}\right)^\theta \quad (3.17)$$

$$Supply_t = \sum_{i=1}^N (Production_{i,t} + Inventory_{i,t}) \quad (3.18)$$

Price differentiation is defined as an adaptive attribute to manufacturers. If the level of market share of a firm drops more than 10%, a firm may choose to offer a different price than its competitors. A firm only adopt this strategy if it can offer a price less than the market price. Only firms whose unit cost is less than the mean of market unit cost apply this strategy. A firm offers a sales price with 20% profit margin on its unit production cost under the effect of demand/supply balance. Each firm's sales price is calculated as in Equation 3.19.

$$SalesPrice_{i,t} = UnitProdCost_{i,t} * ProfitMargin * \left(\frac{Demand_t}{Supply_t}\right)^\theta \quad (3.19)$$

When a firm differentiates price, other firms must follow to decrease the amount of market share in the market because there is a demand portion in market which is sensitive to price differences in the market and change manufacturers according to these differences. This portion of demand is indicated by  $SharedDemand_t$  variable. It is not a constant value but changes according to the magnitude of deviation in sales prices from the mean sales price, which is formulated in Equation 3.22. The algorithm regulates the distribution of demand among the firms with different prices can be found in Figure 3.5.

Calculate the total demand amount to be shared with Equation 3.22;  
**Do** each step for each *manufacturer<sub>j</sub>*;  
**Step 1:** Calculate the ratio of each individual sales price to the mean sales price by Equation 3.20 ;  
**Step 2:** Separate the manufacturers into two groups as above the mean price and below the mean price.  
**Step 3:** Normalize this deviation within each group by Equation 3.21 ;  
**Step 4:** Multiply the normalized deviation of each firm with total demand amount to be shared.  
**Step 5:** Add the share to short term demand share of above the price firms and subtract the share from the below the price firms;

Figure 3.5. Pseudocode for demand distribution under price differentiation.

$$Deviation_{j,t} = \frac{SalesPrice_{j,t}}{\frac{\sum_{j=1}^N SalesPrice_{j,t}}{N}} \quad (3.20)$$

$$NormalizedDev_{j,t} = \frac{Deviation_{j,t}}{\sum_{j=1}^N Deviation_{j,t}} \quad (3.21)$$

$$SharedDemand_t = \min\left\{1, \frac{\sum_{j=1}^N Deviation_{j,t}}{\frac{\sum_{j=i}^N SalesPrice_{j,t}}{N}}\right\} * \min_{\forall j}\{MarketShare_j\} \quad (3.22)$$

Additionally, adaptive pricing strategy can also be applied under supply shock situation. The firm which faces a supply shock and loses the most of its capacity, can offer a sales price less than mean price in the market in next production period in order to gain some of its market share back.

### 3.3. Update of Profiles and Signals

At the end of each production cycle for a product generation, manufacturers update their profiles and signals. These can be listed as demand forecast adjustment ratio, market share, technology adoption rate and capacity profile.

Market share is updated by total sales of a manufacturer to total sales in the market ratio at the end of each production cycle. Technology adoption rate is updated according to profit obtained at the last production cycle to some reference profit\* value. The research and development activities of firms are highly dependent on the profitability. The larger the profit is, the time to enter the market is shortened.

Manufacturers update their demand forecast with a demand forecast adjustment ratio at the end of each production cycle for a generation. They calculate the total demand they received during the production cycle, even if they cannot satisfy that demand. Then, they divide this realized demand with their total demand forecast for this product generation. They update their total demand forecast signalled by product idea of next generation if this ratio is less than 0.9 or more than 1.3. These are the narrower boundaries obtained by repetitive set of experiments to avoid random fluctuations in the demand forecast and capacity investment levels. They update their forecast with Equation 3.23 for  $\forall t$  of new product generation  $p + 1$ .

$$DemandForecast_{j,p+1,t} = DemandForecast_{j,p+1,t} * \left( \frac{TotalRealDemand_{j,p}}{\sum_{t'=1}^{24} DemandForecast_{j,p,t'}} \right)^{0.8} \quad (3.23)$$

The manufacturers may choose to adapt their capacity profiles or stick to one profile until the end of a simulation run. There are two adaptive strategies for capacity profile: independent and coordinative. In independent capacity profile adaptation, in the first few cycles manufacturers pick a random capacity profile (demand-oriented or profit maximizing); then record the total profit obtained from this capacity profile. At the beginning of each cycle, the algorithm compares the profit obtained by demand-oriented capacity profile to profit obtained by profit maximizing capacity profile and assign a new capacity profile with a probability, which depends on the profit ratios of both type of profiles.

In coordinative adaptation, if the last cycle's profit is less than a reference profit value, manufacturer signals its competitors to change their capacity profiles to profit-maximizing. If the number of firms signalling profit-maximizing profile is more than the half of the number of manufacturers, every firm switches to profit-maximizing profile.

As an extension to this coordinative behaviour, firms may defect from the agreement and switch to demand-oriented profile to gain more market share. This probability is defined by defect-probability. If defect-probability is equal to zero, no firms defect from the agreement. If defect-probability is equal to one, it is likely to at least one firm defect from agreement. All manufacturers also has an adaptive behavior to defend themselves from the defects. If one of their competitors defect repetitively, they stop to consider the signal of this player as true.

## 4. MODEL VALIDATION

In this chapter, the model validation process will be explained. Structural validation tests are applied to validate the model behaviour against the real system. First of all, direct structural validation tests, then indirect structural validation tests are conducted.

### 4.1. Direct Structural Validation

The aim of the direct structural validation is to test whether each function works consistently with the real life behaviour and the meanings and units of variables and parameters correspond to real system. Each variable-function relation is examined apart from the overall system. For example, the production quantity set by each manufacturer is checked under a given constant capacity and compared against the demand forecast. It is not expected to have a negative production value or production more than forecasted demand. The change of price level is examined under a sudden increase or decrease in supply or demand. For instance, an increase is expected when the supply level in the market drops to the half. The change in demand is investigated under both endogenous and exogenous demand settings. If demand is exogenous, the demand does not change with the price level. The effect of backlog is considered on price dynamics.

Unit consistency tests are done on the variables and parameters. The meanings and units of all coefficients and parameters are validated in real life. As indirect structural validation, extreme value tests and sensitivity analysis are conducted on selected parameters. The demand and capacity investments are compared against each other to check the feasibility of demand satisfaction in the market.

## 4.2. Indirect Structural Validation

The aim of indirect structural validation tests is to observe the overall behavior of the model under certain parameter changes.

### 4.2.1. Extreme Value Test

In this section extreme value test results on selected parameters will be explained. Extreme value test aims to check whether the behaviour of model outputs are consistent with the expected behaviour from these outputs under these extreme conditions. The selected parameters for this test can be found in Table 4.1.

Table 4.1. Extreme value test parameters.

<b>Parameter Name</b>	<b>Unit</b>
<i>UnitCapacityCost</i>	\$/Product
<i>UnitProdCost<sub>1</sub></i>	\$/Product

The installed capacity amount is dependent on unit capacity cost in profit maximizing capacity investment profile. When unit capacity cost is set to zero, the installed capacity levels increase to almost maximum demand level for a product generation. When unit capacity cost is significantly higher than initial unit production cost, the capacity investment level drops at very low levels because the initial unit production cost determines the profit by setting price. If the profit margin times unit production cost does not justify the capacity cost, the capacity investment will be at a very low level.

When the capacity level is fixed to the 10 USD and profit margin is fixed at 20%, extreme value tests on unit production cost are conducted. If initial unit production cost is set at a low level as one USD, firms will not make any capacity investment under the profit maximizing setting. When initial unit production cost is 100 USD, firms install

capacity more than average of anticipated demand for next product generation. If the profit margin times unit production cost cannot justify the capacity cost (when initial unit production cost is one USD), the capacity investment decision is not logical. When profit margin times initial unit production cost exceeds the unit capacity cost (when initial unit production cost is 100 USD) firms invest more capacity than the average demand.

#### 4.2.2. Sensitivity Analysis

In this section results of sensitivity analysis for selected parameter sets will be explained. The sensitivity analysis aims to observe how sensitive the outputs of model to the changes in parameter values. The selected parameters for sensitivity analysis are shown in Table 4.2.

Table 4.2. Sensitivity parameters.

<b>Parameter Name</b>	<b>Unit</b>
Number of manufacturers	Manufacturers
$\beta$ (Exponent of cost function)	Unitless
$\theta$ (Exponent of price function)	Unitless
DistrustThreshold	No. of defects

As number of manufacturers increase from one to 10 one by one, the price level increases in the market. As production of a firm increases, the unit production cost of that firm decreases. When the number of manufacturers increases, the total production per firm decreases. As a result of this, the production costs stay at higher levels compared to less manufacturers in the market case. However, price pattern is similar for all number of manufacturers in a simple demand-oriented and symmetrical market share distribution case. The summary of this analysis can be seen in Figure 4.1.

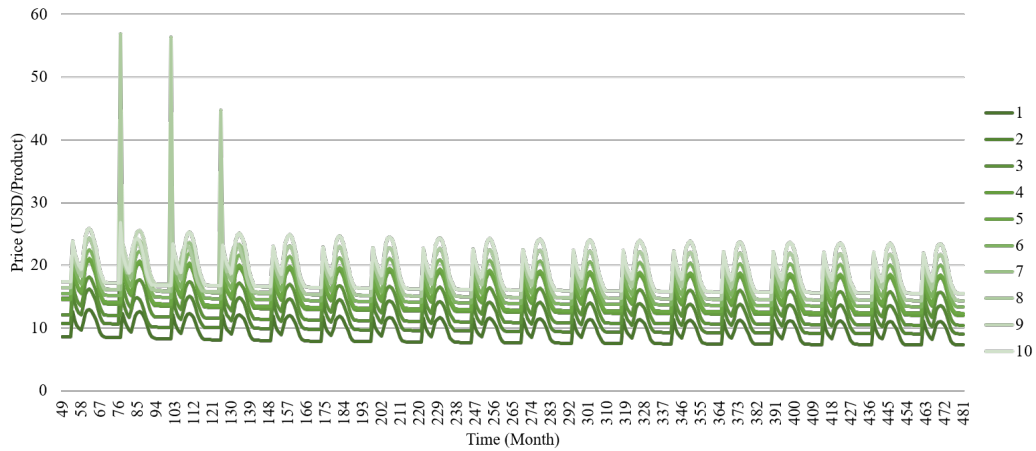


Figure 4.1. Sensitivity analysis for number of manufacturers parameter.

The unit production cost is sensitive to  $\beta$  parameter which is an exponent of the unit production cost function. When  $\beta = 0$  the unit production cost is constant at its initial value. As the  $\beta$  value increases the level of fluctuations in unit production cost from the beginning to end of a production cycle increases. The values between 0.1 and 0.3 yield similar behaviour. As this value increased to 0.4 or 0.5, the cost changes quicker than expected. However the overall behaviour of the system is as acceptable for any  $\beta$  values between 0 and 0.5. The price is sensitive to cost exponent and price exponent. The effect of cost exponent  $\beta$  on price is similar to effect on cost since the price is derived from the cost function. The sensitivity analysis results for cost exponent on price can be seen in Figure 4.2.

Price exponent,  $\theta$ , is tested under values from 0 to 0.5. When  $\theta = 0$  the price pattern follows the cost pattern exactly (only with a shift due to profit margin). It is reasonable because when  $\theta$  is set to zero, it means the demand/supply balance-imbalance has no effect on price. As the  $\theta$  increases the effect of demand/supply ratio increases over price. This also increases the fluctuations in price. The values between 0.1 to 0.4 the fluctuations are acceptable. When  $\theta = 0.5$  the fluctuations in price within a production cycle increase beyond reasonable. The results for effects of price exponent on price can be seen in Figure 4.3.

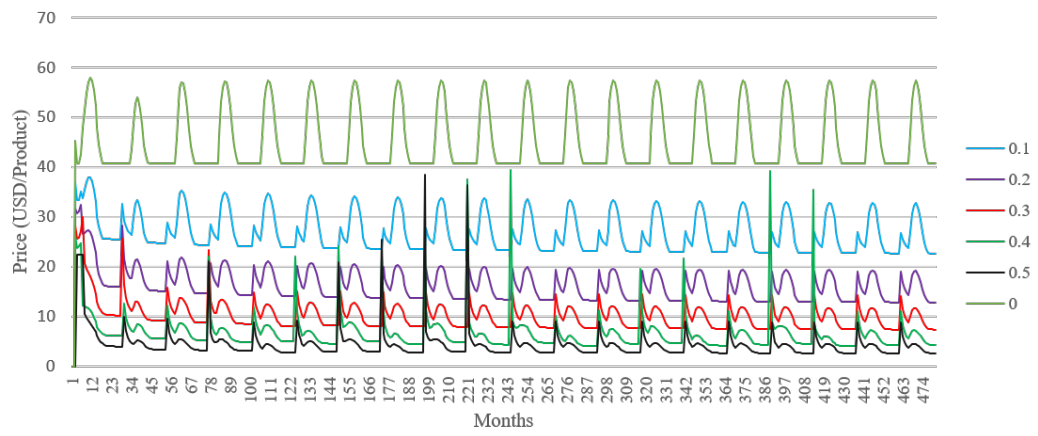


Figure 4.2. Sensitivity analysis for effect of cost exponent on price.

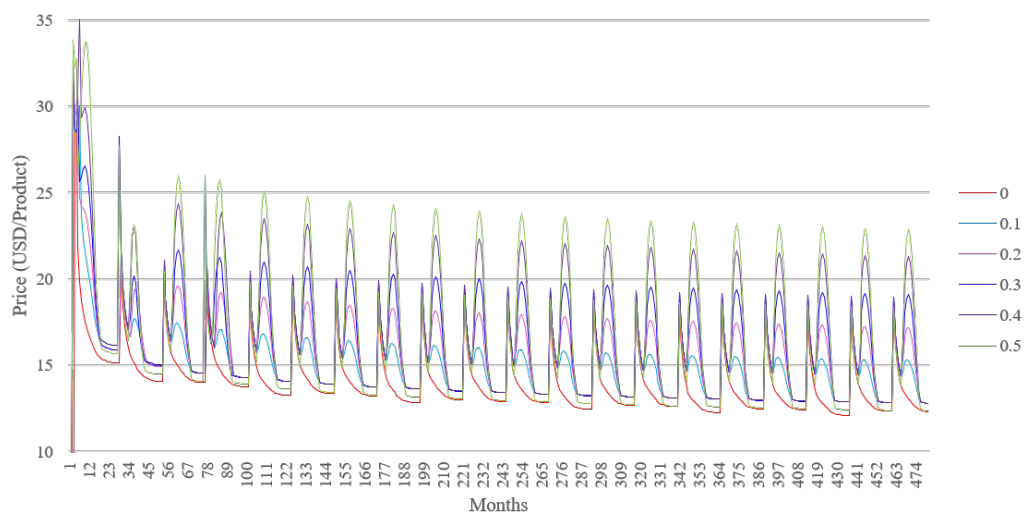


Figure 4.3. Sensitivity analysis for effect of price exponent on price.

Distrust threshold defines the number of times the competitors can defect without a manufacturer firm stops to trust the coordination agreement. For example, if distrust threshold is equal to five, when a competitor defects more than five times, the other manufacturers stops to believe that firm's capacity profile signals and become demand oriented. This parameter only increases or decreases the time of where all manufacturers defect from the initial agreement.

### 4.2.3. Additional Indirect Structural Validation Analysis

The unit capacity cost and initial unit production cost parameters are determined after the a large set of validation runs. This model does not aim to replicate the price levels exactly the same or does not aim to make a point estimation for the future periods. However, it is important to obtain realistic price and cost levels in the system. Unit capacity cost is an important variable determining in the capacity investment levels for profit maximizing manufacturers. The relative value of unit capacity cost and unit production cost is also important on determination of total capacity investment levels. If the profit margin cannot justify the capacity cost, the firms will install very low levels. The value of *UnitCapacityCost* is assigned as 10 USD/product and the value of *UnitProdCost<sub>1</sub>* is assigned as 34 USD/product after these considerations.

As another step of structural validation, the amount of installed capacity to demand is checked. An example is shown in Figure 4.4 for demand-oriented case for symmetric market share distribution. In this graph, the backlogged amount from previous period is also added to the demand generated at current period. The installed capacity amount is enough for satisfying the total demand at the end of production period. Even though capacity level is not enough for satisfying all demand when the demand is at its maximum level, total demand can be satisfied at the end of the production cycle. This conclusion is valid for where all manufacturers invests according to their anticipated demand values only. In case of an under-capacity investment to maximize profit, all demand may not be satisfied. The aim of manufacturers is not to satisfy all demand in the market but to increase price.

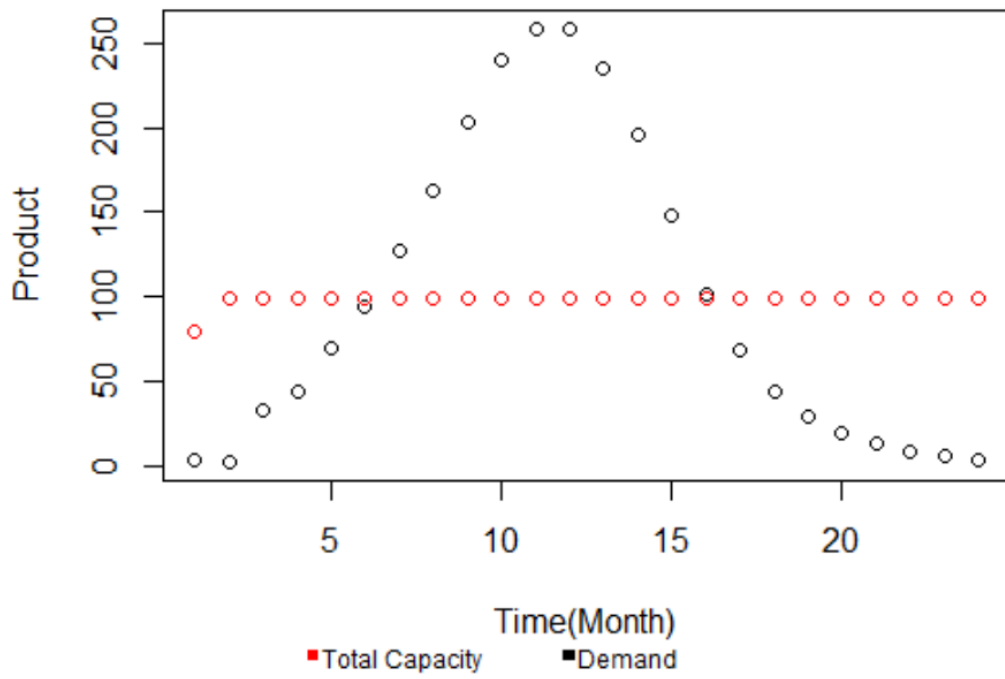


Figure 4.4. Demand and total capacity for one product generation

## 5. EXPERIMENTS AND RESULTS

In this chapter the experiment settings and results of experiments will be explained. The total simulation time for each experiments is 480 months. Each experiment is replicated 50 times because there is randomness in this agent-based model. Some of the initial parameters or attributes of agents are randomly assigned (i.e. capacity profile, total number of sales, technology adoption rate) or parameters like adaptation probability is assigned randomly at each time step. A different seed is used for random number generation for each experiment. The parameter set used in experimentation is shown in Table 5.1. Binary variables with a question mark at the end represents switches in the experiment settings for special scenarios.

Table 5.1. Experiment parameters.

<b>Parameter Name</b>	<b>Value</b>	<b>Unit</b>
Number of Manufacturers	5	Manufacturers
$\theta$ (Price Exponent)	0.3	Unitless
$\beta$ (Cost Exponent)	0.2	Unitless
<i>UnitCapacityCost</i>	10	US Dollars(\$)/Unit
ProfitMargin	1.2	Unitless
<i>UnitProdCost<sub>1</sub></i>	34	US Dollars(\$)/Unit
PriceDifferentiation?	FALSE	Unitless
SupplyShock?	FALSE	Unitless
RandomDemandPattern?	FALSE	Unitless
DemandShock?	FALSE	Unitless
AdaptivePricing?	FALSE	Unitless

### 5.1. First Set of Experiments

The first set of experiments are conducted to establish a base run for complex situations. Because if there are many changing parameters in an experiment, it is hard to observe the effect of the parameters in interest. Complex situations will be explained in Second Set of Experiments, Third Set of Experiments and Fourth Set of Experiments sections in detail. These experiments are done to understand price dynamics under different capacity decision profiles of manufacturers. There are two capacity investment decision profiles in the experiment settings: profit maximizer and demand oriented. However, it is possible to have different combination of these profiles in the market. Additionally, manufacturers may have the same capacity profile during the all simulation run (stationary capacity profiles) or they can change their capacity profiles in order to adapt (adaptive capacity profiles). A summary of the first set of experiment settings can be found in Figure 5.1. The experiment numbers are indicated in blue boxes in the figure.

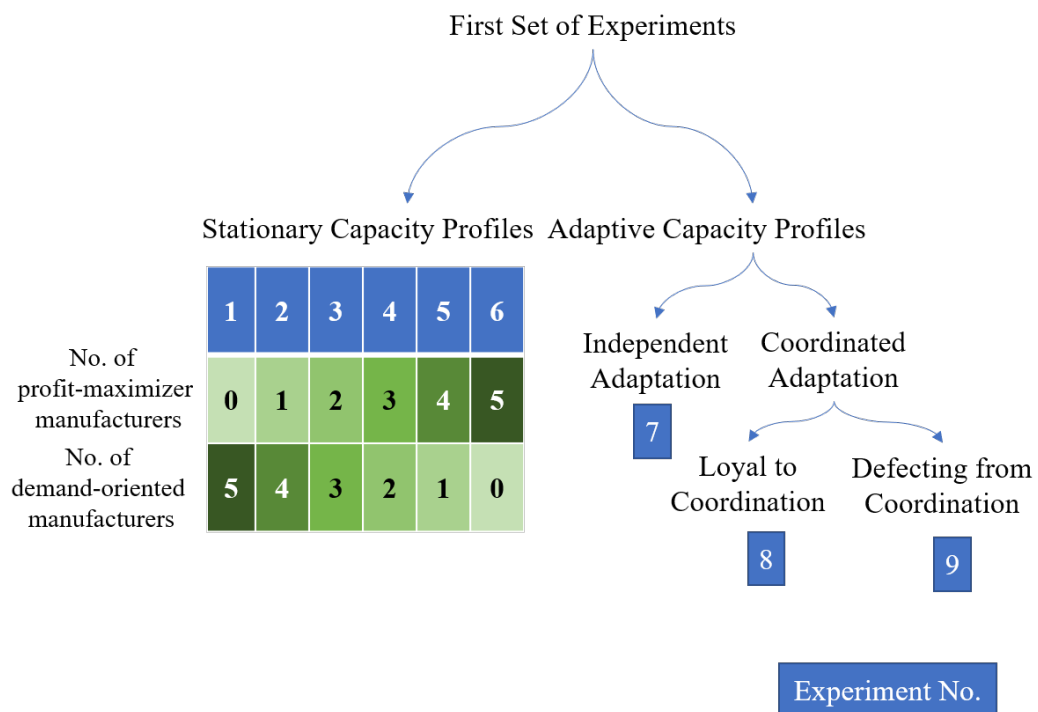


Figure 5.1. Summary of the first set of experiments.

Market share of manufacturers can be distributed in two ways: symmetric and asymmetric. Symmetrically distributed market share means each manufacturer starts the simulation run with equal market shares and equal technology adoption rates. Asymmetrically distributed market is where some of the manufacturers have higher market shares and higher technology adoption rates than the other competitors at the beginning of game. After this point, the equal market share distribution of firms will be called "symmetrical" and indicated by symbol "a" in experiment settings. The differing market share distribution will be called "asymmetrical" and indicated by symbol "b" in experiment settings. In these experiments mainly the change in price levels between product generations will be investigated. As representative purposes change in price level for a single production cycle (product generation) is shown in Figure 5.2. The represented price level is the mean of price levels of 50 experiments. Additionally, the mean of price for each production cycle will be represented to compare the results of different experiments on the same scale. Mean of price for a production cycle indicates the mean value of points represented in Figure 5.2. In the following sections price levels for consecutive production cycles will be shown.

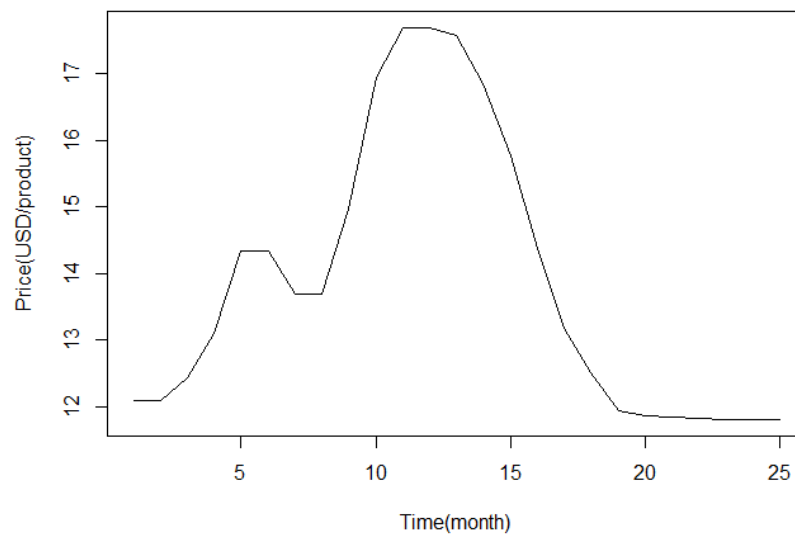


Figure 5.2. An example representation of change in price level for a single production cycle.

### 5.1.1. Experiments for Stationary Capacity Profiles

The experiment settings for the first set of experiments for stationary capacity profiles can be found at in Table 5.2. Changes in price levels are demonstrated in Figure 5.3. First two cycles (48 months) are excluded from the model as warm-up period. Both of these graphs represent the mean price for 50 replications.

Table 5.2. Experiment settings with stationary capacity profiles.

<b>Experiment No.</b>	<b>Capacity Decision</b>
1 (a-b)	Demand Oriented
2 (a-b)	Mixed-# of Profit Maximizer=1
3 (a-b)	Mixed-# of Profit Maximizer=2
4 (a-b)	Mixed-# of Profit Maximizer=3
5 (a-b)	Mixed-# of Profit Maximizer=4
6 (a-b)	Profit Maximizer

Price level differs according to distribution of number of profit maximizer and demand oriented manufacturers in the market. The main reason behind this is the changing demand/supply balance according to this distribution in the market. Capacity is the one of the determinants of production amount in the market. Total installed capacity and demand across time for experiments 1-6 can be seen in Figure 5.4 and 5.5. As the number of profit maximizing manufacturers increases in the market, the total capacity installed in the market decreases. In this case, even though the capacity utilization is 100%, the ratio of demand to total production increases. As a result of this, the price level in the market increases.

Comparison of fully demand-oriented (experiments 1 (a-b)) and fully-profit maximizing cases (experiments 6 (a-b)) showed that the mean price for fully profit maximizing case is significantly higher than fully demand oriented case.

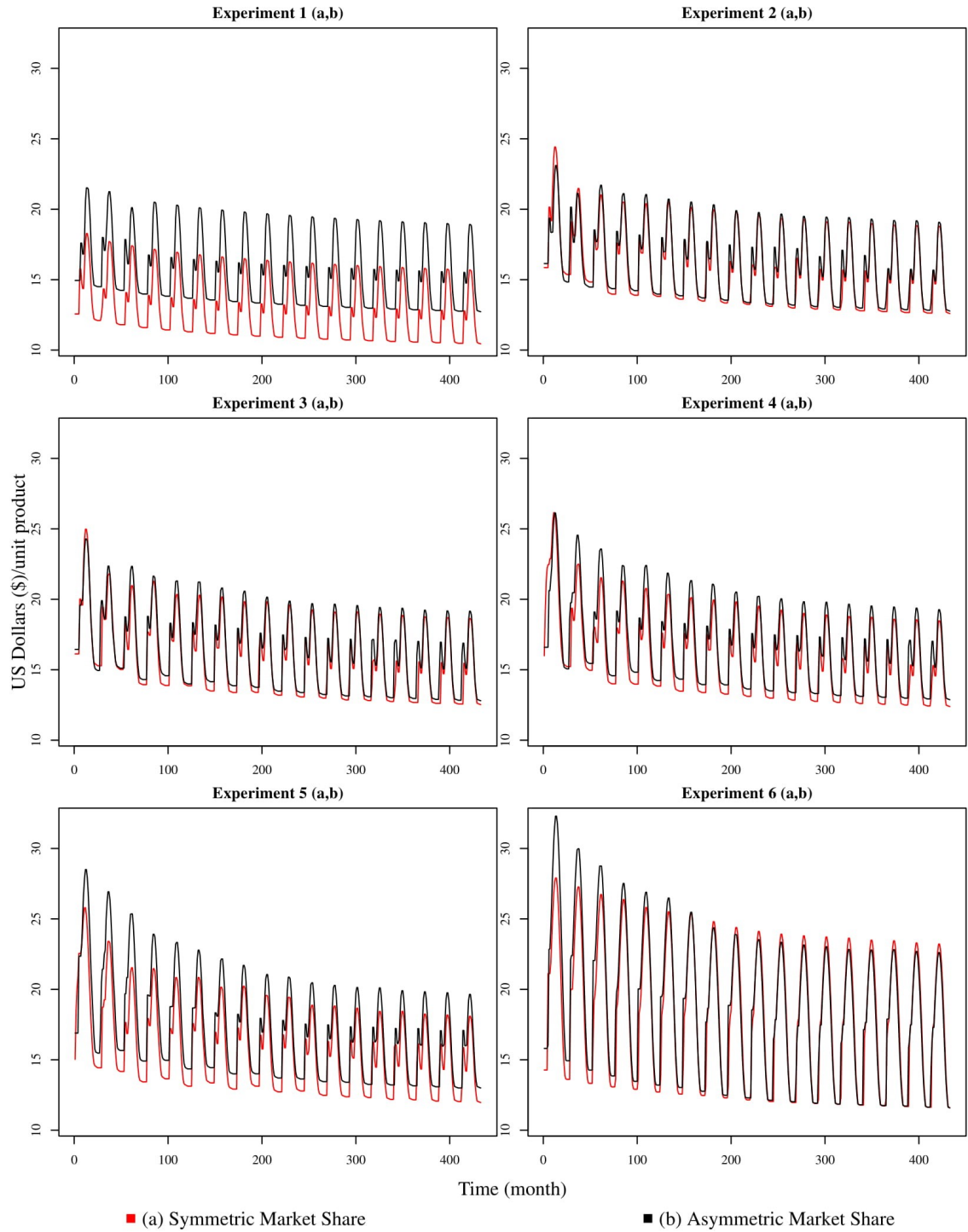


Figure 5.3. Price level comparisons for experiments from 1 to 6.

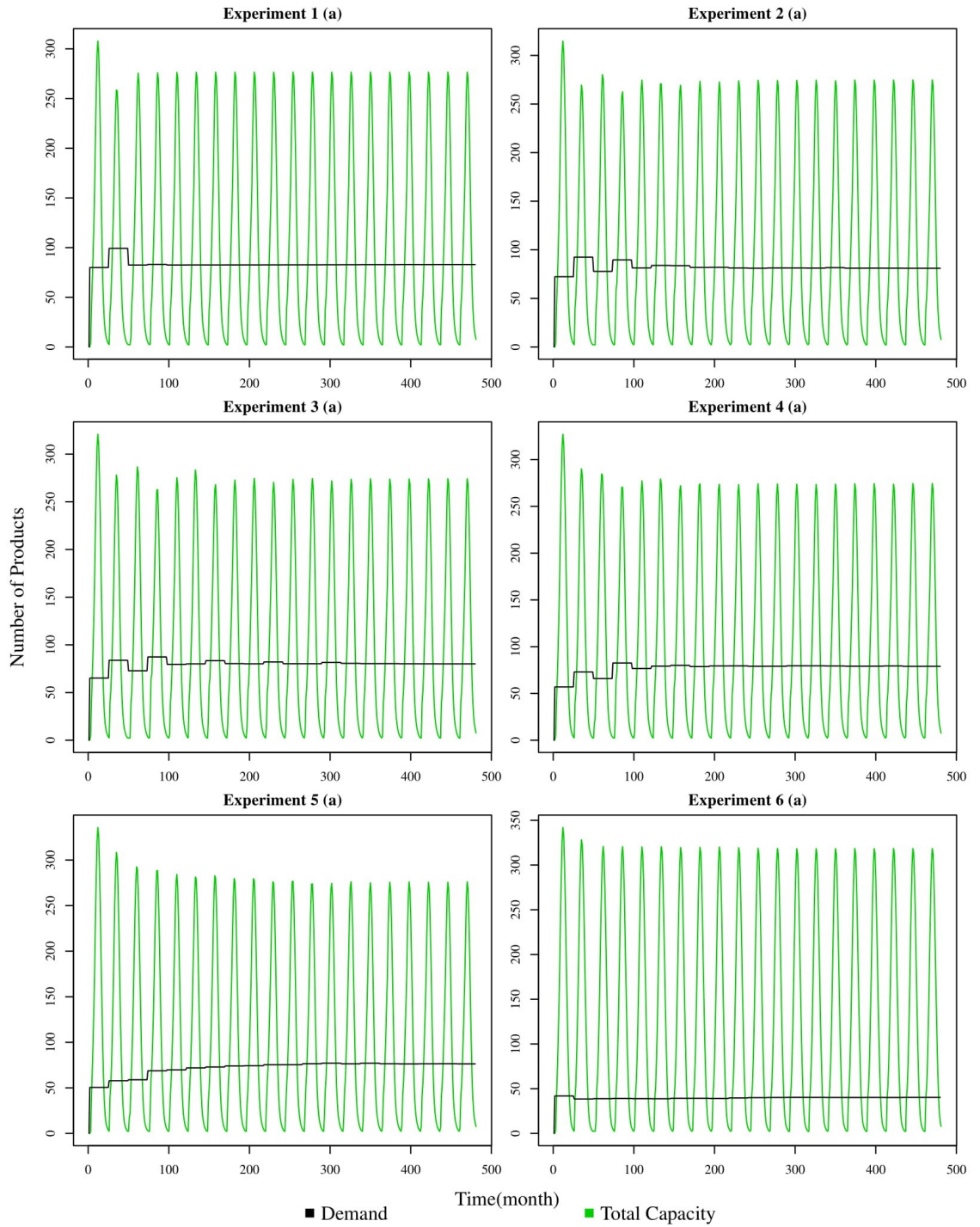


Figure 5.4. Capacity level and demand comparisons for experiments from 1 to 6 (a).



As the number of profit maximizing firms in the market increases, price level increases too, however this increase is not significant for all experimental settings. For example, price means for experiments 2 (a) and 3 (a) are not significantly different. In order to compare the mean price levels between different experimental settings, t-test for samples with unequal population variances (Welch's t-test) is applied. Null hypothesis claims that the difference between the means of two data is equal to zero. Alternative hypothesis claims that the difference between the means of two data is not equal to zero. The detailed statistical analysis are in Table A.3 and in Table A.4.

When symmetric and asymmetric market share distribution cases are compared against each other, the price levels are not significantly different for experiments 2, 3 and 6. Price levels are significantly greater for asymmetrical initial market share distribution for experiments 1, 4 and 5. In experiments where price levels are different for a and b settings, the effect of unit production cost on price dominates the price function. In experiments where price levels are not significantly different, the effect of demand/supply ratio on the price dominates the effect of the unit production costs on price. The unit production of a firm depends on the total production amount over time. The market share of a firm is key determinant of the total production amount. Change in market shares of firms can be seen in Figure 5.6. Where the market share of the smallest firm is less for experiment setting b, the price level is more for experiment setting b. From this point, the results for experiment settings a and b will be documented, however there will be not any further discussion on the differences of these settings.

Market share graphs are shown for a single simulation run rather than the mean of 50 experiments. The same seed is used to compare different experimental settings' effects on the market shares. The random behavior of manufacturers in each simulation run for different seed is the reason for demonstrating market share as a single run. They start each run with a different initial settings. In Figure 5.6, the manufacturers which are initially demand oriented are represented with tones of magenta, the manufacturers which are initially profit maximizer are represented with tones of blue.

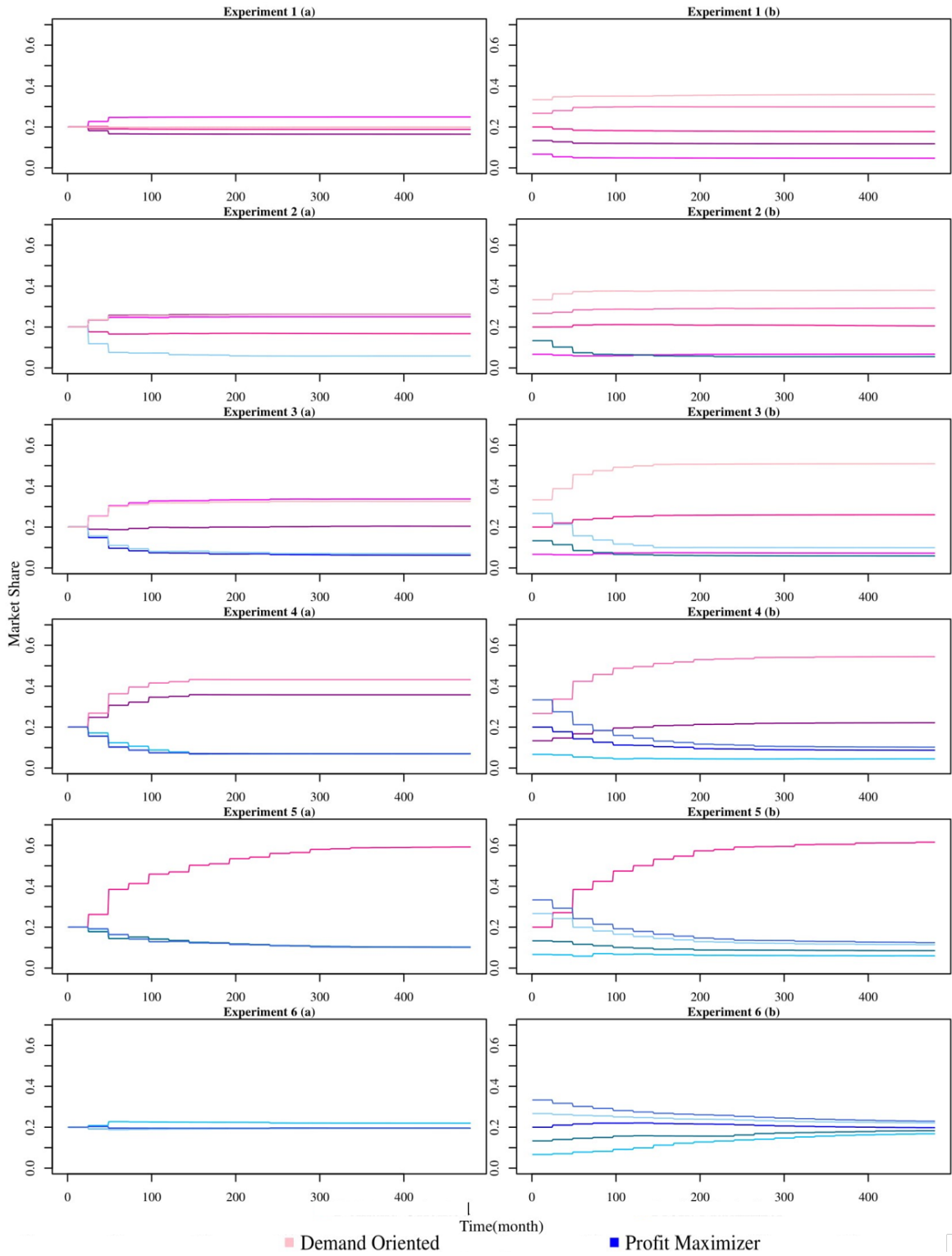


Figure 5.6. Change in market shares for experiments from 1 to 6 (a-b).

As an important result of this experiments, the firms with demand oriented capacity profiles gain the market share from the profit maximizer firms in each run. The initial market share of the firms does not relevant on this result. Even if there is only one firm in the market which is demand oriented it gathers the market share of the other firms. On the other hand, the increase in price levels are minor in a mixed capacity profile market compared to fully profit maximizing case (experiment 1). It will be a very important conclusion for policy makers to decrease the increasing price in the market. The further discussion on this will be held in adaptive capacity profiles section.

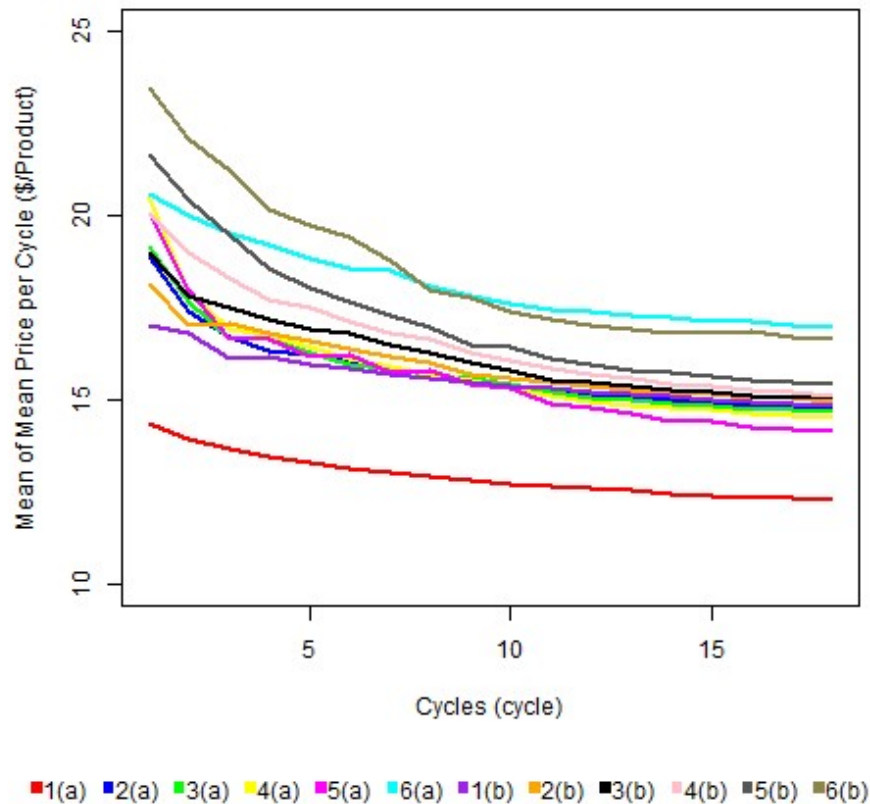


Figure 5.7. Change in mean price between cycles for experiments 1-6 (a-b).

Mean price levels for consecutive cycles for experiments 1-6 (a-b) can be seen Figure 5.7. When the mean price of consecutive cycles compared to each other, for fully profit maximizing setting, it is seen that the price level drops suddenly after the eighth and ninth cycle. This point corresponds where the change in market shares

stops. Market shares gets closer at every cycle until that point. As the market share of firms converge to each other, their technology level converges too, which means a decrease in maximum unit cost.

### 5.1.2. Experiments for Adaptive Capacity Profiles

The settings of the first set of experiments for adaptive capacity profiles are in Table 5.3. In this settings, the firms start with random capacity profiles and change this profile according to their adaptive abilities. The manufacturers can adapt their capacity profiles independently or in coordination. Coordinative case has two sub-settings: manufacturers are loyal to coordination and defecting from the coordination.

Mean price levels for 50 experiments during 480 months are shown in Figure 5.8. The comparison of mean price levels of consecutive cycles for experiment 7-9 can be found in Figure 5.9. For independent settings (experiment 7 (a-b)), price levels are less than fully profit maximizing settings (experiments 6 (a-b)) however more than fully demand oriented settings (experiments 1 (a-b)). There is a decrease in price levels over cycles, however the decrease in unit production costs are mainly responsible for this behaviour. In loyal coordination (coordination without defect) setting (experiments 8 (a-b)), the firms agree to become profit maximizer after the initial coordination signals is sent. The mean price level is higher than independent adaptive settings for coordination without defect setting.

Table 5.3. Experiment settings with adaptive capacity profiles.

<b>Experiment No.</b>	<b>Capacity Decision</b>
7 (a-b)	Independent
8 (a-b)	Coordinated-Loyal
9 (a-b)	Coordinated-Defecting

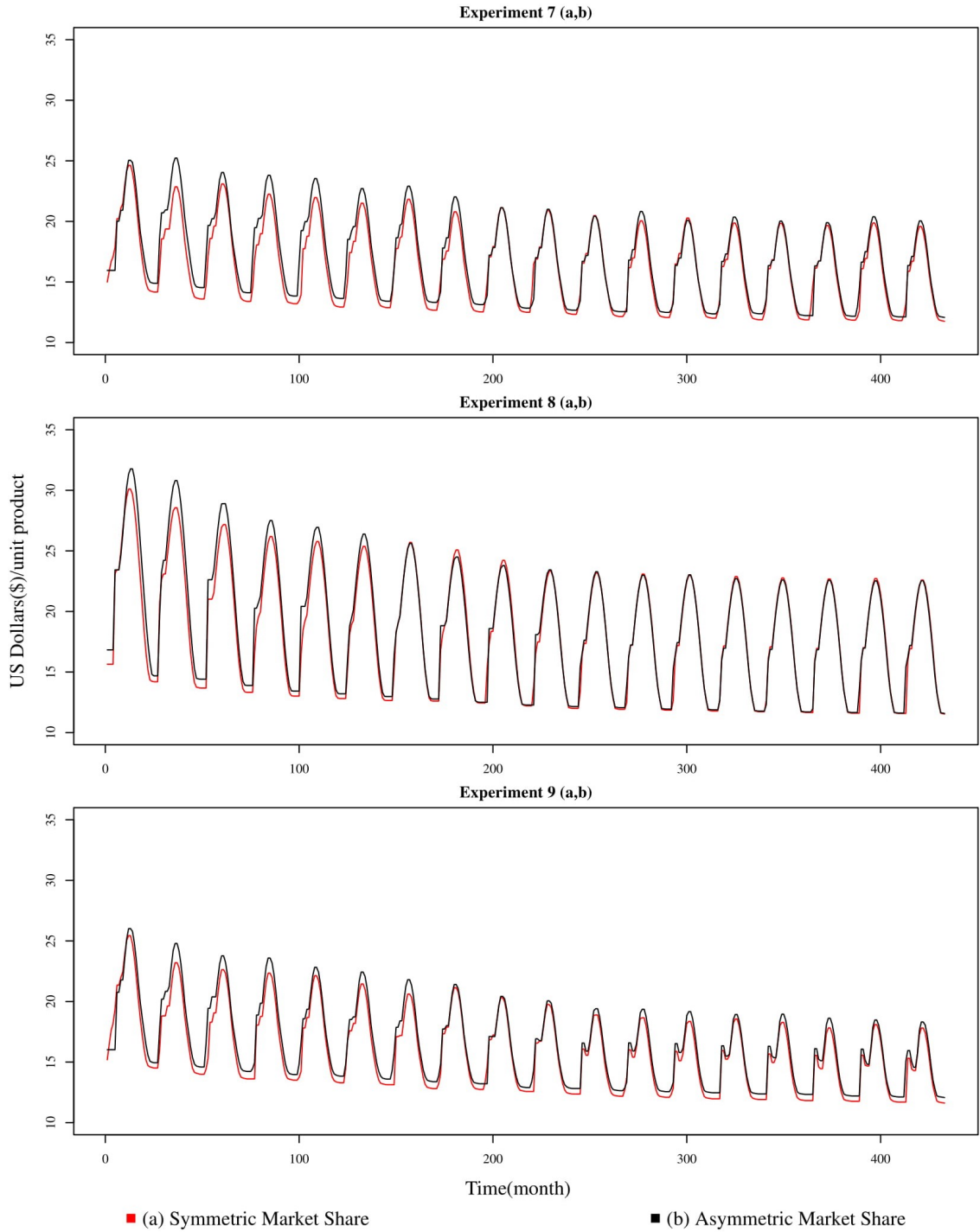


Figure 5.8. Price level comparisons for experiments from 7 to 9 (a-b).

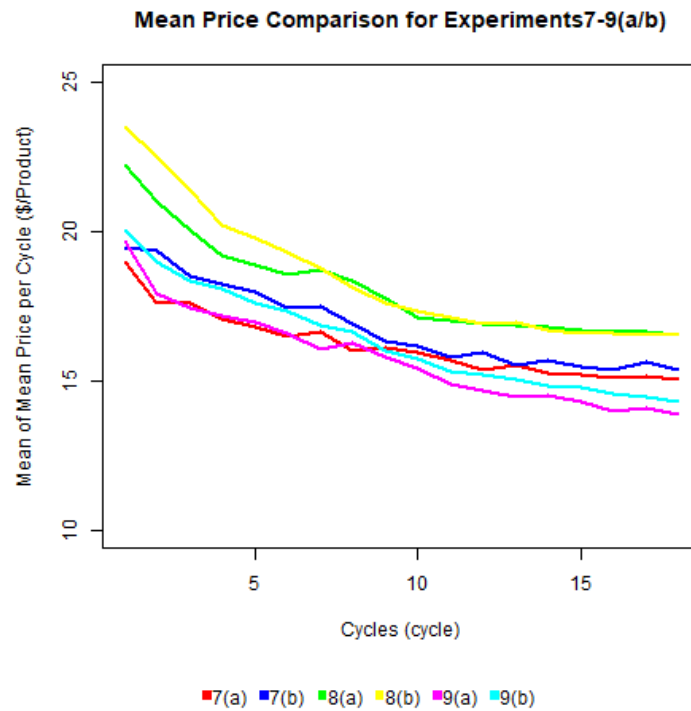


Figure 5.9. Change in mean price between cycles for experiments 7-9 (a-b).

In coordinated but defecting setting (experiments 9 (a-b)), the distrust threshold is set to five. This means after a firm defects from an agreement more than five times, the other firms stop to trust the capacity profile signals of this firm and become demand oriented to prevent any more loss of market share. The price levels for coordinated but defecting setting are first at the similar levels with independent adaptation settings (experiments 7 (a-b)), then drops below the independent adaptation price levels. When all firms coordinate in loyalty, in the long run all firms become profit maximizing. If all firms coordinate at the beginning but some firms defect from this coordination, non-defecting firms get harm from this coordination policy.

As it is discussed in experiments with stationary capacity profiles, if only one firm is demand-oriented in the market, that firm gains the market share of other profit maximizing firms. So they also defect from demand oriented profile. Therefore, in the long run all firms become demand oriented and mean price level drops.

The change of market shares can be seen in Figure 5.10 under experimental settings 7-9. From experiments 7-9 (a-b), there are some key conclusions can be driven. The price level in independent adaptive setting is lower than the coordination in loyalty setting. If firms coordinate, they raise the overall price in the market. However, as it is seen in coordinated by defecting setting, if only one firm defects from the coordination, the price level falls below the independent setting. If policy makers can force only one firm in the market to defect from the coordination, overall market price drops. Additionally, the defecting firm gain market share from other firms. Even though other firms defect from agreement and increase their capacity levels after a defecting firm, they cannot gain their market share back unless the leader firm decreases its capacity investments.

## 5.2. Second Set of Experiments

In the second set of experiments, some special cases are selected from the first set of experiments and special scenarios are applied and their impacts on overall model is observed. Cases which are selected as the base for the rest of experiments are stated as follow: fully demand oriented settings (experiments 1 (a-b)), fully profit maximizing settings (experiments 6 (a-b)), independent adaptive settings (experiments 7 (a-b)), coordination with loyalty settings (experiments 8 (a-b)) and coordinated but defecting settings (experiments 9 (a-b)).

The special scenarios are random demand level change between product generations (experiments 10-14 (a-b)), a sudden decrease in supply levels (supply shock) (experiments 15-19 (a-b)), a sudden increase in demand levels (experiments 20-24 (a-b)) and a sudden decrease in demand levels (experiments 25-29 (a-b))(demand shocks). A summary of second set of experiments are shown in Figure 5.11.

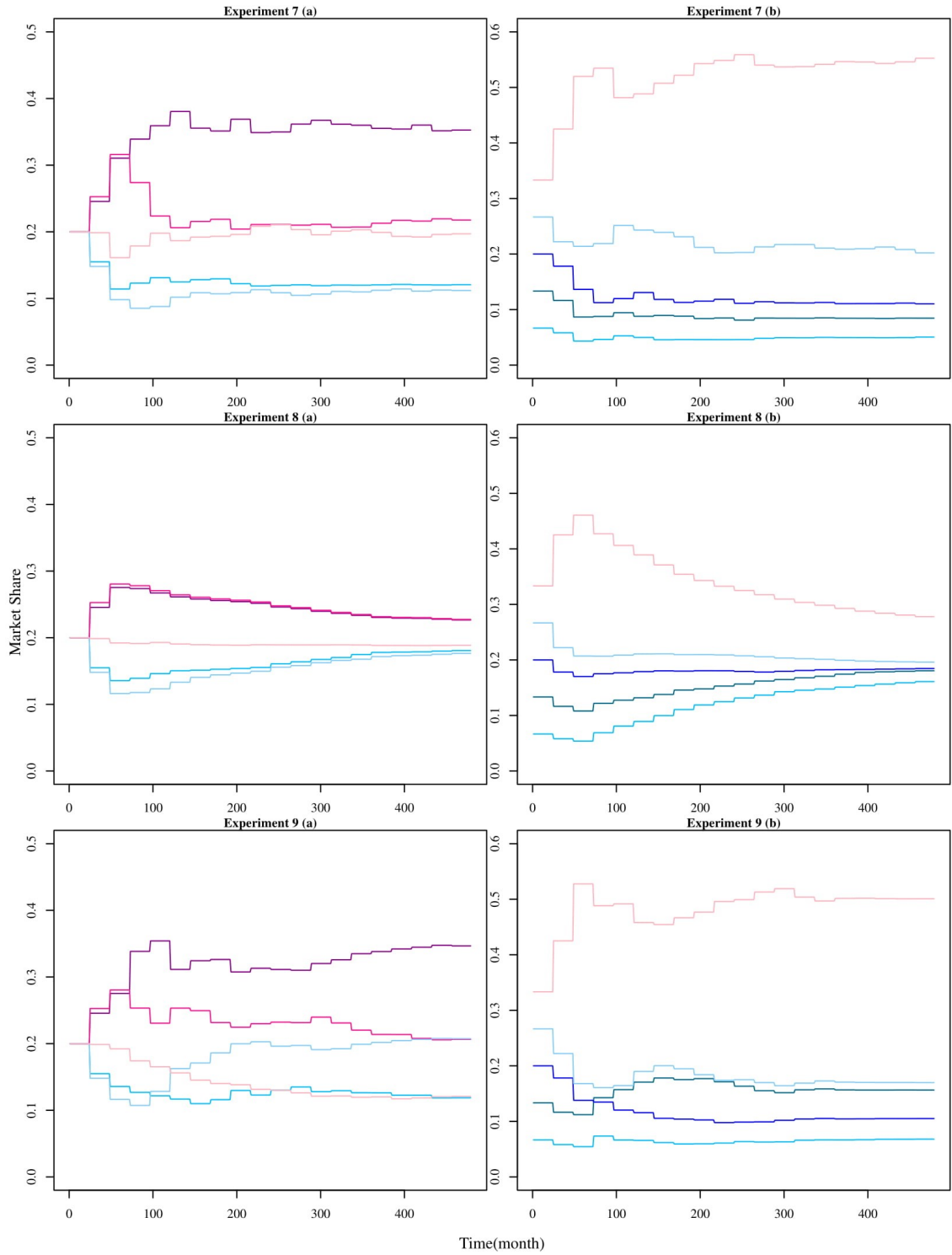


Figure 5.10. Change in market shares for experiments from 7 to 9 (a-b).

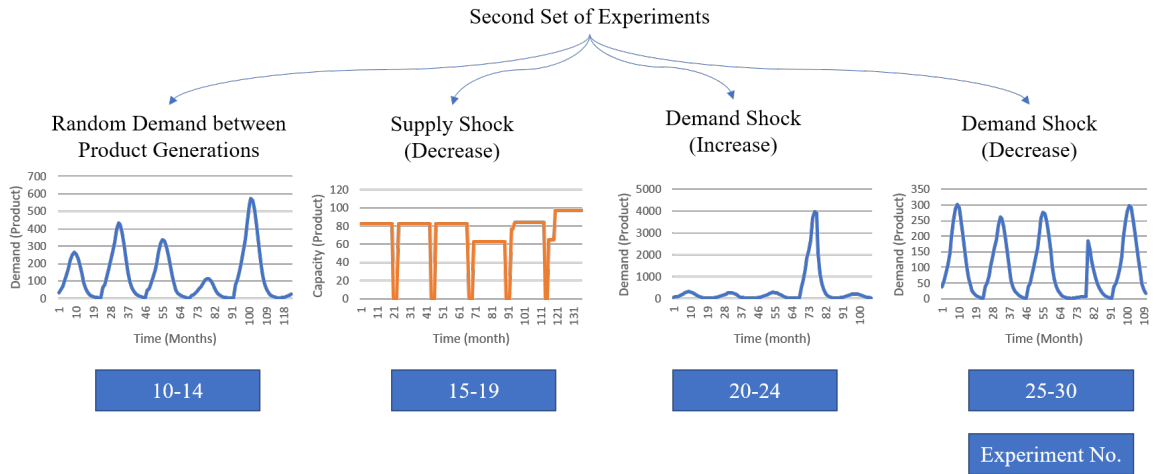


Figure 5.11. Summary for second set of experiments.

### 5.2.1. Randomly Changing Demand between Product Generations

In previous experiments, the initial demand levels are same for each product generation. Experiments for randomly changing demand levels between generations will be held in this section and experiment settings are stated in Table 5.4. A single example run for demand change between generations is provided in Figure 5.12. Result of experiments due to change in price can be seen in Figure 5.13. Comparison of mean prices over consecutive cycles can be found in Figure 5.14.

Table 5.4. Experiment settings under randomly changing demand pattern.

Experiment No.	Capacity Decision
10 (a-b)	Demand Oriented
11 (a-b)	Profit Maximizing
12 (a-b)	Independent
13 (a-b)	Coordinated-Loyal
14 (a-b)	Coordinated-Defecting

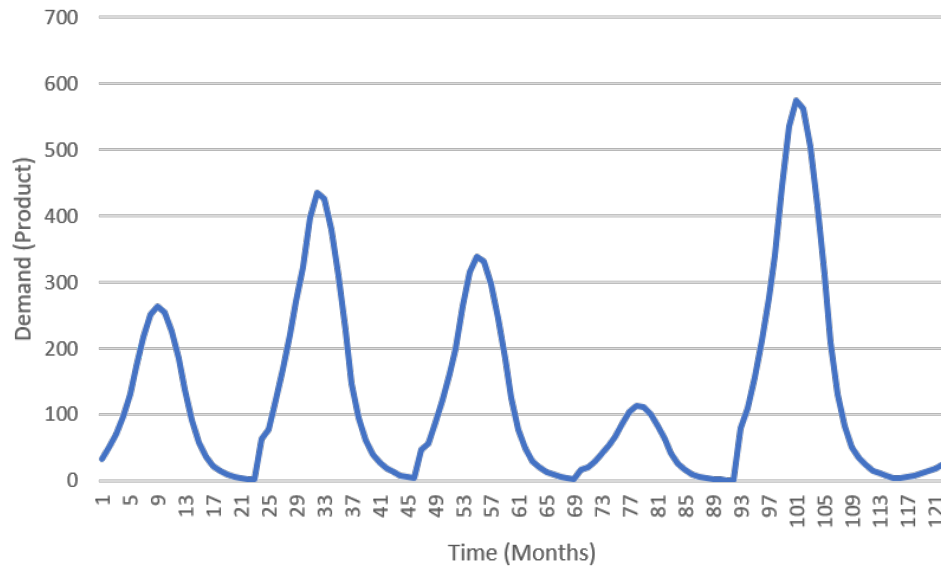


Figure 5.12. An example run for randomly changing demand between product generations.

When experiments with stationary demand levels between generations (experiments 1, 6, 7, 8, 9 (a-b)) against the experiments with randomly changing demand setting (experiments 10-14 (a-b)), the price levels are significantly different for fully profit maximizing cases (experiments 6-11 and experiments 8-13). The price level is higher for randomly changing demand setting (experiment 6, 8) than the stationary demand setting (experiment 11, 13). Detailed t-test results of comparison between random demand case to stationary demand case can be found in Table A.8.

Experiments 11 and 13 also yield higher price levels than other experiments with randomly changing demand. As a result, in a market with full of profit maximizing firms, change in demand between generations raises the price levels even more. It is a valid assumption to continue the experiments with stationary demand between product generations in order to observe the dynamic behaviour of price.

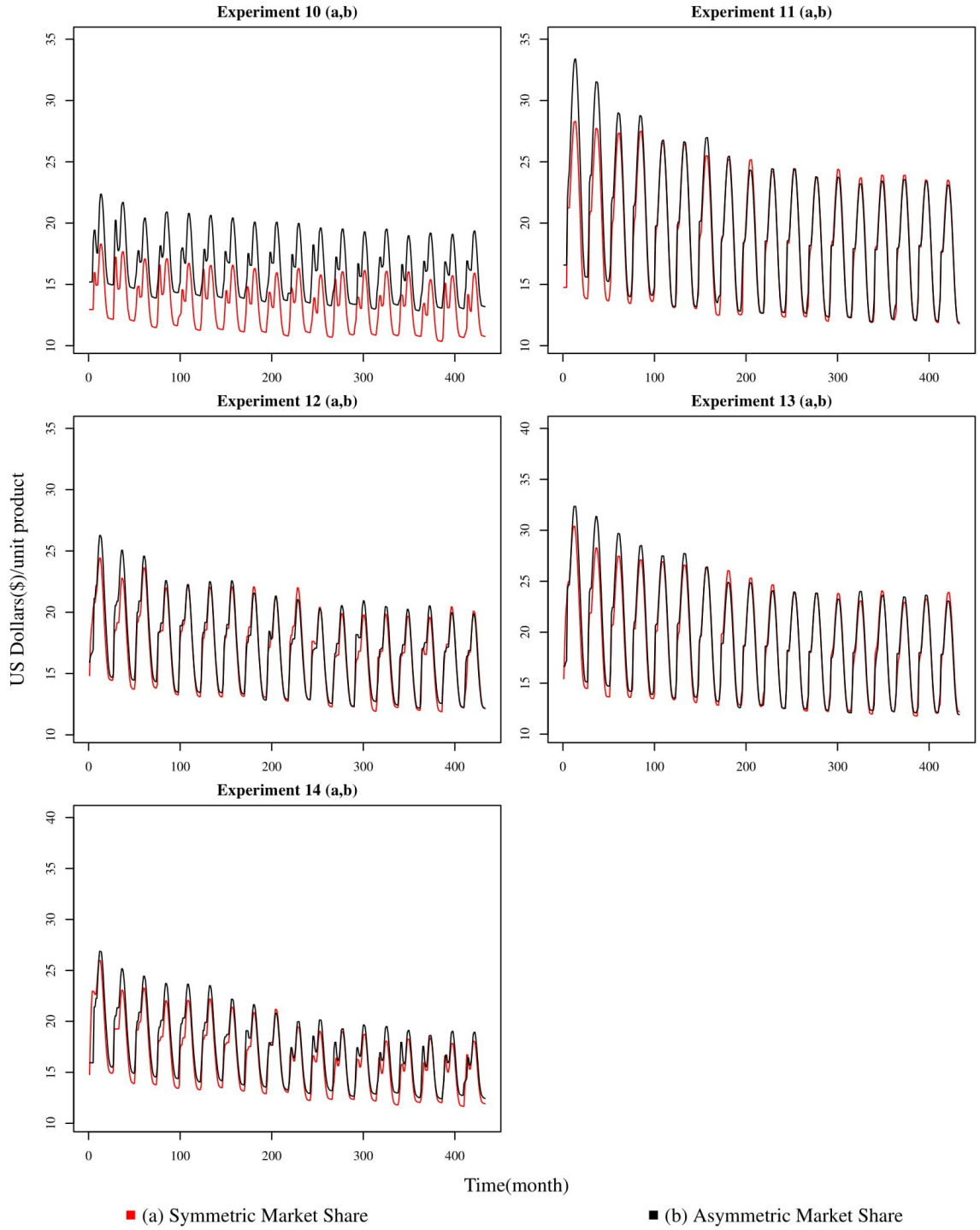


Figure 5.13. Price level comparisons for experiments from 10 to 14 (a-b).

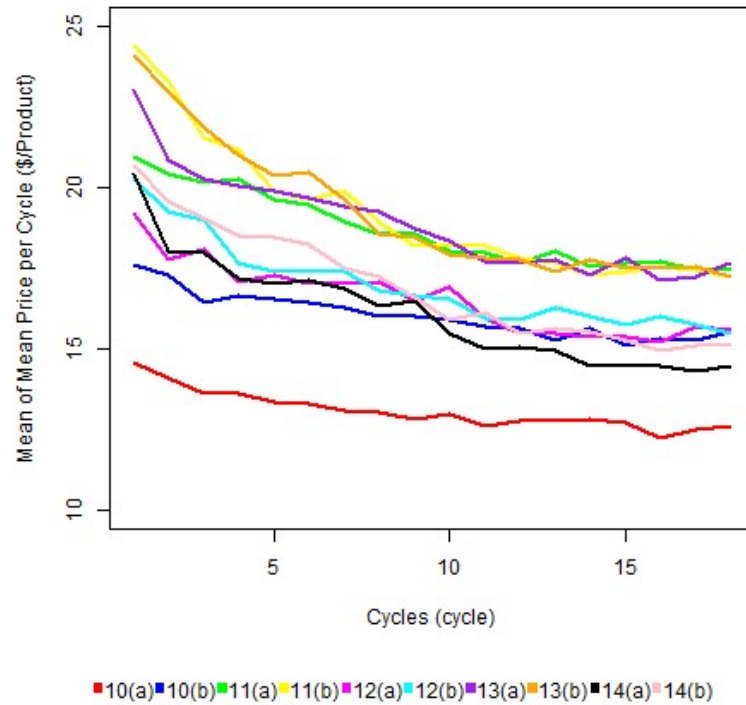


Figure 5.14. Change in mean price between cycles for experiments 10-14 (a-b).

### 5.2.2. Supply Shock

Supply shock indicates a sudden drop in supply levels in the market. In this experimental settings, a supply shock is created by destroying the all capacity investments of the leader firm in terms of market share in a single period. In these experiments, it will be investigated that which capacity adaptation algorithm is more robust to supply shock in order to prevent sudden change in price and loss of market share. An example of a supply shock from a single run can be seen in Figure 5.15. A supply shock creates a minor bullwhip effect in the market. After a supply shock, an over-investment in capacity follows this supply shock. During the shock, firms encounter relatively more demand than expected. Then, they invest more capacity in next periods.

The change in capacity for asymmetric market share distribution case can be seen in Figure 5.16. The firm, who faces the destruction in capacity, loses some amount of its market share to the competitors. The market share change of firms can be seen in

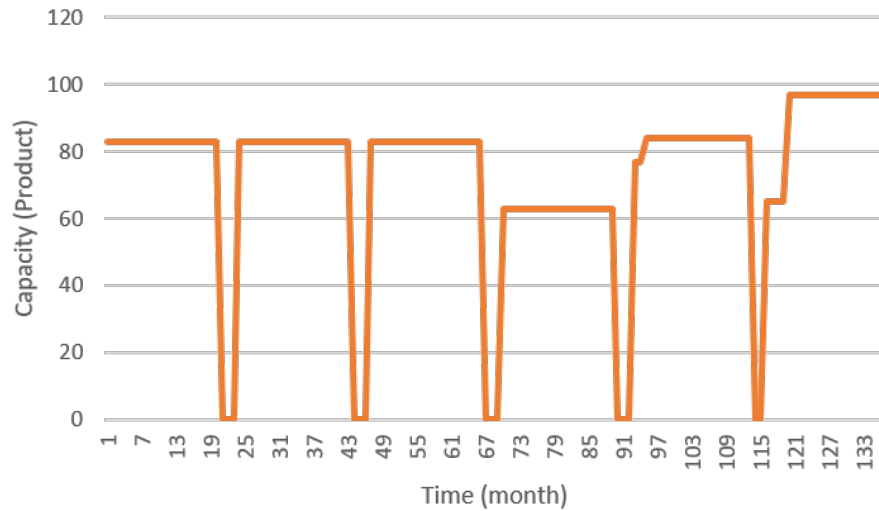


Figure 5.15. An example run for a supply shock.

Figure 5.17. The manufacturer who faces the capacity loss is indicated by red color. In coordinated but defecting and independent adaptive capacity settings the firm that has lost its capacity, restores their market share immediately if they choose a demand oriented capacity profile. In the existence of profit maximizing firms, demand oriented investment is a way to gain market share. Additionally, the technology adoption rate of the firm that faces the supply shock decreases. It enters the market later than its competitors and loses its cost advantage on them.

Table 5.5. Experiment settings under supply shock.

Experiment No.	Capacity Decision
15 (a-b)	Demand Oriented
16 (a-b)	Profit Maximizing
17 (a-b)	Independent
18 (a-b)	Coordinated-Loyal
19 (a-b)	Coordinated-Defecting

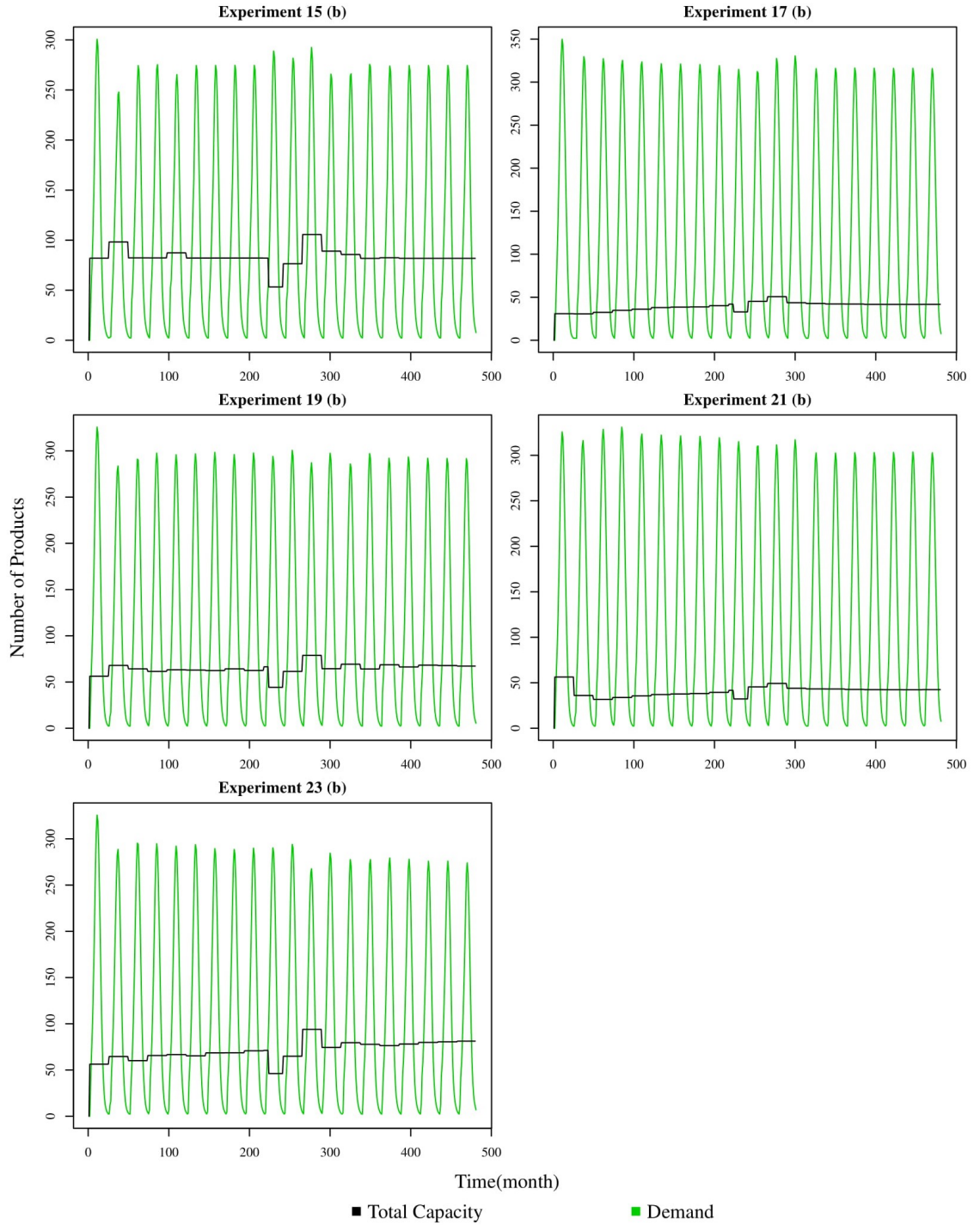


Figure 5.16. Capacity level and demand comparisons for experiments from 15 to 19.

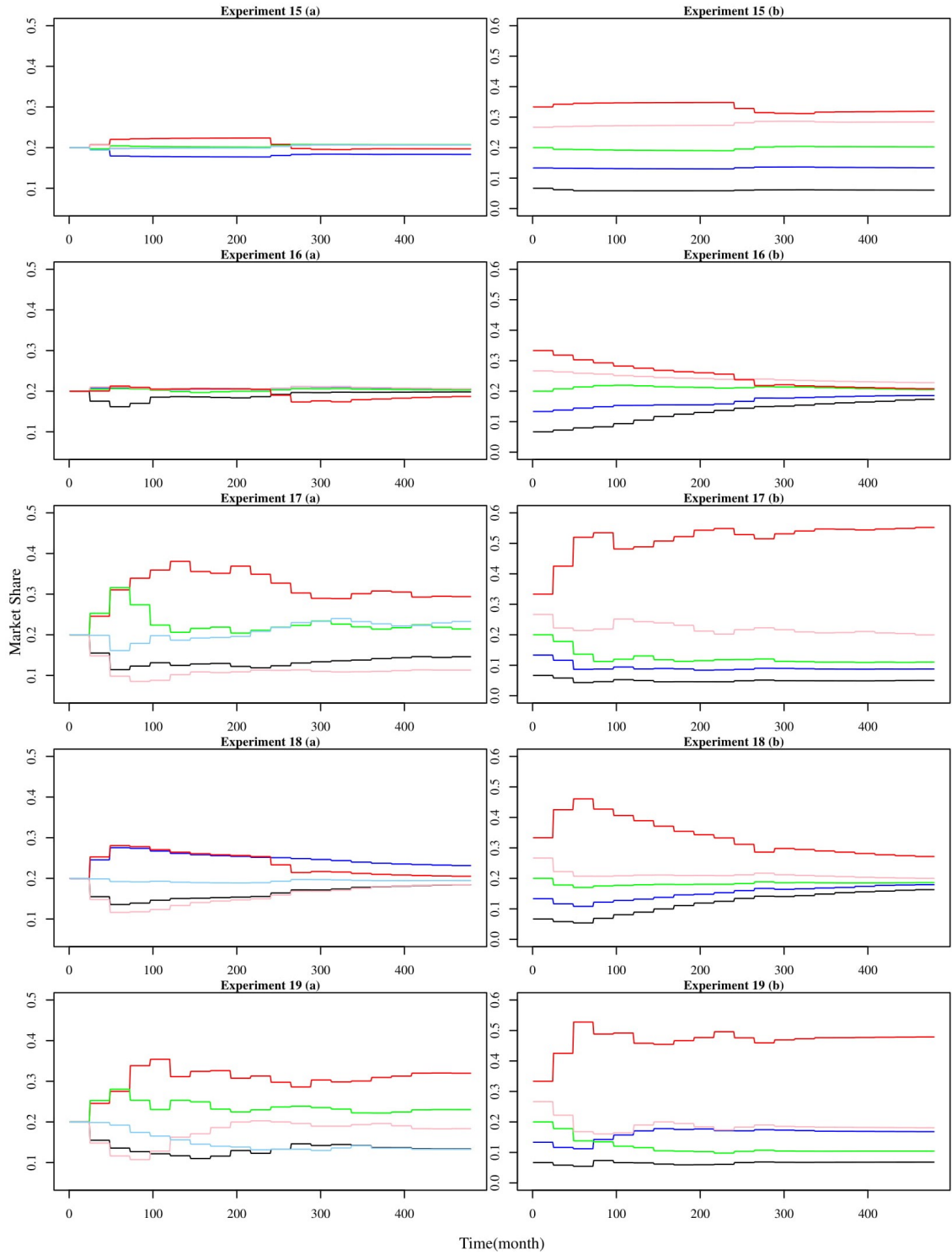


Figure 5.17. Change in market shares for experiments from 15 to 19 (a-b).

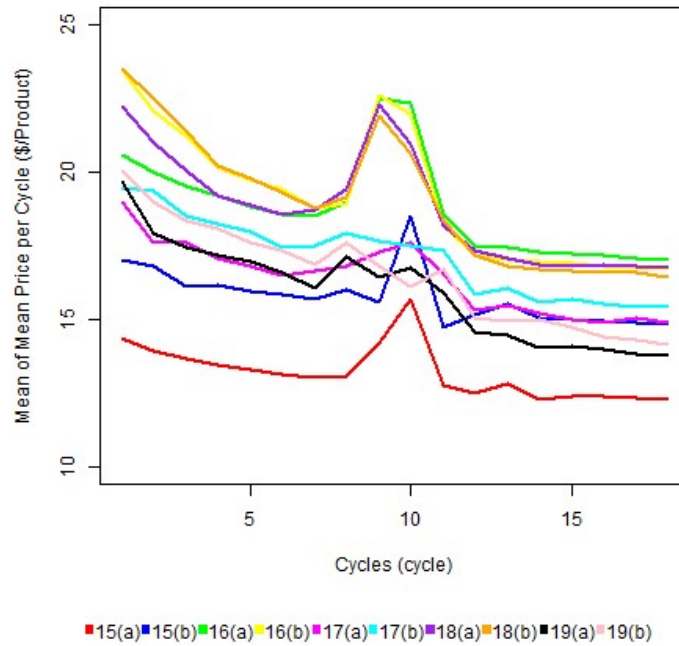


Figure 5.18. Change in market shares for experiments from 15 to 19 (a-b).

The mean of prices for each cycle for 50 experiments is shown in Figure 5.18. In a mixed capacity profile market (presence of both demand oriented and profit maximizing firms) (independent (experiment 17), defecting from coordination (experiment 19) the effect of supply shock on price is absorbed by the natural fluctuations in price when mean of 50 experiments is computed. The single experiments results for experiments 17, 18 and 19 (a-b) can be seen in Figure A.1, Figure A.2, Figure A.3, Figure A.4, Figure A.5 and Figure A.6.

Even though the random fluctuations in price is high in mixed capacity profile market, the effect of a supply shock will not be reflected on price in the presence of both demand oriented and profit maximizing firms. As an another important result, after a supply shock the market can recover itself by its own dynamics after a few cycles.

### 5.2.3. Demand Shock

Demand shock is defined as a sudden increase or decrease in demand during the life time of a product generation. Experiment settings for demand shock can be seen in Table 5.6. An increase in demand is indicated by symbol "I", a decrease in demand is indicated by symbol "D". An example for demand shock by an increase in demand can be found in Figure 5.19, an example for demand shock by a decrease in demand can be found in Figure 5.20.

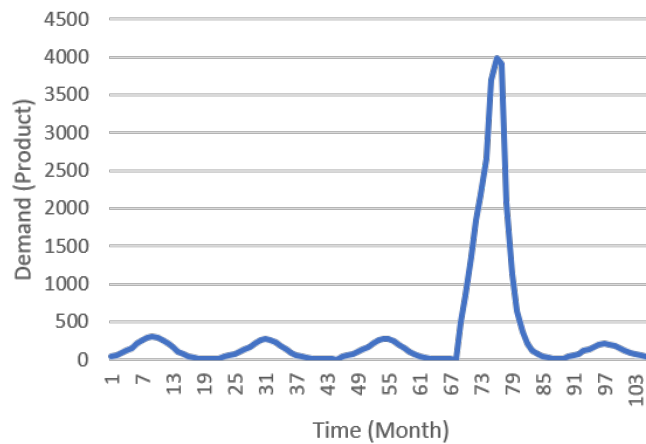


Figure 5.19. An example run for a demand shock by increase in demand.

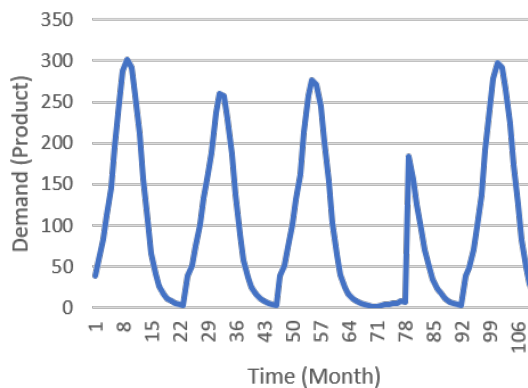


Figure 5.20. An example run for a demand shock by decrease in demand.

Table 5.6. Experiment settings under demand shock.

<b>Experiment No.</b>	<b>Capacity Decision</b>	<b>Direction</b>
20 (a-b)	Demand Oriented	I
21 (a-b)	Profit Maximizing	I
22 (a-b)	Independent	I
23 (a-b)	Coordinated-Loyal	I
24 (a-b)	Coordinated-Defecting	I
25 (a-b)	Demand Oriented	D
26 (a-b)	Profit Maximizing	D
27 (a-b)	Independent	D
28 (a-b)	Coordinated-Loyal	D
29 (a-b)	Coordinated-Defecting	D

The results of experiments with demand shock can be seen in Figures 5.21 and 5.22. Demand shocks affect the market for only a few cycles then the market adjusts itself. A sudden and major increase in demand affects the next production cycle by reducing the prices. After a demand shock, manufacturers invest more capacity with the expectation of more demand. A sudden decrease in demand affects the price and capacity investments with the same pattern but into opposite direction. A sudden change in the system creates a bullwhip effect. Demand shock shows the same effect on price pattern for all experimental settings. The change in price is more for experiments with profit maximizing manufacturers (experiments 21, 23 (a-b)).

### 5.3. Third Set of Experiments

As the third set of experiments, the effect of adaptive pricing with different capacity adaptation profiles will be examined. The price level comparisons of different settings under adaptive pricing strategy is given in Figure 5.23.

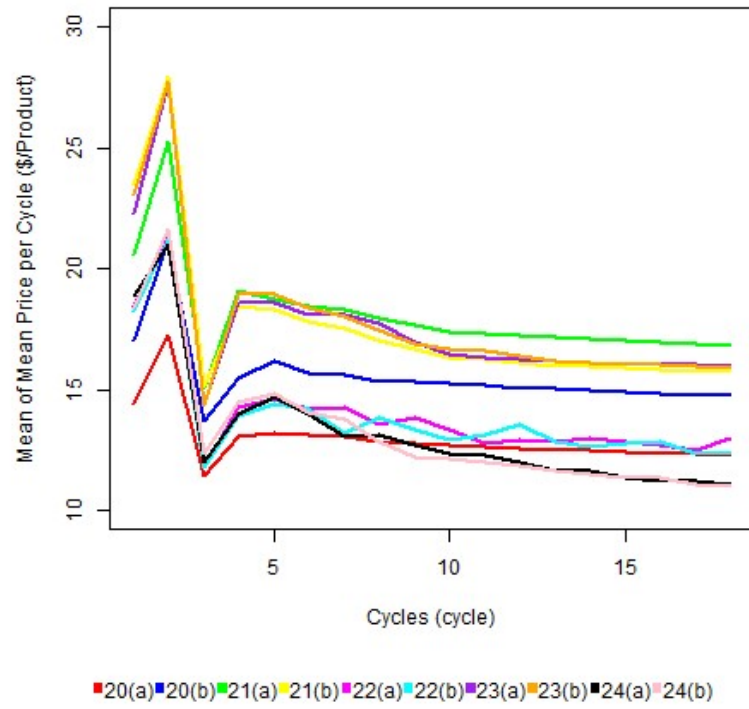


Figure 5.21. Change in mean price levels for experiments from 20 to 24 (a-b).

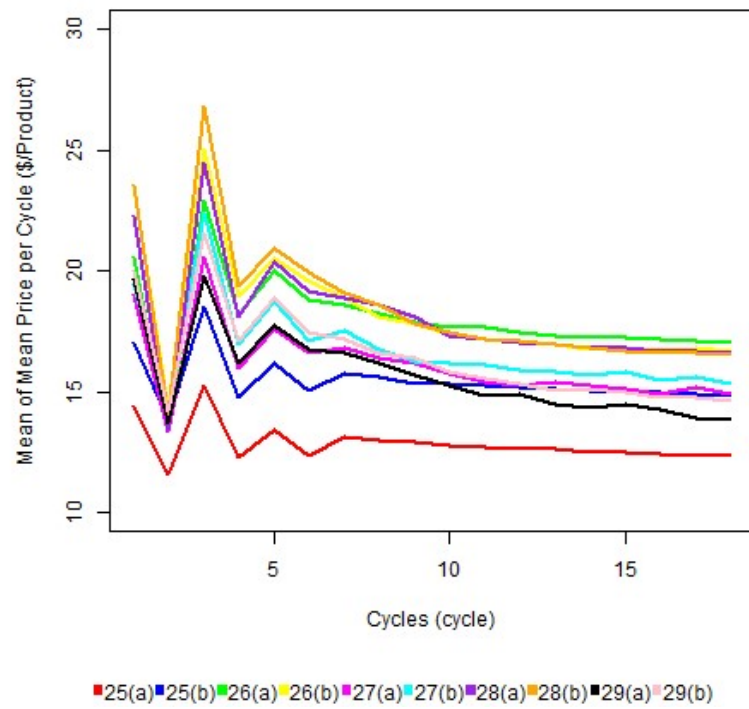


Figure 5.22. Change in mean price levels for experiments from 25 to 29 (a-b).

Price values represented in figures are the weighted averages of each firm's sales price with respect to their sales quantity. The comparison of price levels for experiments 30-34 (a-b) against base experiments (experiments 1, 6, 7, 8, 9 (a-b)) are stated in Table A.12. The price level drops significantly for independent adaptive market (experiments 32 (a-b)) and coordinative but defecting adaptive market (experiments 34 (a-b)) because some firms offer lower price to the market. The reflection of adaptive pricing strategy on market shares can be seen in Figure 5.24 and compared against to Figure 5.10.

Table 5.7. Experiment settings for adaptive pricing strategy.

<b>Experiment No.</b>	<b>Capacity Decision</b>
30 (a-b)	Demand Oriented
31 (a-b)	Profit Maximizing
32 (a-b)	Independent
33 (a-b)	Coordinated-Loyal
34 (a-b)	Coordinated-Defecting

By adaptive pricing strategy the firms with lower unit production costs, gets an competitive advantage on prices and gain more market share from their competitors under some experimental settings. These settings are independent adaptive strategy and coordinated but defecting adaptive strategy (experiments 32 (a-b), experiments 34 (a-b)). In adaptive strategy, a market leader firm may not get benefit as desired but the second or third firms in terms of market share can gain extra share (i.e. experiment 32 (b)). In other experimental settings the capacity strategies dominates the pricing strategy.

A possible reason for this domination is the capital-intensive structure of the market. The level of capacity investment is at the average of the demand in the best case scenario. Supply in the market is always limited. Even though a firm offers very

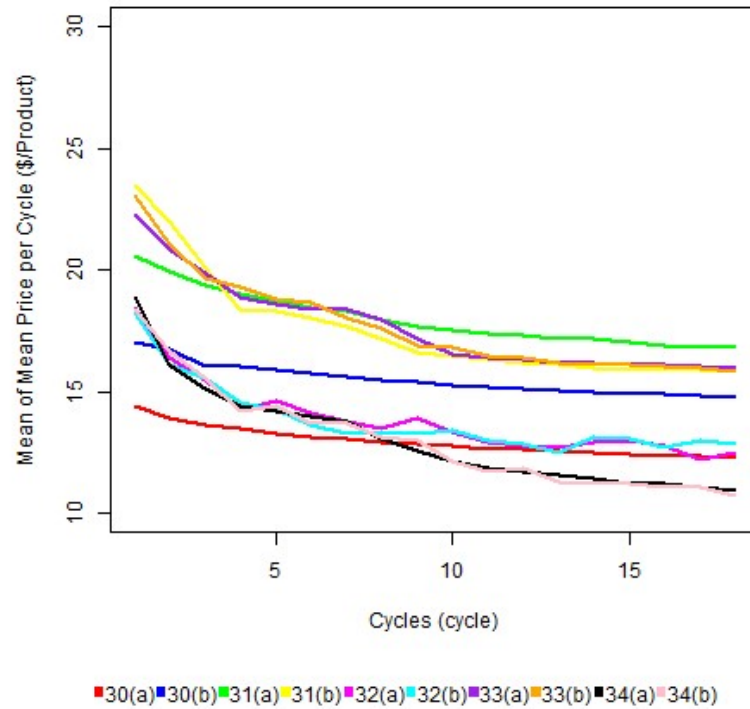


Figure 5.23. Change in mean price levels for experiments from 30 to 34 (a-b).

low prices to the market, it cannot always satisfy the extra demand comes from pricing decision due to limited capacity.

The firms will respond the increasing demand to their products by increasing their demand forecasts for next product generations before they make a new capacity investment decision. However, the capacity cost in the profit maximizing setting is still a factor that taken in the consideration during the capacity decision. So the capacity levels will not always increase with the same rate as the increase in demand. As a result, pricing decisions are effective if they are not constrained by the capacity decisions.

### 5.3.1. Adaptive Pricing Under Supply Shock

The effects of adaptive pricing strategy under supply shock scenario will be investigated in this section. If a firm faces a supply shock, it may use price differentiation as a strategy to gain some of its market share back.

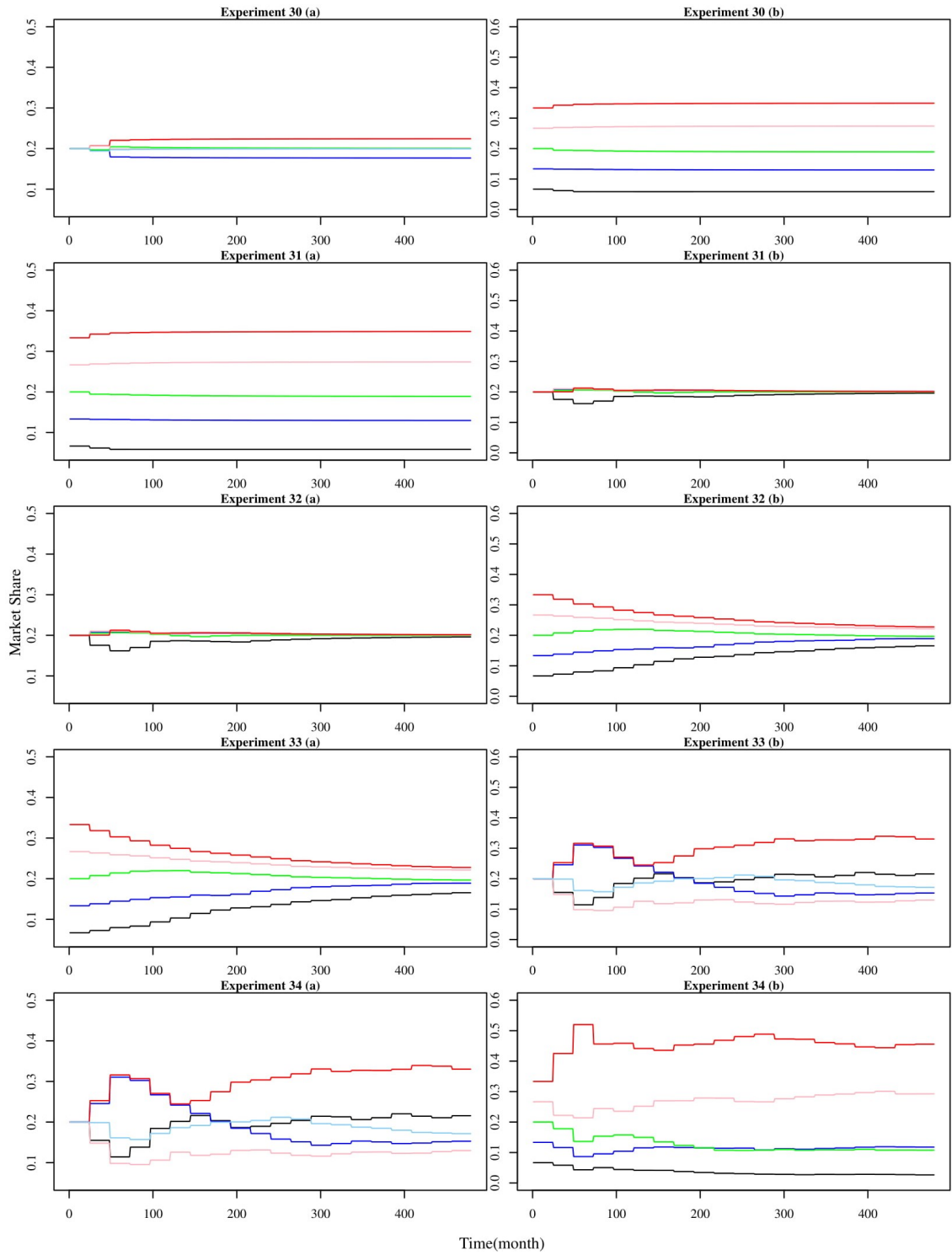


Figure 5.24. Change in market shares for experiments from 30 to 34 (a-b).

The experiment settings for adaptive pricing strategy under supply shock are stated in Table 5.8. In order to compare supply shock (experiments 15-19) and adaptive pricing under supply shock scenarios (experiments 35-29), the same seed is used to compare change in market shares.

Table 5.8. Experiment settings for adaptive pricing strategy under a supply shock.

<b>Experiment No.</b>	<b>Capacity Decision</b>
35 (a-b)	Demand Oriented
36 (a-b)	Profit Maximizing
37 (a-b)	Independent
38 (a-b)	Coordinated-Loyal
39 (a-b)	Coordinated-Defecting

As it can be seen in Figure 5.17 and Figure 5.25, price differentiation only works for certain cases. In asymmetrical cases the leading firm does not lose the most of its market share during a supply shock, so with or without price differentiating, it can save its market share. In symmetrical market distribution setting, only the firms can stay above the other manufacturers in terms of market share, can get benefit from price differentiation. If a firm cannot anticipate its final market share after a supply shock, it must not start an adaptive pricing mechanism in the market. In this settings, it is enough for one firm to initiate with price differentiation as an adaptive strategy setting. Other firms must follow this act to prevent loss of their market shares. Capacity strategies affect the dynamics more than pricing strategy.

#### **5.4. The Fourth Set of Experiments**

In the first three set of experiments a generalized market structure is studied for different capacity investment and pricing strategies under different scenarios. The insights obtained from these experiments give an opportunity to specify an experiment for the DRAM market in detail.

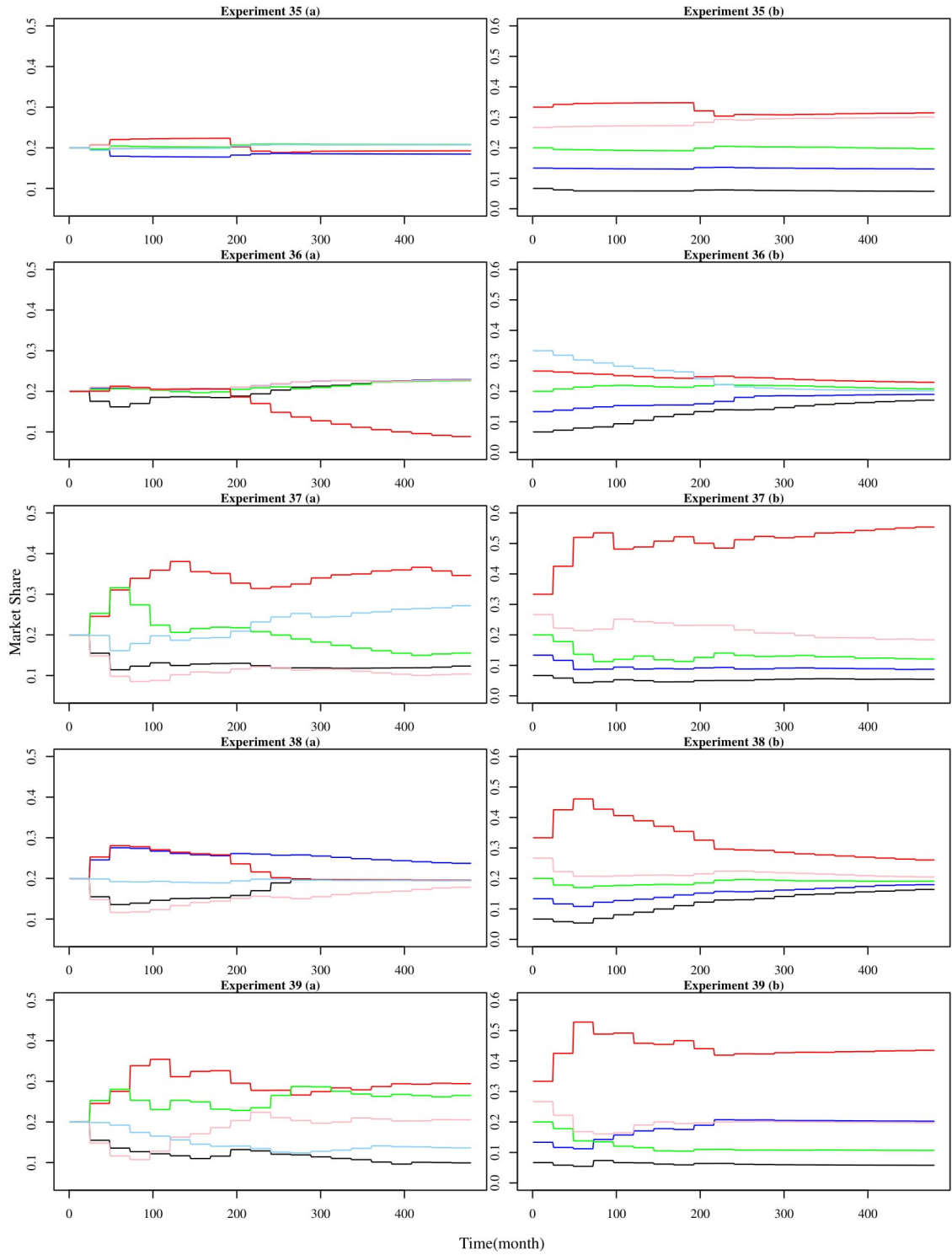


Figure 5.25. Change in market shares for experiments from 35 to 39 (a-b).

As fourth set of experiments, different experimental settings are scheduled consecutively to replicate the price dynamics in DRAM market between 2003-2018 period. The real price dynamics for this interval can be seen in Figure 1.4 and 1.5. There are two experiments in this set: demand oriented behaviour by manufacturers after a supply shock and coordinative behaviour for capacity under-investment of manufacturers after a supply shock. The supply shock is designed as to destroy the capacity of the firm, which is at second place in terms of market share, since the factory fire of SK Hynix is replicated in this experiment set.

In this experimental settings, the manufacturers start the simulation as demand oriented firms (between months 0-169), this period corresponds the pre-2013 period in the market. Then the manufacturer with the second largest market share faces with a supply shock at month 169. There are two type of behaviours after this supply shock. In experiment 40, manufacturers continue their demand oriented behaviour in capacity investment decisions. In experiment 41, manufacturers decide to coordinate for capacity under-investment two cycles after supply shock at month 224, so they can raise the prices. In real life the date corresponds to 2017-2018 period. The market share distribution is asymmetrical for this experiment in order to represent the real DRAM market. The change in mean price level over cycles for experiment 40 and 41 can be seen in Figure 5.26 and Figure 5.27.

After a supply shock, it is possible to observe a price increase in the market in two cycles as a result of these experiments. However, the trend of the price is decreasing if there is no coordination for capacity under-investment in the market.

The price increase in 2016 can be explained by aftershock of capacity crisis in 2013. However, according to experiment 40 it expected to see a downward trend in price levels in 2018. It can be stated that a supply shock is unlikely to be the reason behind a permanent increase in price level. One possible and reasonable explanation of a steady increase in price levels since the beginning of 2017 is low capacity investment by coordination in the market.

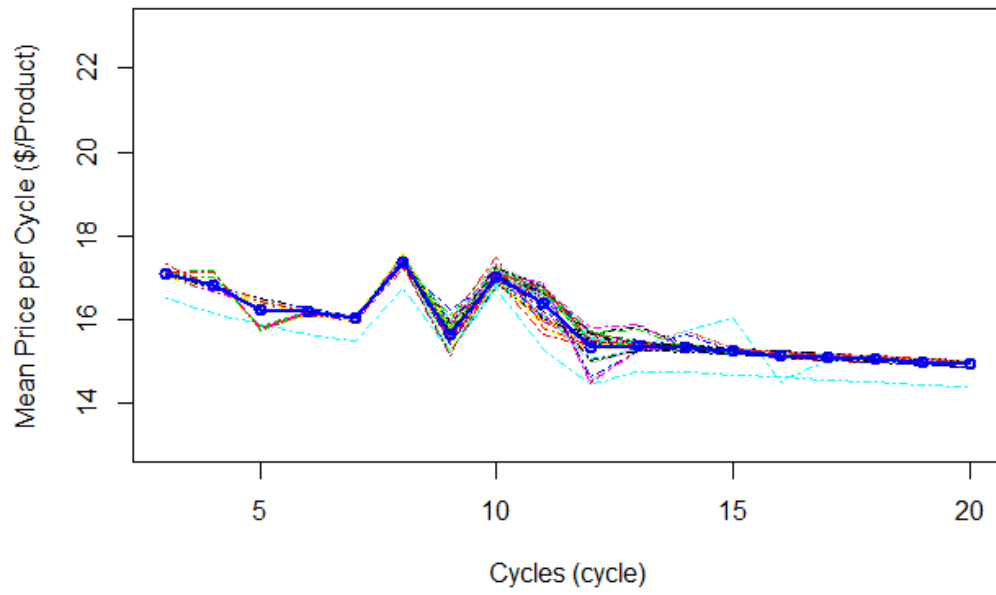


Figure 5.26. Change in mean price level for experiment 40.

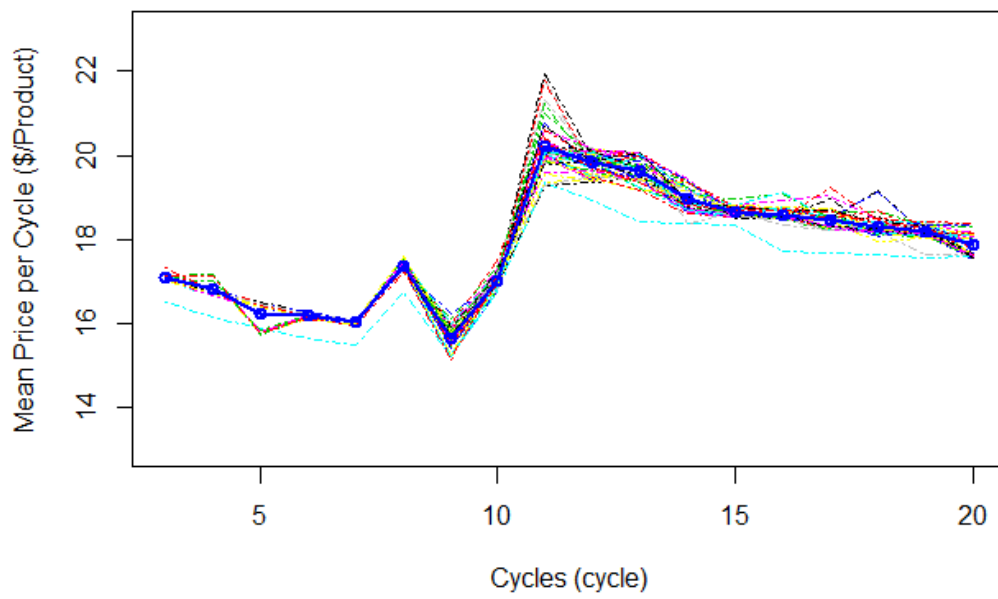


Figure 5.27. Change in mean price level for experiment 41.

From the experiments on coordination but defecting, it is known that if only one firm defects and invest more capacity to the market, defecting firm will gain more market share and obtain a cost advantage against its competitors. From a policy maker point of view, forcing only one firm from a possible agreement is enough to restore the prices in the market.

## 6. CONCLUSION

The change of price levels in DRAM market is an issue that affects many parties from manufacturers to customers. The capital intensive and oligopolistic structure of the market determines the main price dynamics. The capacity and production decision of manufacturers are the key determinants of the price of a certain product generation. In this study, the price dynamics in DRAM market is examined under different capacity investment and pricing mechanisms that are plausible to mimic the real-life behaviour of the DRAM market. Besides that, different scenarios are examined such as random demand change between product generations, supply or demand shocks. Firms in the market change their strategies according to their experiences and external effects on the market. Because of that, adaptive strategies of manufacturer firms are considered in this study both as independent adaptiveness and coordination adaptiveness.

There are two important factors that affect the price: unit costs of manufacturers and the demand/supply balance in the market. Both of these factors are directly related to the production decisions of the manufacturers. However, it is seen from experiments that one of the effects may be dominant the other under different market share distributions. In cases where the unit costs of firms are very high due to low production levels, the effect of unit cost is the reason behind a price level increase. The production levels are directly related to the market share of the firm. Especially when there is a manufacturer with considerably less market share than its competitors, the price level will increase if other firms offer the same price with this firm. The distribution of market shares amongst the manufacturers in the market is an important determinant of price dynamics from this perspective.

Controlling the demand/supply balance is an effective and indirect tool to raise the price levels in the market. The manufacturers can increase price in the market with their capacity decisions. If all firms take capacity investment decisions purely based on their demand forecasts, the overall price level in the market will be low. A manufacturer

may prefer to take an investment decision with a profit maximization strategy, which considers the future price, demand and other manufacturer's investment levels. When all firms agree to decrease the level of capacity investment by an estimated profit maximization function for next product generation, the overall price level in the market will increase.

Besides following the same strategy over periods, firms may choose to invest more for some product generations and invest less for some product generations according to their profitability levels. This is called as an adaptive capacity investment strategy. If they adapt their capacity investment decisions independent of each other, the market price will be more than the case where they invest capacity purely depending on demand anticipation and less than case where all of them invest according to profit maximization because there will be a mixture of different capacity investment profiles in the market.

As a different adaptive strategy, firms may want to coordinate together to embrace a profit maximizing strategy. If they succeed to coordinate, the overall price level increases in the market. The products become scarce under a loyal coordination and all firms get benefit from it. In order to get desired result from a profit maximizing strategy, all firms must agree to stay in coordination. Only one defecting firm from the coordination will both decrease the price level in the market and result with the loss of market share for other firms. It is an important outcome for policy makers to use against a possible coordination in the market.

The change of demand randomly between each product generation does not affect the level of price, except when all manufacturers are profit maximizers. When all manufacturers embrace the profit maximization strategy, the average price in the market is more than stationary demand case. Only within cycle price fluctuations are seen more frequently in experiments with randomly changing demand between generations. However, the price levels are not significantly different than the settings with stationary demand between generations. Random changes in demand between product generations is unlikely to be the reason behind the steep increase in price levels.

As another conclusion of this study, the market recovers itself after a supply shock, i.e. loss of capacity in large amounts during a production cycle. An over-investment period follows a supply shock, which results in a decrease in the prices. Supply shock creates sudden increase and decrease in prices, however the effects are not permanent in the market. After full recovery, market dynamics return to pre-shock period. In a market with mixed capacity profiles (the presence of both demand oriented and profit maximizing manufacturers in the market) change in price level is milder than the market with homogeneous capacity profiles.

Demand shocks, i.e. a sudden increase or decrease in demand, create bullwhip effect in the market. An increase in price is followed by a steep decrease in price in the next production cycle. In experiments on demand shock, the magnitude of price changes are higher in a market with profit maximizing firms. In mixed capacity profiles in the market, the change in price is less than coordination to profit maximize setting. Price level in the market will be affected more in a supply or demand shock scenario in a market filled with profit maximizing manufacturers.

Price differentiation as an adaptive pricing strategy may prevent the firms lose their market share in case of a sudden drop in their market shares. The adaptive pricing strategy is more effective in the market with mixed capacity profiles (the presence of both demand oriented and profit maximizing manufacturers).

In case of a supply shock, adaptive pricing strategy should be considered carefully. When a firm loses most of its market share and falls behind the other firms, then applies the adaptive pricing strategy, this strategy may not yield to results in the favour of this firm. If this firm lose more market share than it anticipates and its market share falls behind the market share of its competitors, it may not decrease its price more than its competitors. When the competitors will follow the price differentiation, the price offered by the firm that faces a supply shock may be higher than its competitors and suffer more by this adaptive pricing strategy by loss of extra market share.

In the final experiment, all of the outcomes of previous experiments are taken into consideration and a possible set of scenarios are scheduled consecutively to replicate the actual market dynamics between 2003-2018 periods. This scenario starts with a market full of demand oriented manufacturers. Then the second largest firm in terms of market share faces a supply shock, which corresponds SK Hynix factory fire in 2013. Then there are two experimental settings, the firms in the market may choose to stay in demand oriented capacity investment strategy or they can coordinate to make under-investment with profit maximization strategy two cycles after the supply shock. These experiments do not aim to replicate the price dynamics point by point but aim to replicate the dynamics pattern-wise.

The sudden and short term changes in price can be explained by a supply shock. The market recovers from a shock after a few periods later. Increase in price levels due to aftershock of capacity loss can be seen in the market after two cycles according to experiments. However, if the shift in the prices is constant or price level has an upward trend in the long-term, the reason behind this behaviour might be the coordinative capacity under-investment behaviour of manufacturers in order to increase profits, rather than a aftershock in the market.

By referring to the past price data in the real market, there was a price increase in 2013 after SK Hynix factory fire. This increase can be explained by a supply shock. In experiments after a supply shock, market recovers by new investments. In real case, price levels has decreased by new capacity investments between 2015-2016. According to experiments, a price increase is possible between 2016-2017 due to the supply shock in 2013. Because manufacturers try to adjust their capacity investment levels according to demand of previous period, but this adjustment takes time to return pre-shock conditions. However, if there is not any under-investment coordination between the firms, the market price must be showing a downward trend in 2017-2018 period due to experiments. The upward trend in price between 2017-2018 years supports the court's claim of coordination. The law suit filed against the DRAM manufacturers in April 2018 claimed that after 2016 manufacturers coordinate to invest less than anticipated

demand to increase prices in the market. Policy makers must force some firms out of coordination to decrease the price levels and to have a market with independently acting manufacturers.

As a final conclusion, when capacity and pricing strategies are compared against each other, the effects of capacity strategies dominate the effects of pricing strategies on market dynamics. The main reason behind this dominance is the capital-intensive structure of the market. The supply in the market is always limited compared to demand. Capacity becomes a constraint on a price differentiation adaptive strategy in order to gain extra market share from the competitors.

As future work, the exit and entry decisions of firms can be added to the model to examine the market dynamics from a broader perspective. Information sharing between manufacturers in different levels can be investigated. Production strategies are short-term decisions for firms to control market dynamics. The effects of different production strategies will be another research question for this study. Different adaptive production strategies can be investigated under supply and demand shocks in the market. The current model is capable of to adopt these extensions and study on similar markets to DRAM market.

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## APPENDIX A: ADDITIONAL TABLES AND FIGURES

Statistics for each experiment setting can be found below in Tables A.1, A.2, A.6, A.7, A.9, A.10 and A.11. The comparison of means of experiments for Experiments 1-6 (a-b) can be found in Table A.3, A.4 and A.5. The comparison of mean price of experiments 10-14 against experiments 1, 6, 7, 8, 9 can be found in Table A.8. The p-values compared against the  $\alpha = 0.05$  significance level.

Table A.1. Price statistics for experiments 1-6 (a).

<b>Experiment No.</b>	<b>Mean</b>	<b>Variance</b>	<b>Range</b>	<b>Maximum</b>
1(a)	13.19	4.76	7.89	18.34
2(a)	16.21	9.36	22.53	35.13
3(a)	16.28	10.62	27.63	40.15
4(a)	16.36	11.56	27.13	39.52
5(a)	16.22	13.15	22.85	34.81
6(a)	18.16	23.10	16.46	28.05

Table A.2. Price statistics for experiments 1-6(b).

<b>Experiment No.</b>	<b>Mean</b>	<b>Variance</b>	<b>Range</b>	<b>Maximum</b>
1(b)	15.92	6.89	15.78	28.50
2(b)	16.49	10.15	30.60	43.38
3(b)	16.85	12.61	30.69	43.49
4(b)	17.27	15.33	34.92	47.79
5(b)	17.79	17.98	34.04	47.04
6(b)	18.69	26.07	20.79	32.37

Table A.3. Comparison of means with t-test for experiments 1-6 (a).

Experiments	Means	T-statistic	Df	P-value	Result
1-6 (a)	13.19-18.16	-19.59	602.78	$<2.2 * e^{-16}$	Signif. diff.
1-2 (a)	13.19-16.21	-16.69	781.18	$<2.2 * e^{-16}$	Signif. diff.
2-3 (a)	16.21- 16.28	-0.35	860.56	0.7274	Not diff.
2-4 (a)	16.21- 16.36	-0.68	854.54	0.4951	Not diff.
2-5 (a)	16.21- 16.22	-0.04	840.12	0.9647	Not diff.
5-6 (a)	16.22 - 18.16	-6.73	803.49	$3.26 * e^{-11}$	Signif. diff.

Table A.4. Comparison of means with t-test for experiments 1-6 (b).

Experiments	Means	T-statistic	Df	P-value	Result
1-6 (b)	16.24-18.69	-8.50	725.51	$<2.2 * e^{-16}$	Signif. diff.
1-2 (b)	15.92-16.49	-2.86	833.37	0.0044	Signif. diff.
1-3 (b)	15.92-16.85	-4.35	795.47	$1.52 * e^{-5}$	Signif.diff.
1-4 (b)	15.92-17.27	-5.95	754.89	$4 * e^{-9}$	Signif. diff.
1-5 (b)	15.92-17.79	-7.81	720.54	$1.95 * e^{-14}$	Signif. diff.
5-6 (b)	17.79-18.69	-2.80	835.86	0.0052	Signif. diff.

Table A.5. Comparison of means for experiment settings a-b for experiments 1-6.

Experiments	Means	T-statistic	Df	P-value	Result
1(a)-1(b)	13.19-15.92	-16.64	836.12	$<2.2 * e^{-16}$	Signif. diff.
2(a)-2(b)	16.21-16.49	-1.33	862.56	0.1830	Not diff.
3(a)-3(b)	16.28-16.85	-2.44	857.70	0.0151	Not diff.
4(a)-4(b)	16.36-17.27	-3.67	847.26	0.0002	Signif. diff.
5(a)-5(b)	16.22-17.79	-5.89	843.67	$5.68 * e^{-9}$	Signif. diff.
6(a)-6(b)	18.16-18.69	-1.56	860.86	0.1194	Not diff.

Table A.6. Price statistics for experiments 7-9 (a-b).

<b>Experiment No.</b>	<b>Mean</b>	<b>Variance</b>	<b>Range</b>	<b>Maximum</b>
7(a)	16.87	17.14	19.86	31.61
7(b)	17.48	18.17	19.78	31.85
8(a)	18.25	25.09	27.21	38.74
8(b)	18.66	26.68	23.65	35.23
9(a)	16.38	15.03	20.98	32.60
9(b)	16.94	15.49	21.39	33.46

Table A.7. Price statistics for experiments 10-14 (a-b).

<b>Experiment No.</b>	<b>Mean</b>	<b>Variance</b>	<b>Range</b>	<b>Maximum</b>
10(a)	13.60	4.35	8.81	19.38
10(b)	16.68	7.50	22.48	34.81
11(a)	18.29	22.72	18.26	29.32
11(b)	19.18	25.89	21.83	33.43
12(a)	16.91	12.82	15.69	26.85
12(b)	17.05	11.66	14.84	26.72
13(a)	17.36	20.75	18.59	29.15
13(b)	17.29	16.74	16.28	27.38
14(a)	16.57	13.72	17.75	28.68
14(b)	16.00	9.74	19.80	31.31

Table A.8. Comparison of means with t-test for experiments 10-14 (a-b) to without random demand settings.

Experiments	Means	T-statistic	Df	P-value	Result
1(a)-10(a)	13.19-13.47	-1.91	861.92	0.0564	Not different
1(b)-10(b)	16.21-16.42	-1.15	823.10	0.2516	Not different
6(a)-11(a)	16.22-18.81	-8.99	804.68	$<2.2 * e^{-16}$	Signif. diff
6(b)-11(b)	18.16-19.37	-3.56	859.91	$4 * e^{-4}$	Signif. diff.
7(a)-12(a)	16.87-17.09	-0.85	834.98	0.3955	Not diff.
7(b)-12(b)	17.48-17.48	0.01	837.85	0.9895	Not diff.
8(a)-13(a)	18.25-19.05	-2.37	863.73	0.0178	Signif. diff.
8(b)-13(b)	18.66-19.40	-2.11	863.98	0.0348	Signif. diff.
9(a)-14(a)	16.38-16.60	-0.86	849.12	0.3883	Not diff.
9(b)-14(b)	16.94-17.39	-1.79	849.94	0.0742	Not diff.

Table A.9. Price statistics for experiments 15-19 (a-b).

Experiment No.	Mean	Variance	Range	Maximum
15(a)	13.53	7.62	19.96	30.41
15(b)	16.19	10.82	24.44	37.13
16(a)	18.99	33.54	34.78	46.39
16(b)	19.42	35.60	33.32	44.91
17(a)	17.10	18.96	21.11	32.82
17(b)	17.81	19.40	20.36	32.42
18(a)	19.04	32.05	30.51	42.07
18(b)	19.32	32.69	32.65	44.33
19(a)	16.54	16.36	21.01	32.60
19(b)	17.12	16.62	21.47	33.46

Table A.10. Price statistics for experiments 20-29 (a-b).

<b>Experiment No.</b>	<b>Mean</b>	<b>Variance</b>	<b>Range</b>	<b>Maximum</b>
20(a)	13.25	8.09	21.45	31.66
20(b)	15.99	13.62	30.12	42.28
21(a)	18.12	32.74	38.26	49.38
21(b)	17.67	43.24	45.84	53.87
22(a)	14.73	32.04	59.93	67.27
22(b)	14.64	32.18	58.81	65.99
23(a)	17.81	47.03	62.48	71.90
23(b)	18.02	48.17	56.41	65.24
24(a)	13.93	26.79	52.13	59.55
24(b)	13.99	30.81	62.31	69.45
25(a)	13.16	6.08	16.06	26.01
25(b)	15.82	8.66	17.66	29.51
26(a)	18.12	26.71	21.69	33.22
26(b)	18.47	29.41	24.48	36.08
27(a)	16.72	18.89	19.11	30.73
27(b)	17.38	20.40	20.16	32.20
28(a)	18.23	29.32	23.83	35.38
28(b)	18.64	32.44	26.93	38.51
29(a)	16.25	15.65	20.99	32.61
29(b)	16.93	16.45	20.10	32.29

Table A.11. Price statistics for experiments 30-35 (a-b).

Experiment No.	Mean	Variance	Range	Maximum
30(a)	13.19	4.76	7.89	18.34
30(b)	15.83	6.90	15.89	28.50
31(a)	18.03	24.19	16.94	28.05
31(b)	17.67	31.31	23.11	32.37
32(a)	14.59	21.33	27.78	34.96
32(b)	14.56	21.13	27.76	35.07
33(a)	17.79	29.31	27.87	37.35
33(b)	17.92	31.77	27.03	36.24
34(a)	13.72	17.43	24.80	31.98
34(b)	13.78	19.65	29.52	36.51
35(b)	18.59	21.25	33.98	46.39

Table A.12. Comparison of means with t-test for experiments 30-34 (a-b) to against base demand settings.

Experiments	Means	T-statistic	Df	P-value	Result
1(a)-30(a)	13.19-13.19	0.00	864.00	1	Not diff.
1(b)-30(b)	16.21-15.83	1.94	844.72	0.0532	Not diff.
6(a)-31(a)	16.22-18.03	-6.17	794.54	1.1198*e <sup>-09</sup>	Signif. diff.
6(b)-31(b)	18.16-17.67	1.40	844.77	0.1622	Not diff.
7(a)-32(a)	16.87-14.59	7.66	853.88	4.9010*e <sup>-14</sup>	Signif. diff.
7(b)-32(b)	17.48-14.56	9.70	859.14	<2.2*e <sup>-16</sup>	Signif. diff.
8(a)-33(a)	18.25-17.79	1.30	858.85	0.1956	Not diff.
8(b)-33(b)	18.66-17.92	2.01	857.49	0.0445	Not diff.
9(a)-34(a)	16.38-13.72	9.74	859.31	<2.2*e <sup>-16</sup>	Signif. diff.
9(b)-34(b)	16.94-13.78	11.09	852.07	<2.2*e <sup>-16</sup>	Signif. diff.

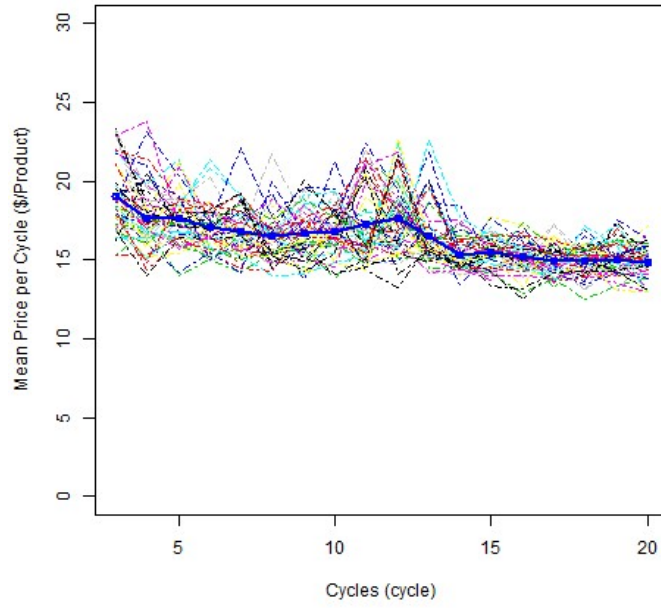


Figure A.1. Change in price means over cycles for each single experiment 17 (a).

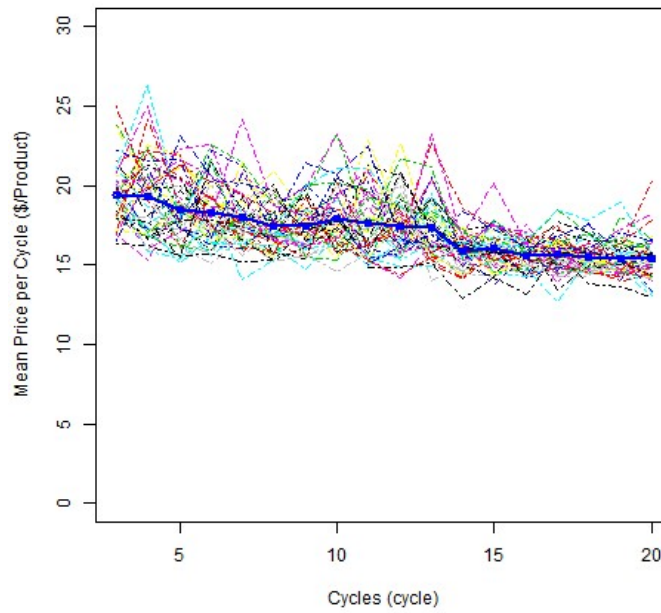


Figure A.2. Change in price means over cycles for each single experiment 17 (b).

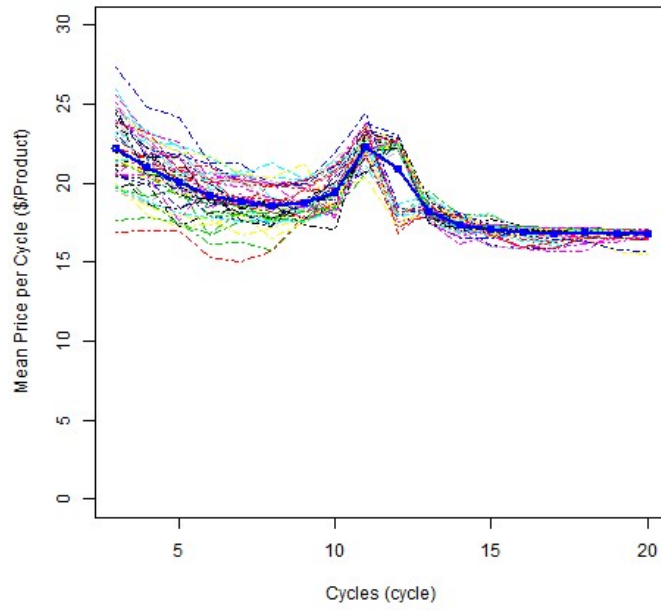


Figure A.3. Change in price means over cycles for each single experiment 18 (a).

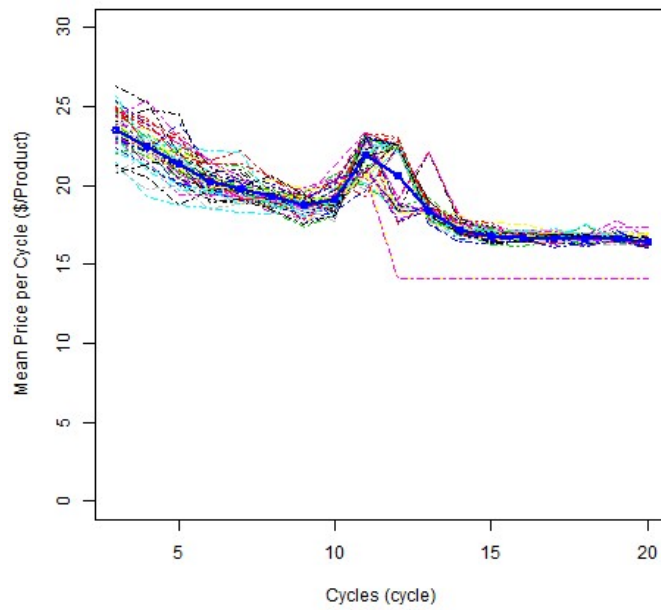


Figure A.4. Change in price means over cycles for each single experiment 18 (b).

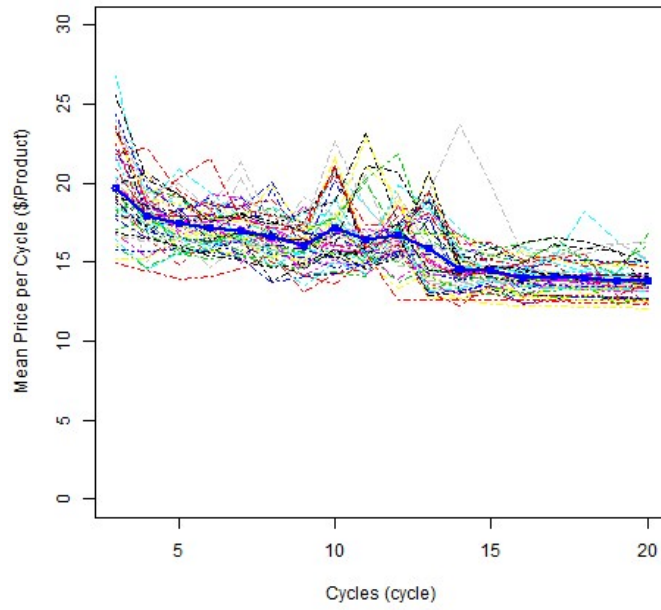


Figure A.5. Change in price means over cycles for each single experiment 19 (a).

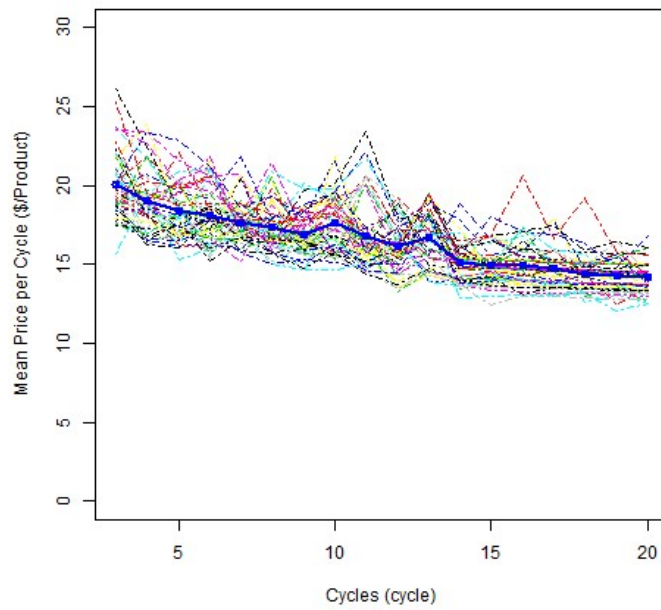


Figure A.6. Change in price means over cycles for each single experiment 19 (b).

## **APPENDIX B: CODES FOR MODEL**

Codes for model can be found in the compact disk (CD) attached to this thesis with a list of files in the disk, detailed documentation of software and hardware requirements.