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Introduction

There has been continuous attention drawn onto the issues regarding competition from the economists, market agents and policy makers. While these issues are important in the study of market efficiency and social welfare, they also bring up significant complexity due to the heterogeneity of market agents, the multiplicity of competition tools, the difference in exogenous market features, etc. Here, I mainly discuss three types of market environments: credence goods markets, platform competition with network effects, and capacity precommitment and price competition in the markets with perfectly inelastic demand.

Chapter 1 discusses the fraudulent behavior and market inefficiency in credence goods markets. The most distinctive feature in such markets for expert services is that there is significant information asymmetry among market agents. Different from many other traditional markets, customers seeking for expert services usually lack the knowledge of what kinds of problems they have as well as the treatment quality they receive. Naturally, sufficient information advantage is granted to the experts as they can learn the needs of their customers by performing diagnosis and provide the treatments or services. Given this feature, fraudulent behaviors are the main concern in such markets and have essential influence on market efficiency.

Many studies have addressed the fraudulent behaviors in markets for expert services. Certainly, their predictions do not all match real-life observations, depending on their specific assumptions. In the seminal paper by Dulleck and Kerschbamer (2006), a general theoretical model is developed to analyze experts' behaviors and market outcomes. They mainly show that, with some specific assumptions, efficient market outcome, in which experts always provide the proper treatments and all the customers are treated, can be sustained in equilibrium. However, these results are mainly built on an implicit assumption that experts can always perform perfect diagnosis. Many real-life observations suggest that experts' diagnostic ability can hardly be perfect. Using a quasi-experimental approach, Xue et al. (2019) find that lack of sufficient diagnostic knowledge is an important driver of the large amount of inappropriate antibiotic prescription in rural China. By studying the performance of radiologists in the U.S., Chan et al. (2022) show that diagnostic skills play an important role in explaining the variation of their diagnostic performance of pneumonia.

To study how diagnostic abilities affect market outcomes in credence goods markets, we extend the model in Dulleck and Kerschbamer (2006) by assuming that experts are heterogeneous in their diagnostic abilities. We find that inefficient market outcomes are possible in equilibrium when customers cannot observe experts' abilities before entering the market.

Chapter 2 takes the view onto platform competition, of which the market features and analysis differ from traditional markets in several aspects. First, as platforms facilitate the interactions of market agents from different groups, the utilities of the agents depend not only on the goods or services they purchase, but also on the network size they are associated with. Second, given the features of agents' utilities, price structures of platforms also appear in a different form from that of traditional markets (see Armstrong (2006) and Tan and Zhou (2021)). The third one is the interdependency of equilibrium prices on different sides (*see-saw effects*). Since agents value network size, lowering the price on one certain side may lead to price increase on the other side(s) (see Rochet and Tirole (2003) and Weyl (2009)).

Inspired by the price interdependency in such markets, I study a model of platform competition with endogenous locations. My results show that the equilibrium locations depend on the specified pricing policies and competition modes. Considering *mill pricing policy* and *unbalanced competition*, I find that, in contrast to the *principle of maximum differentiation* in the standard Hotelling model, platforms may choose to have more intensified competition on one side, when the difference of cross-sided network externalities is sufficiently high. Given this pricing policy, the *principle of maximum differentiation* still holds under *balanced competition*. With *discriminatory delivered pricing policy*, the tendency of agglomeration emerges in equilibrium under both *unbalanced* and *balanced* competition. Actually we can find out that location choices can also play the role of commitment device in the market.

In the third chapter, I discuss another kind of commitment device in a different setup, in which firms decide on their capacities prior to price competition. Using a downward sloping demand function, Kreps and Scheinkman (1983) prove that this two-stage game finally yields Cournot outcome. I modify the model in Kreps and Scheinkman (1983) by assuming perfectly inelastic demand and analyze the equilibrium outcomes with different cost structures. I provide complete characterizations of the best responses in the stage of capacity decisions. My results mainly show that the monopoly outcome can always be sustained in equilibrium. In addition, there exists a capacity equilibrium in which only a fraction of consumers are served with increasing marginal cost of capacity installation.

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Chapter 1

The Role of Diagnostic Ability in Markets for Expert Services

with Alexander Rasch, Marco A. Schwarz and Christian Waibel

1.1 Introduction

In markets for expert services – such as medical treatments, repairs, and financial and legal advice – diagnostic abilities differ across experts and are far from perfect. For instance, Chan et al. (2022) show that skill plays an important role in pneumonia diagnoses by U.S. radiologists; Xue et al. (2019) show in their quasi-experimental study that lack of sufficient diagnostic knowledge is an important driver of the large amount of inappropriate antibiotic prescription in rural China; and the ECDC Technical Report (2019) finds that "uncertain diagnosis" was a common reason for antibiotic prescribing in cases in which prescribers (mostly medical doctors in EU/EEA countries) would have preferred not to prescribe (26% stated this as a reason occurring at least once during the previous week).[1]

Nevertheless, the theoretical literature following Dulleck and Kerschbamer (2006) generally assumes that experts can perfectly diagnose their customers' problems, and sometimes makes predictions that do not seem to be in line with real-world observations. For example, Dulleck and Kerschbamer (2006) highlight that fraudulent behavior does not occur, and experts serve customers efficiently when customers are ex ante homogeneous, when they are committed to undergoing treatment after receiving a diagnosis, and when either the treatment is verifiable, or experts are liable; yet, inadequate treatments are an important issue in real-life credence goods markets.[2]

We theoretically analyze whether and how experts' diagnostic abilities change

[1]Further examples include Lambert and Wertheimer (1988) (diagnoses of psychopathology), Brammer (2002) (psychological diagnoses), Coderre et al. (2009) (diagnostic performance for clinical problems), Kondori et al. (2011) (diagnoses by dentists), and Mullainathan and Obermeyer (2022) (diagnoses of heart attacks).

[2]In the U.S. healthcare market, for example, the FBI estimates that up to 10% of the 3.3 trillion US$ of yearly health expenditures are due to fraud (Federal Bureau of Investigation, 2011). For an overview of the phenomenon of so-called physician-induced demand (PID), see McGuire (2000). Gottschalk et al. (2020) show that 28% of dentists' treatment recommendations involve overtreatment recommendations. Fraud in repair services has been documented for cars (Taylor, 1995; Schneider, 2012; Rasch and Waibel, 2018), cellphones (Hall et al., 2019), and computers (Kerschbamer et al., 2016, 2019; Bindra et al., 2020). Balafoutas et al. (2013) and Balafoutas et al. (2017) document fraud in the market for taxi rides. Moreover, fraudulent behavior has been reported in several lab experiments on credence goods (see, for instance, Dulleck et al., 2011; Mimra et al., 2016a,b). Kerschbamer and Sutter (2017) provide an overview of the experimental literature on credence goods markets.

the market outcome in a credence goods market. Our model captures two types of scenarios that represent a wide range of important real-life credence goods markets. First, our set-up applies to those markets in which customers require immediate care, and in which experts must rely on talent, experience, or specific knowledge (for example, mathematical and statistical skills), which cannot be acquired or extended in the short or medium term.[3] Such a limitation to invest in skills may also be due to capacity or time constraints. Another reason for a lack of investment may be that experts are not even aware of their limited skills for a specific task. On a related note, we stress that incorrect diagnoses occur despite the high entry barriers in such markets in which experts are required to have a specific qualification. This may be due to the fact that certain skills are not included in the curriculum in the certifying stage.[4]

Second, as we show in an extension, our results extend to many situations in which experts exert unobservable effort to increase their diagnostic ability, or in which such effort is observable, but experts are homogeneous with regard to the effort costs involved.

Importantly, we assume that prices are not completely fixed,[5] and that they are at least partially borne by customers, as is the case for most repair services and many dental and some medical treatments in numerous countries. Whereas it is true that costs for many of the above-mentioned services are covered by insurance, customers often have to pay rather large amounts for some

[3] Brush Jr et al. (2017) provide an overview of research that analyzes diagnostic decision-making by expert clinicians. The authors highlight the importance of expertise and experience when they conclude that "[t]he ability to rapidly access experiential knowledge is a hallmark of expertise. Knowledge-oriented interventions [...] may improve diagnostic accuracy, but there is no substitute for experience gained through broad clinical exposure" (pp. 632–633).

[4] For example, in Germany, it is criticized that physicians are not sufficiently trained in mathematics and statistics during their university studies, which may be problematic for the success of the vaccination campaign to fight the spread of COVID-19 (see `https://www.spiegel.de/panorama/bildung/corona-impfung-warum-fehlende-mathekenntnisse-unter-aerzten-den-impferfolg-gefaehrden-a-8ce4fb92-69b9-4212-9064-cff9b8bbd4b0`, accessed on January 5, 2023).

[5] For example, the website `clearhealthcosts.com` reports that for magnetic resonance imaging (MRI), different facilities (hospital, radiology center, doctor's office) charge a great range of diverging prices. See `https://clearhealthcosts.com/blog/2012/11/how-much-does-an-mri-cost-part-2/` (accessed on January 5, 2023).

of these services out of their own pocket.[6] For instance, Adrion et al. (2016) analyze medical claims for inpatient hospitalizations across the United States. The authors find that out-of-pocket spending is substantial, even among insured individuals.[7] For healthcare in China, Li et al. (2017) stress the low reimbursement caps in outpatient care, leading to a coverage of only three to five typical outpatient visits. In addition, not all services are covered by health insurance. On a more general note, according to OECD (2019), patients in OECD countries on average pay one in every five health dollars out of their own pocket, where out-of-pocket payments vary across services and goods. On average, almost two-thirds of dental care spending are paid directly.[8]

Our model bases on the standard credence goods model by Dulleck and Kerschbamer (2006).[9] A credence good is a good for which customers do not know which type of quality they need. By contrast, experts learn the necessary quality after performing a diagnosis. Because experts often perform both the diagnosis and the treatment, experts may exploit their informational advantage in one of three different ways. First, when experts overtreat customers, they provide more expensive treatments than necessary. Second, when experts undertreat their customers, they provide an insufficient treatment. Third, when experts overcharge their customers, they charge for more expensive treatments than provided. In this paper, we focus on the first two forms of fraud and the inefficiencies caused by such a behavior. In our set-up, (inefficient) overtreatment and/or undertreatment can occur due to the heterogeneity in experts' diagnostic abilities. Experts can have low or high diagnostic ability, but customers do not observe the type of experts with whom they interact. We are interested in how such differences in diagnostic quality affects expert behavior and market efficiency, and whether better diagnostic abilities yield more efficient outcomes. In contrast to earlier contributions (see the literature overview below) and mo-

[6]For experimental studies that analyze the implications of insurance coverage in the context of credence goods markets, see Kerschbamer et al. (2016) and Balafoutas et al. (2020).

[7]Moreover, Pham et al. (2007) use data from a survey among American physicians, and find that physicians do not routinely consider patients' out-of-pocket costs when making decisions with regard to more expensive medical services.

[8]Note also that co-payments or partial insurance in percentage terms could be readily incorporated into the model, resulting in different equilibrium prices, but without changing the results qualitatively. Because this is not the focus of this paper, we abstract away from such payments.

[9]The seminal article on credence goods markets is by Darby and Karni (1973).

tivated by the above-mentioned circumstances in many credence goods markets, our basic model assumes that diagnosis outcomes are exogenous, that is, more effort or higher investments do not affect diagnostic quality. This has important welfare implications because always recommending the major or minor treatment can be socially optimal in this case.

Our results can be summarized as follows. As a benchmark, we analyze the situation in which expert types are known. In this case, we find that a low-ability expert who performs a correct diagnosis only with some probability – just like a high-ability expert who always correctly identifies a customer's major or minor problem – efficiently serves the market. In contrast to a high-ability expert type, however, such efficient behavior can require to always perform the major or minor treatment.

With unobservable types, multiple pooling equilibria exist. There always exists an efficient equilibrium. Depending on the diagnostic ability and the probability for a high-ability expert type, inefficient equilibria can also exist, which means that increasing the observability of types – for example, via certification – weakly increases efficiency in our setting. An inefficient equilibrium is characterized by the low-ability expert type relying on the diagnosis too often, by both types always providing the major treatment, or by both types always providing the minor treatment. Increasing the probability for a high-ability expert type or marginally improving the low-ability's diagnostic ability can be a pure waste. When the expert types and the customers coordinate on an equilibrium in which both types exclusively provide the major treatment, the increase in the probability of a high-ability expert and the improvement in diagnostic ability do not lead to a better market outcome. A sufficiently strong increase in the low-ability expert's diagnostic ability, however, guarantees an efficient outcome. We also show that our results are robust to certain forms of diagnosis effort and to competition. Moreover, we find that warranties or fines are effective policy tools when the success or the failure of a treatment is verifiable.

The remainder of the paper is organized as follows. In the next section, we provide an overview of the related literature. We describe the model set-up in Section 1.3. In Section 1.4, we derive the equilibria, distinguishing between the cases of observable types (Section 1.4.1) and unobservable types (Section 1.4.2). In Section 1.5, we discuss the different equilibria in terms of efficiency and comparative statics and analyze extensions of our model: diagnosis effort, competition, and fines and warranties. Section 1.6 concludes and provides some policy implications.

1.2 Related Literature

Our paper is related to the literature investigating expert heterogeneity in credence goods markets. Typically, the literature offers evidence that the efficiency benchmark result with homogeneous experts and customers and liability or verifiability breaks down when heterogeneity is introduced.[10] Dulleck and Kerschbamer (2009) investigate credence goods markets with heterogeneous experts in a retail environment.[11] Customers need a costly diagnosis to find out which service they need. High-ability experts ("specialized dealers") can provide a diagnosis, whereas low-ability experts ("discounters") cannot. High-ability experts can provide both minor and major services. By contrast, low-ability experts can only provide the minor service.[12] In a dynamic set-up in which customers can visit multiple experts, the incentive for experts to provide a diagnosis diminishes if customers' switching costs are sufficiently low.[13]

Frankel and Schwarz (2014) also employ a dynamic set-up, to study experts heterogeneous with respect to their costs. Customers return to an expert who provides the minor treatment and visit another expert with positive probability if they receive a major treatment when costs are observable. If experts' costs are not observable for customers, the first best cannot be implemented.

[10]Emons (1997, 2001) does not rely on heterogeneity, but shows that if a monopolist expert's capacities are not fully utilized, the expert fills these unused capacities by overtreatment. Gottschalk et al. (2020) provide experimental evidence.

[11]Fong (2005), Dulleck and Kerschbamer (2006), Hyndman and Ozerturk (2011), and Jost et al. (2021) study customer heterogeneity in credence goods markets. Szech (2011) analyzes expert heterogeneity in a health-care market with one type of problem.

[12]Alger and Salanié (2006) and Obradovits and Plaickner (2020) also look at settings with (observable) high-ability experts and discounters, but they only consider the case in which the high type's diagnostic ability is exogenously perfect, and the discounter's ability is non-existent.

[13]By contrast, Bester and Dahm (2018) build on Dulleck and Kerschbamer (2009) and allow for an additional service in the second period in case the service in period one turns out to be insufficient, where the delay in service is costly. The authors show that if the delay costs are sufficiently high – that is, if a second service does not improve customers' utilities –, the first-best allocation can be implemented.

Relatedly, Hilger (2016) extends Dulleck and Kerschbamer (2006)'s model by assuming heterogeneity in experts' treatment costs. Treatment costs are no longer observable to customers. Hence, experts cannot credibly signal to provide the appropriate treatment anymore.[14] Then, experts can take advantage of their expert status, resulting in equilibrium mistreatment in a wide range of price-setting and market environments.[15]

Moreover, Kerschbamer et al. (2017) find theoretical and experimental evidence that inefficient market outcomes with fraud can arise due to the heterogeneity in experts' social preferences. In particular, experts displaying a strong inequity aversion are reported to overtreat or undertreat customers to reduce differences in payoffs.

All of those papers look at very different dimensions of expert heterogeneity that are unrelated to differences in diagnostic abilities, and thus complement the mechanisms and policy implications in our paper.

The article closest to ours is Schneider and Bizer (2017a), who offer an extension of the setup in Pesendorfer and Wolinsky (2003).[16] Whereas Pesendorfer and Wolinsky (2003) assume that experts are homogeneous and must decide whether they exert high or low diagnosis effort, Schneider and Bizer (2017a) consider two types of experts. Again, both types must decide whether to exert high or low diagnosis effort, and both types perform an accurate diagnosis when they choose high effort. Experts differ, however, when they decide to only exert low effort: In this case, the low-ability expert type always misdiagnoses a customer's problem, which is drawn from a continuum of problems, but the high-ability expert type recommends the accurate treatment with some probability. In contrast to the present setup, customers can search for multiple

[14]Liu (2011), Fong et al. (2014) (in an extension), and Heinzel (2019a) study a credence goods market with selfish and conscientious experts. The authors show that the existence of conscientious experts in a market can lead to a more fraudulent behavior of the selfish type.

[15]Heinzel (2019b) studies the impact of expert heterogeneity with respect to cost for treating a minor problem on the customers' search for second opinions.

[16]Chen et al. (2022) analyze a model in which experts sometimes have heterogeneous diagnosis costs. Inderst and Ottaviani (2012a,b,c) and Inderst (2015) consider homogeneously imperfect diagnostic abilities in markets for financial advice. Balafoutas et al. (2020) study the interaction of homogeneously imperfect diagnostic abilities and insurance coverage. Fong et al. (2021) analyze a model in which doctors with homogeneously imperfect diagnostic abilities can refer patients to labs for (further) testing. Schniter et al. (2021) experimentally investigate the interaction of a rating system and both (homogeneous) diagnosis and service uncertainty.

opinions. The authors find that with a sufficient number of high-ability experts, there is the possibility for a second-best equilibrium in which welfare is maximized even without a policy intervention of fixing prices. Moreover, in line with Pesendorfer and Wolinsky (2003), given a small share of high-ability experts, a second-best equilibrium requires fixed prices.

Schneider and Bizer (2017b) experimentally test this model.[17] They find that experimental credence goods markets with expert moral hazard regarding the provision of truthful diagnoses are more efficient than predicted by theory. With regard to better expert qualification (in the sense of a larger share of high-ability experts), the authors find that market efficiency increases with fixed prices but remains unaffected or even declines with price competition.

Finally, Crettez et al. (2020) show that awareness campaigns may reduce overtreatment in a setting in which experts have different diagnostic abilities. Crucially, experts in their setting do not set prices, and respond to moral rather than direct monetary incentives of the different treatments. Moreover, low-ability experts do not get any information from the diagnosis in their setting.

1.3 Model

Building on Dulleck and Kerschbamer (2006), we consider the following credence goods market with a mass one of customers and a monopolistic expert. Each customer is aware that they have a problem, and that they need a major treatment with probability h or a minor treatment with probability $1-h$. Each customer decides whether to visit the expert. When customers decide to do so, they are committed to undergoing the recommended treatment and paying the price charged for that treatment.[18] Customers can verify the treatment performed and can see whether the treatment is sufficient to solve the problem.

[17] In a similar framework with ex-ante homogeneous experts, Momsen (2021) experimentally investigates how transparency influences outcomes in credence good markets.

[18] A possible justification for this assumption is that search costs may simply be too high, and that these costs are not outweighed by the potential savings from searching for a second opinion and avoiding an unnecessary major treatment. In general, what happens if customers are not committed to undergoing the recommended treatment is already an interesting question in itself (see, for example, Fong et al. (2014)). For homogeneous experts, Baumann and Rasch (2022) analyze how diagnostic uncertainty interacts with customers' possibility to search for a second opinion.

Hence, customers can observe undertreatment but not overtreatment. If the problem is solved, a customer receives a gross payoff equal to v. If it is not solved, a customer receives a gross payoff of zero. Like most of the literature, we assume that customers are rational and indifferent customers decide in favor of a visit.

The expert can be one of two types, which is common knowledge.[19] When the expert has high diagnostic ability, which happens with commonly known probability x, he performs an accurate diagnosis with certainty (at no cost), that is, he identifies the necessary treatment without making mistakes.[20] When the expert has low ability, which happens with probability $1 - x$, he performs an accurate diagnosis with commonly known probability $q \in [1/2, 1)$.[21] Hence, a low-ability expert can make two types of errors, which occur both with probability $1 - q$. When the expert makes a false positive error, he diagnoses a major problem, although the customer only has a minor problem. Under a false negative error, the expert diagnoses a minor problem, but the customer has a major problem.

The expert has costs of $\bar{c}$ and $\underline{c}$ for providing the major and minor treatment (with $\underline{c} < \bar{c}$). The major treatment solves any of the two problems, whereas the minor treatment only solves the minor problem. We assume that $v > \bar{c}$ holds, which means that it is always (that is, even ex post) efficient to treat a customer. Furthermore, the expert sets prices $\bar{p}$ and $\underline{p}$ for the major and minor treatment and charges the customer for the recommended (verifiable) treatment. An expert's profit amounts to the price-cost margin per customer treated. When customers do not visit the expert, the expert makes zero profit. We assume that the expert cannot be held liable when providing an insufficient

[19]One can extend our model to n types. Where applicable, the expert with the lowest ability determines thresholds. Our results do not change qualitatively, but the notation would become cumbersome.

[20]Our results would not change qualitatively if the high-ability expert type also made mistakes (with a lower probability than the low-ability expert type). Moreover, our results are largely robust to a (potentially heterogeneous) small positive diagnosis cost (when the performance of a diagnosis is verifiable). It would simply reduce profits as long as both types make non-negative profits. Otherwise, the type with the higher diagnosis cost will not serve any customers.

[21]Note that a probability lower than one half does not make sense because in this case, the expert could provide better services by performing the treatment that was *not* diagnosed.

treatment.[22]

The timing of events, which is illustrated in *Figure 1.1*, is as follows:

1. Nature determines whether the expert has high ability (with probability x) or low ability (with probability $1 - x$).

2. The expert learns his type and chooses a price vector $\mathbf{P} = (\bar{p}, \underline{p})$, which specifies a price for each of the two treatments.

3. Customers observe the prices, form beliefs $\mu(\mathbf{P})$ that an expert setting a price vector $\mathbf{P}$ is a high-ability expert, and decide whether to visit the expert. When customers do not visit the expert, the game ends, and both players receive payoffs of zero.

4. When customers visit the expert, nature determines whether they have a major problem (with probability h) or a minor problem (with probability $1 - h$).

5. When the expert has low ability, nature determines the outcome of the diagnosis, which is accurate with probability q. A low-ability expert type has beliefs $\bar{\mu}$ ($\underline{\mu}$) that a customer indeed faces the major (minor) problem when the diagnosis points to a major (minor) problem. A high-ability expert type always performs an accurate diagnosis.

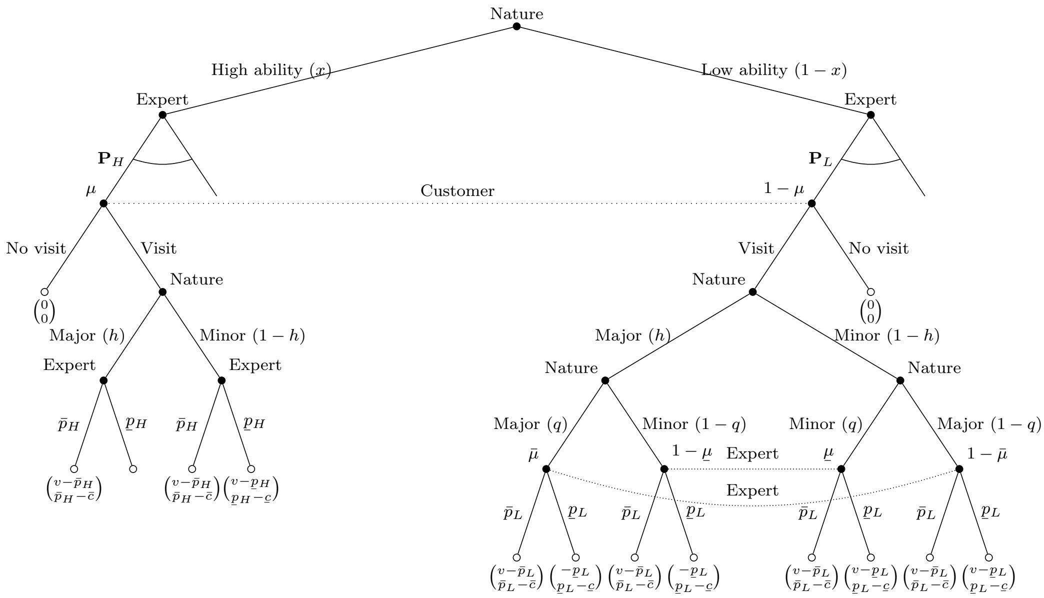
6. The expert recommends and performs a treatment and charges the price for that treatment. Then, payoffs realize.

Whereas a customer only decides whether to visit an expert, an expert's strategy consists of a (potentially type-dependent) price vector and a treatment decision that can depend on the type, the price vector, and the signal.

1.4 Analysis and Results

Now we derive the (non-trivial) equilibrium outcomes in the credence goods market specified above. We distinguish between two cases in which expert types

[22] We discuss liability in Section 1.5.5.



Notes: We refrain from explicitly stating the treatment choice in the game tree because due to verifiability, the expert's price choice implies the respective treatment. Note further that the first (second) entry in the payoff vector represents customer (expert) payoff.

Figure 1.1: Timing of events in the expert market.

are (i) observable and (ii) unobservable. We employ subgame-perfect equilibria and perfect Bayesian equilibria when analyzing games with complete and incomplete information. By "non-trivial", we mean equilibria with interaction, that is, we exclude equilibria in which the customer believes that an indifferent expert would recommend the opposite of what he should recommend from a customer's point of view, and, therefore, no customer visits an expert. We start by analyzing the benchmark case with observable types.

1.4.1 Benchmark: Observable types

To analyze the optimal pricing and treatment decisions by the two expert types, we look at the relative price-cost margins for the two treatments.

1.4.1.1 Price-cost margins

Three scenarios are possible: (i) The profit margin is larger for the major treatment; (ii) the profit margin is larger for the minor treatment; and (iii) the profit margins for the major and the minor treatments are the same. We focus on those equilibria that yield the highest profits in each (sub-)scenario.

Only major treatments.

In scenario (i), the expert – independent of his type (and, hence, observability) – finds it optimal to recommend only the major treatment, which implies that even for a high-ability expert type, overtreatment occurs sometimes. Denote this case by superscript o and note that a monopolistic expert always appropriates all surplus from trade, which means that optimal prices are given by

$$\bar{p}^{\mathrm{o}} = v \tag{1.1}$$

and

$$\underline{p}^{\mathrm{o}} \leq v - \Delta c. \tag{1.2}$$

Here, $\Delta c := \bar{c} - \underline{c}$ denotes the difference in treatment costs. The resulting profit amounts to

$$\pi^{\mathrm{o}} = v - \bar{c}. \tag{1.3}$$

Only minor treatments.

In scenario (ii), the expert – again independent of his type – finds it optimal to exclusively recommend the minor treatment to his customers. This means that even a high-ability expert type always chooses the minor treatment, and, hence, sometimes undertreats his customers. In this case, denoted by superscript u, optimal prices are given by

$$\bar{p}^{\mathrm{u}} \leq (1-h)v + \Delta c \tag{1.4}$$

and

$$\underline{p}^{\mathrm{u}} = (1-h)v. \tag{1.5}$$

The profit in this case amounts to

$$\pi^{\mathrm{u}} = (1-h)v - \underline{c}. \tag{1.6}$$

Equal markups.

Given the observability of types, the pricing decision in scenario (iii), denoted by superscript e, depends on the expert's type because different abilities result in different expected gains from trade for customers.[23] Then, for a high-ability expert type (denoted by subscript H), the combination of the customers' binding participation constraint and equal markups leads to prices of

$$\bar{p}^{\mathrm{e}}_H = v + (1-h)\Delta c$$

and

$$\underline{p}^{\mathrm{e}}_H = v - h\Delta c.$$

The profit for this expert type equals

$$\pi^{\mathrm{e}}_H = v - \underline{c} - h\Delta c. \tag{1.7}$$

Similarly, the prices set by the low-ability expert type, denoted by subscript L, amount to

$$\bar{p}^{\mathrm{e}}_L = (1-h+hq)\,v + (h-2hq+q)\,\Delta c$$

and

$$\underline{p}^{\mathrm{e}}_L = (1-h+hq)\,v - (1-h+2hq-q)\,\Delta c.$$

The profit for this type equals

[23] Scenario (iii) is a special case of the other two scenarios, but for the sake of brevity, we will not repeat the analyses of (i) and (ii) when analyzing (iii), although they also apply.

$$\pi_L^{\text{e}} = (1 - h + hq)\, v - \bar{c} + (h - 2hq + q)\, \Delta c. \tag{1.8}$$

Note that it holds that

$$\frac{\partial \pi_L^{\text{e}}}{\partial q} = hv + (1 - 2h)\Delta c > 0, \tag{1.9}$$

which is due to the fact that $v > \bar{c}$. Not surprisingly, because customers' expected benefit from visiting an expert increases with the probability of receiving the accurate (sufficient) treatment, profits increase with better abilities.

Efficiency.

Before characterizing the two types' optimal pricing behavior, let us briefly comment on efficiency. Efficiency is determined by two factors: (i) whether customers' problems are solved, and (ii) at what cost these problems are solved. Because the expert can fully extract the surplus, the expert is interested in maximizing customers' expected valuation. As a consequence, the expert weighs the additional costs of providing the more expensive major treatment against the increase in probability that the problem is solved, realizing the customer valuation v. As such, the expert opts for the most efficient treatment. Note further that social welfare consists of the sum of (expected) expert and customer surplus, where transfers between the two sides are assumed to be welfare neutral. As a consequence, whenever an expert opts for a certain pricing scheme given observability of the type, this is optimal from a social welfare point of view and efficient. As mentioned, for the low-ability type, profits under equal markups increase with better abilities, which means that the same is true for welfare.

Define $\mathbf{P}^{\text{o}} := (\bar{p}^{\text{o}}, \underline{p}^{\text{o}})$, $\mathbf{P}^{\text{u}} := (\bar{p}^{\text{u}}, \underline{p}^{\text{u}})$, and $\mathbf{P}_i^{\text{e}} := (\bar{p}_i^{\text{e}}, \underline{p}_i^{\text{e}})$ (with $i \in \{H, L\}$). We can now analyze the pricing and treatment decisions of the two types. We start with the high-ability expert type.

1.4.1.2 High-ability expert type

The pricing decision of the high-ability expert type, if the expert can commit to a strategy, has been studied before and can be characterized as follows:

Lemma 1.1 (Dulleck and Kerschbamer, 2006)**.** *An observable high-ability expert type efficiently serves all customers and sets a price vector* $\mathbf{P}_H^{\mathrm{e}}$.

Proof. Follows from a straightforward comparison of expression (1.7) and expressions (1.3) and (1.6), respectively, and the assumption that $v > \bar{c}$. □

We can thus point out that the high-ability expert type benefits from offering equal-markup prices. By doing so, the expert can charge higher markups because the expert credibly commits to treating customers honestly. At the same time, every problem is solved at the lowest cost, that is, the outcome is efficient.

1.4.1.3 Low-ability expert type

In order to specify the optimal prices set by a low-ability expert, we note that

$$\pi^{\mathrm{o}} \lesseqgtr \pi_L^{\mathrm{e}} \Leftrightarrow h \lesseqgtr \frac{q\Delta c}{(1-q)v-(1-2q)\Delta c} =: h_L^{\mathrm{o}}$$

and

$$\pi^{\mathrm{u}} \lesseqgtr \pi_L^{\mathrm{e}} \Leftrightarrow h \gtreqless \frac{(1-q)\Delta c}{qv+(1-2q)\Delta c} =: h_L^{\mathrm{u}}.$$

Given these comparisons and definitions, we can state the following proposition:

Proposition 1.1. *Given that a low-ability expert type makes diagnosis errors, an observable low-ability expert type efficiently serves his customers and sets the following prices:*

$$\begin{cases} \mathbf{P}^{\mathrm{u}} & \text{if } h \in [0, h_L^{\mathrm{u}}]\,, \\ \mathbf{P}_L^{\mathrm{e}} & \text{if } h \in (h_L^{\mathrm{u}}, h_L^{\mathrm{o}}], \\ \mathbf{P}^{\mathrm{o}} & \text{else.} \end{cases}$$

Figure 1.2 illustrates the pricing and treatment decisions by the low-ability expert type. We point out that always choosing the major or the minor treatment can be efficient.[24] For example, when the probability of a major problem is not too low, and the probability of an accurate diagnosis is not too high, it is optimal to always recommend and perform the major treatment. In this case,

[24] This is related to a similar result in Bester and Dahm (2018). There, if the diagnosis cost is too high, it is optimal to implement a treatment without a diagnosis.

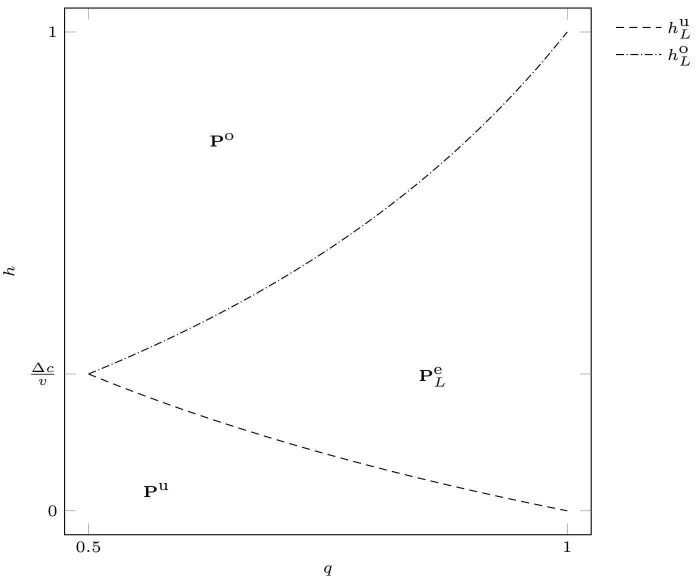


Figure 1.2: Pricing of an observable low-ability expert type.

the likelihood of failing to solve the customer's problem is greater than that of unnecessarily incurring the higher costs.

We now turn to the case with unobservable expert types.

1.4.2 Unobservable types

In this part, we first present general features of the equilibrium outcomes in our set-up. We then derive the equilibria and discuss two refinements.

1.4.2.1 Preliminaries

With regard to equilibrium profits, we can state the following:

Lemma 1.2. *In any equilibrium, both expert types make the same profit.*

Proof. If one expert type made a strictly higher profit in an equilibrium by posting a certain price menu, the other type could easily mimic this offer and make the same strictly higher profit. Because ability does not directly affect profits here, both types make the same profit as long as they charge the same prices. □

Note that this implies that, given a costly opportunity to invest in their diagnostic ability, experts would not have an incentive to do so unless this was observable.

Corollary 1.1. *If expert types are unobservable, there are no private benefits to a better diagnostic ability.*

This means that in settings in which ex ante investments by experts are important, a policymaker should try to make investments or abilities visible (for example, through certification).

There are equilibria in which different expert types post the same price vector as well as separating equilibria. In the price-pooling equilibria, different expert types achieve identical profits because their costs do not differ. For any separating equilibrium, there is a price-pooling equilibrium in which the expert provides the same treatment, and the customer pays the same price along the equilibrium path, such that payoffs are the same. The only difference between these two types of equilibria concerns the price for the treatment that is never chosen. Hence, we have:

Corollary 1.2. *For any separating equilibrium, there is an outcome-equivalent equilibrium without separation in prices.*

Thus, we focus on pure-strategy equilibria with price pooling. Among those, we focus on the equilibria that yield the highest profits.[25]

1.4.2.2 Definition and existence of equilibria with price pooling

Given the comparison of the two price-cost margins, there are three classes of equilibria: price pooling with (i) only major-treatment recommendations, with (ii) only minor-treatment recommendations, and with (iii) equal markups. The prices and profits for the first two scenarios are the same as in Subsection 1.4.1 (see expressions (1.1)–(1.6)).

To simplify the specification of the equilibria, we define the following values of the probability for a high-ability expert type:

[25] Additional equilibria exist in which both expert types provide the same treatments, but post uniformly lower prices. Customers have off-equilibrium beliefs that any expert posting higher prices is a low-ability expert with sufficiently high probability. Hence, a customer would not visit the expert that posts higher prices.

$$\bar{x}^{\text{o}} := 1 - \frac{(1-h)\Delta c}{(1-q)(hv + (1-2h)\Delta c)} \tag{1.10}$$

and

$$\bar{x}^{\text{u}} := \frac{-hqv + (1-q-h+2hq)\Delta c}{(1-q)(hv - (1-2h)\Delta c)}. \tag{1.11}$$

We start by defining the first class of equilibria:

Definition 1.1 (Major-treatment equilibria). *Major-treatment equilibria with price pooling are characterized as follows:*

- *Both expert types choose the price vector* $\mathbf{P}^{\text{o}}$.
- *Both expert types always recommend and perform the major treatment.*
- *The low-ability expert type has beliefs* $\bar{\mu} = \underline{\mu} = q$.
- *On the equilibrium path, customers' beliefs equal* $\mu(\mathbf{P}^{\text{o}}) = x$, *and customers always visit the expert.*
- *Off the equilibrium path, customers have beliefs:*
  - $\mu \in [0, \bar{x}^{\text{o}}]$ *if* $\underline{p} - \underline{c} = \bar{p} - \bar{c}$ *and* $\bar{p} > \bar{p}^{\text{o}}$,
  - $\mu \in [0, 1]$ *otherwise.*

Next we define the second class of equilibria:

Definition 1.2 (Minor-treatment equilibria). *Minor-treatment equilibria with price pooling are characterized as follows:*

- *Both expert types choose the price vector* $\mathbf{P}^{\text{u}}$.
- *Both expert types always recommend and perform the minor treatment.*
- *The low-ability expert type has beliefs* $\bar{\mu} = \underline{\mu} = q$.
- *On the equilibrium path, customers' beliefs equal* $\mu(\mathbf{P}^{\text{u}}) = x$, *and customers always visit the expert.*
- *Off the equilibrium path, customers have beliefs:*

- $\mu \in [0, \bar{x}^{\mathrm{u}}]$ *if* $\underline{p} - \underline{c} = \bar{p} - \bar{c}$ *and* $\underline{p} > \underline{p}^{\mathrm{u}}$,
- $\mu \in [0, 1]$ *otherwise.*

Let us briefly comment on the structure of these equilibria. In the major-recommendation equilibria with price pooling, both expert types choose their price vectors, such that they always optimally recommend the major treatment, independent of the customer's problem. Analogously, in the minor-recommendation equilibria with price pooling, both types choose their price vectors, such that it is always optimal to recommend the minor treatment. A low-ability expert type believes to have received the correct diagnosis with a probability that is equal to the accuracy of his diagnosis. Given that both expert types set identical prices, that is, no information concerning expert types is conveyed, customers believe to face a certain expert type with the ex ante probability that this type is chosen by nature whenever the major-treatment (or minor-treatment) price vector is observed.

With regard to customers' off-equilibrium beliefs, we distinguish two cases: First, when customers observe prices that are lower than those actually charged along the equilibrium path, there is no restriction with regard to the beliefs. This is due to the fact that both expert types do not have any incentive to set lower prices in the first place because this would only result in lower profits. Second, customers would be willing to pay a higher price to the high-ability type when they receive an appropriate treatment with a higher probability in return. This means that customers must have a sufficiently weak belief that an expert setting higher prices than those to be charged along the equilibrium path indeed has high ability. Given sufficiently weak beliefs, the high-ability type cannot make a higher profit from deviating to equal-markup prices because customers' expected surplus does not increase compared to a situation in which they always receive the major or minor treatment. Comparing the profits for these cases gives expressions (1.10) and (1.11).

We now turn to equal-markup equilibria. In these equilibria, each type of expert may choose to either condition the treatment on the diagnosis, or to always perform one of the two treatments. Thus, special cases of the major-treatment and minor-treatment equilibria can be equal-markup equilibria. To get the intuition, consider the scenario in which both types of expert follow their diagnosis (subscript dd). In this case, prices for equal markups are given by

$$\bar{p}^{\mathrm{e}}_{dd} = (1-h+hq-hqx+hx)\,v + (h-2hq+2hqx-2hx+q-qx+x)\,\Delta c$$

and

$$\underline{p}^{\mathrm{e}}_{dd} = (1-h+hq-hqx+hx)\,v - (1-h+2hq-2hqx+2hx-q+qx-x)\,\Delta c.$$

The profit for each type equals

$$\begin{aligned}\pi^{\mathrm{e}}_{dd} = {} & (1-h+hq-hqx+hx)\,v \\ & - \underline{c} - (1-h+2hq-2hqx+2hx-q+qx-x)\,\Delta c. \end{aligned} \tag{1.12}$$

A comparison of profits in the different scenarios reveals that

$$\pi^{\mathrm{o}} \lesseqqgtr \pi^{\mathrm{e}}_{dd} \Leftrightarrow h \lesseqqgtr \frac{(q-qx+x)\Delta c}{(1-q+qx-x)v-(1-2q+2qx-2x)\Delta c} =: h^{\mathrm{o}}_{dd}$$

and

$$\pi^{\mathrm{u}} \lesseqqgtr \pi^{\mathrm{e}}_{dd} \Leftrightarrow h \gtreqqless \frac{(1-q+qx-x)\Delta c}{(q-qx+x)v+(1-2q+2qx-2x)\Delta c} =: h^{\mathrm{u}}_{dd}.$$

It holds that

$$\frac{\partial h^{\mathrm{o}}_{dd}}{\partial q}, \frac{\partial h^{\mathrm{o}}_{dd}}{\partial x} > 0, \tag{1.13}$$

and

$$\frac{\partial h^{\mathrm{u}}_{dd}}{\partial q}, \frac{\partial h^{\mathrm{u}}_{dd}}{\partial x} < 0. \tag{1.14}$$

Thus, both probabilities have a very similar effect on the two thresholds. This is due to the fact that the scenarios with only major-treatment/minor-treatment recommendations are affected by neither of the two probabilities because the two expert types do not differ in their recommendations. Under equal-markup pricing, efficiency is affected by diagnostic quality. Because the expected gain from interaction is always zero for the customer, however, it does not make any difference for the customer from an ex ante point of view whether the customer faces a high-ability expert with probability x (and consequently receives the accurate treatment with certainty), or whether the customer faces a low-ability expert type and receives the accurate treatment with probability q.

More generally, let $\mathbf{P}^{\mathrm{e}}_{jk} := (\bar{p}^{\mathrm{e}}_{jk}, \underline{p}^{\mathrm{e}}_{jk})$, where $j \in \{d, o, u\}$ specifies whether the high-ability expert type always follows his diagnosis or recommends the major or the minor treatment, where $k \in \{d, o, u\}$ characterizes the respective recommendation decision for the low-ability expert type, and where

$$\begin{aligned} \bar{p}^{\mathrm{e}}_{jk} = \underline{p}^{\mathrm{e}}_{jk} + \Delta c = x\left[\mathbb{1}_{j=o}v + \mathbb{1}_{j=u}((1-h)v + \Delta c) + \mathbb{1}_{j=d}(v + (1-h)\Delta c)\right] \\ + (1-x)\left[\mathbb{1}_{k=o}v + \mathbb{1}_{k=u}((1-h)v + \Delta c)\right. \\ \left.+\mathbb{1}_{k=d}(v(1-h(1-q)) + ((1-h)q + h(1-q))\Delta c)\right], \end{aligned} \tag{1.15}$$

where $\mathbb{1}$ is the indicator function. The profits are $\pi^{\mathrm{e}}_{jk} = \bar{p}^{\mathrm{e}}_{jk} - \bar{c}$.[26]

Given the above prices, we can define equal-markup equilibria:

Definition 1.3 (Equal-markup equilibria). *Equal-markup equilibria with price pooling are characterized as follows:*

- *Both expert types choose the price vector* $\mathbf{P}^{\mathrm{e}}_{jk}$.
- $j \in \{d, o, u\}$ *specifies whether the high-ability expert type always follows his diagnosis or recommends and performs the major or the minor treatment, and* $k \in \{d, o, u\}$ *does so for the low-ability expert type.*
- *The low-ability expert type has beliefs* $\bar{\mu} = \underline{\mu} = q$.
- *On the equilibrium path, customers' beliefs equal* $\mu(\mathbf{P}^{\mathrm{e}}_{jk}) = x$, *and customers always visit the expert.*
- *Off the equilibrium path, customers have beliefs:*

[26] Note that our results do not depend on the assumption that the low-ability expert type's diagnosis is correct with a probability q that does not depend on the underlying problem. If we allow for that and let $\bar{q}$ and $\underline{q}$ be the according probabilities, we have $\bar{p}^{\mathrm{e}}_{jk} = \underline{p}^{\mathrm{e}}_{jk} + \Delta c = x\left[\mathbb{1}_{j=o}v + \mathbb{1}_{j=u}((1-h)v + \Delta c) + \mathbb{1}_{j=d}(v + (1-h)\Delta c)\right] + (1-x)\left[\mathbb{1}_{k=o}v + \mathbb{1}_{k=u}((1-h)v + \Delta c) + \mathbb{1}_{k=d}(v(1-h(1-\bar{q})) + ((1-h)\underline{q} + h(1-\bar{q}))\Delta c)\right]$.

– $\mu \in [0, x]$ *if* $\underline{p} - \underline{c} = \bar{p} - \bar{c}$ *and* $\underline{p} > \underline{p}^{e}_{jk}$,

– $\mu \in [0, 1]$ *otherwise.*

Given identical markups, any treatment recommendation is equally profitable for an expert – independent of his type. As in the previously defined equilibria, a low-ability expert type believes to have received the correct diagnosis with a probability that equals the accuracy of his diagnosis. Again, no information concerning expert types is revealed through the price setting, which means that customers believe that they face a certain expert type with this type's (ex ante) probability to be selected by nature whenever the equal-markup price vector is posted by the expert.

With regard to customers' off-equilibrium beliefs, prices that are higher than those to be charged along the equilibrium path must be accompanied by a sufficiently weak belief that the expert has high ability.[27] Again, there is no restriction with respect to the beliefs when customers observe prices that are lower than those charged along the equilibrium path.

Using these definitions, we can thus state equilibrium existence as follows:

Proposition 1.2. *The existence of equilibria with price pooling is characterized as follows:*

(i) For $h \in [0, h^{u}_{L}]$*, there exist minor-treatment equilibria;*

(ii) for $h \in [h^{o}_{L}, 1]$*, there exist major-treatment equilibria;*

(iii) for $h \in [0, 1]$*, there exist equal-markup equilibria.*

There exist several different types of equal-markup equilibria, some of which appear to be implausible. The usual equilibrium selection criteria do not have bite here because the expert's type does not affect his profits directly, but only indirectly via equilibrium prices that depend on customers' beliefs. We continue with a further analysis of equal-markup equilibria by imposing two assumptions on equilibrium selection that are relevant in different contexts.

[27] We constrain off-equilibrium beliefs in that case by assuming that customers believe that indifferent experts will not hurt them on purpose. More precisely, customers believe that indifferent experts either follow their diagnosis or perform the ex ante optimal treatment.

1.4.2.3 Refinements: Recommendation behavior

Having a closer look at the different recommendation options expert types have when they are indifferent due to equal-markup pricing, we first analyze the case in which experts follow their diagnosis. Then, we analyze the case in which experts maximize their customers' expected utility.

Indifferent expert type follows his diagnosis.

A scenario in which both expert types follow their diagnosis when they are indifferent may be relevant if experts are overconfident or completely unaware of their type, or if they might want or need to justify their decision (for example, when presenting diagnosis outcomes in court).[28]

We describe the set of equilibria in this case in the following proposition:

Proposition 1.3. *The existence of equilibria with price pooling when indifferent experts follow their diagnosis is characterized as follows:*

(i) For $h \in [0, h_L^{\text{u}}]$, there exist minor-treatment equilibria;

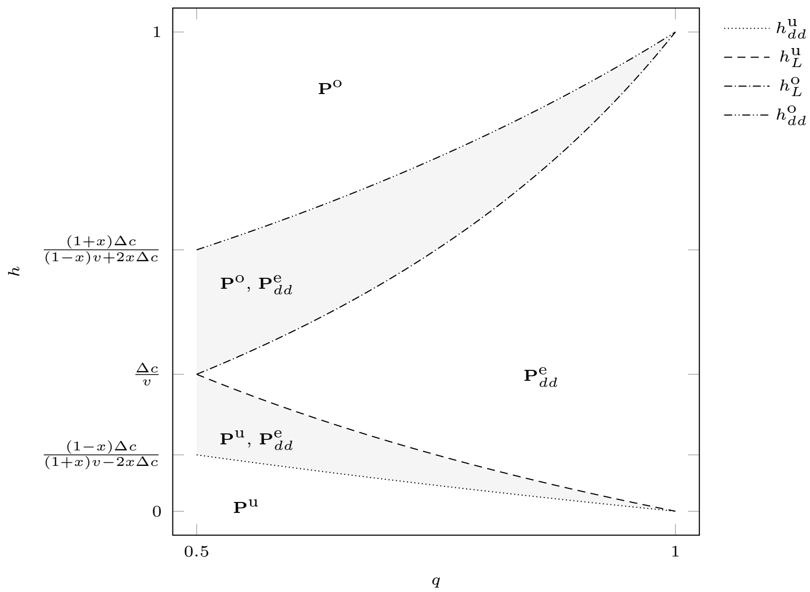
(ii) for $h \in [h_{dd}^{\text{u}}, h_{dd}^{\text{o}}]$, there exist equal-markup equilibria in which each expert type follows his diagnosis; and

(iii) for $h \in [h_L^{\text{o}}, 1]$, there exist major-treatment equilibria.

Because $h_{dd}^{\text{u}} < h_L^{\text{u}}$ and $h_{dd}^{\text{o}} > h_L^{\text{o}}$, there are multiple equilibria for some values of h but not for others.

Figure 1.3 illustrates the existence of the different equilibria. In all figures, the size of the gray areas (that is, combinations of q and h) is determined by customers' off-equilibrium beliefs when observing higher (equal-markup) prices than those to be charged in the respective equilibria. The figures show the largest possible size of gray areas when higher-than-equilibrium equal-markup prices lead customers to believe that they face a low-ability expert type with certainty. When the customers' off-equilibrium belief about the probability of a high-ability expert type increases, the parameter space where major- and minor-treatment equilibria exist shrinks.

[28] Note that following their diagnosis may come with another benefit that we abstract away from in our analysis: A low-ability expert might learn and improve his ability over time.



Note: The size of the gray area (that is, combinations of q and h) is determined by customers' off-equilibrium beliefs when observing higher prices than those to be charged in the respective equilibria. The figure shows the largest possible area when higher-than-equilibrium prices lead customers to believe that they face a low-ability expert type with certainty. When the customers' off-equilibrium belief about the probability of a high-ability expert type increases, the parameter space where major- and minor-treatment equilibria exist shrinks.

Figure 1.3: Equilibrium pricing when an indifferent expert type follows his diagnosis.

Indifferent expert type maximizes customers' expected utility.

If both expert types maximize their customers' expected utility when they are indifferent, after setting the prices, experts behave as if their type were observable, that is, the high-ability expert type will always follow his diagnosis, whereas the low-ability expert type will only do so if his diagnosis is correct with a sufficiently high probability. Otherwise, the low-ability expert type will always perform the major or the minor treatment, depending on which will lead to a higher expected utility for customers. The set of equilibria in this case is described in the following proposition:

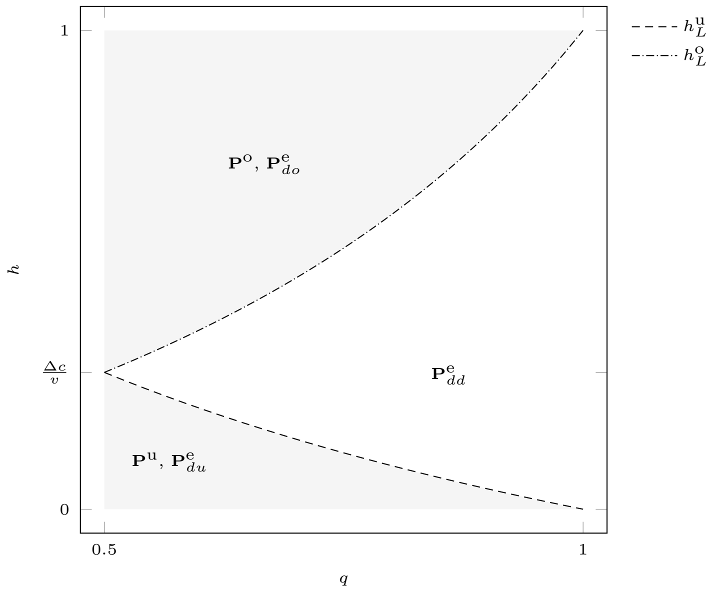
Proposition 1.4. *The existence of equilibria with price pooling when indifferent experts maximize customers' expected utility is characterized as follows:*

(i) *For* $h \in [0, h_L^{\text{u}}]$*, there exist minor-treatment equilibria;*

(ii) *for* $h \in [h_L^{\circ}, 1]$*, there exist major-treatment equilibria;*

(iii) *for* $h \in [0, 1]$*, there exist equal-markup equilibria. In those, the high-ability expert type always follows his diagnosis. The low-ability expert type follows his diagnosis if* $h \in (h_L^{\text{u}}, h_L^{\circ}]$*, always performs the minor treatment if* $h \in [0, h_L^{\text{u}}]$*, and always performs the major treatment if* $h \in (h_L^{\circ}, 1]$*.*

Figure 1.4 illustrates the existence of the different equilibria.



Note: The size of the gray area (that is, combinations of q and h) is determined by customers' off-equilibrium beliefs when observing higher prices than those to be charged in the respective equilibria. The figure shows the largest possible area when higher-than-equilibrium prices lead customers to believe that they face a low-ability expert type with certainty. When the customers' off-equilibrium belief about the probability of a high-ability expert type increases, the parameter space where major- and minor-treatment equilibria exist shrinks.

Figure 1.4: Equilibrium pricing when an indifferent expert type maximizes his customers' expected utility.

1.5 Discussion

In this section, we discuss the welfare properties of the equilibria considered and analyze how better diagnostic outcomes impact the efficiency of these equilibria. Moreover, we analyze how robust our results are to diagnosis effort, competition, and fines and warranties.

1.5.1 Efficiency and welfare

We compare efficiency and social welfare in the equilibria derived in the previous section. A first observation is that the minor-treatment and the major-treatment equilibria are never efficient because the high-ability type could always provide the correct diagnosis, which would result in cost savings. By contrast, the equal-markup equilibria in which the low-ability expert type maximizes his customers' utility are the efficient equilibria. For $h \in (h_L^{\mathrm{u}}, h_L^{\mathrm{o}}]$, these efficient equilibria coincide with the equal-markup equilibria in which both expert types follow their diagnosis. For all other parameter values, the equal-markup equilibria in which both expert types follow their diagnosis are inefficient. We can hence state the following result:

Proposition 1.5. *Consider the equal-markup equilibria in which the high-ability expert type always follows his diagnosis, and the low-ability expert type follows his diagnosis if $h \in (h_L^{\mathrm{u}}, h_L^{\mathrm{o}}]$, performs the minor treatment if $h \in [0, h_L^{\mathrm{u}}]$, and performs the major treatment if $h \in (h_L^{\mathrm{o}}, 1]$. These equilibria are efficient. The maximum prices and the resulting profits are weakly higher than those in any other equal-markup equilibrium with price pooling.*

We can use this insight to analyze the effects of improvements in diagnostic quality.

1.5.2 Better diagnostic performance

From a policy perspective, it is an important question whether better diagnostic performance improves the market outcome (that is, efficiency and social welfare) – especially when such an endeavor involves substantial costs. An improvement can come in two forms: First, the low-ability expert type may become better at supplying an accurate diagnosis (that is, q increases). Second, the probability that an expert is a high type increases (that is, x increases). We discuss each improvement separately and start with better diagnostic precision.

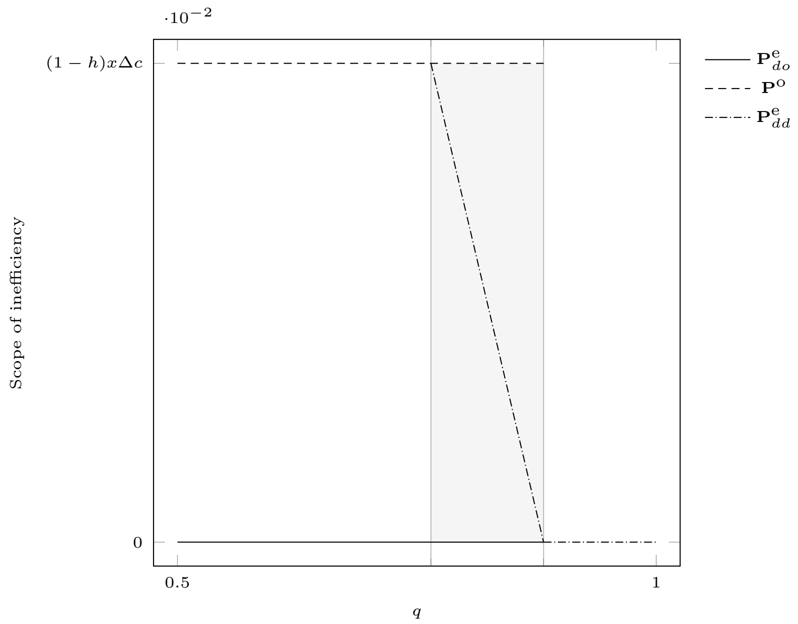
1.5.2.1 Increase in diagnostic precision

The effect of an increase in the diagnostic precision crucially depends on the ex ante probability of customers with a major problem and the equilibrium that is played. We first outline the impact of an increase in diagnostic precision on social welfare under the efficient equilibria. Then, we compare how social welfare in the other equilibria is affected by an increase in diagnostic precision.

For the efficient equilibria and a high ex ante probability of customers having a major problem ($h \in (h_L^{\text{o}}, 1]$), the low-ability expert always provides the major treatment. Hence, a marginal increase in the diagnostic precision does not change the surplus. This also holds for a low likelihood that customers suffer from a major problem ($h \in [0, h_L^{\text{u}}]$), where the low-ability expert always chooses the minor treatment independent of his diagnostic signal. By contrast, whenever customers have the major problem with some intermediate probability ($h \in (h_L^{\text{u}}, h_L^{\text{o}}]$), both expert types follow their diagnostic signal. Then, a more precise diagnosis leads to a higher surplus because the low-ability expert provides the appropriate treatment for customers more often.

Next, we investigate the impact of a higher precision of diagnostic ability in the other equilibria on efficiency relative to the above benchmark. We differentiate three cases based on the ex ante probability that a customer suffers from a major problem h: high ($h > (1+x)\Delta c/((1-x)v + 2x\Delta c)$), medium ($h \in (\Delta c/v, (1+x)\Delta c/((1-x)v + 2x\Delta c))$), and low probability ($h < (1-x)\Delta c/((1+x)v - 2x\Delta c)$).

For the case of a high probability for the major problem, (inefficient) major-treatment equilibria exist besides the efficient equal-markup equilibria for low values of q. *Figure 1.5* illustrates this case. For low values of q, it is efficient that a low-ability expert always provides the major treatment. Hence, an increase in diagnostic precision neither changes the behavior of experts in a major-treatment equilibrium nor in the efficient equal-markup equilibrium. The inefficiency of the major-treatment equilibrium does not change. For medium values of q, equal-markup equilibria exist in which both expert types follow their

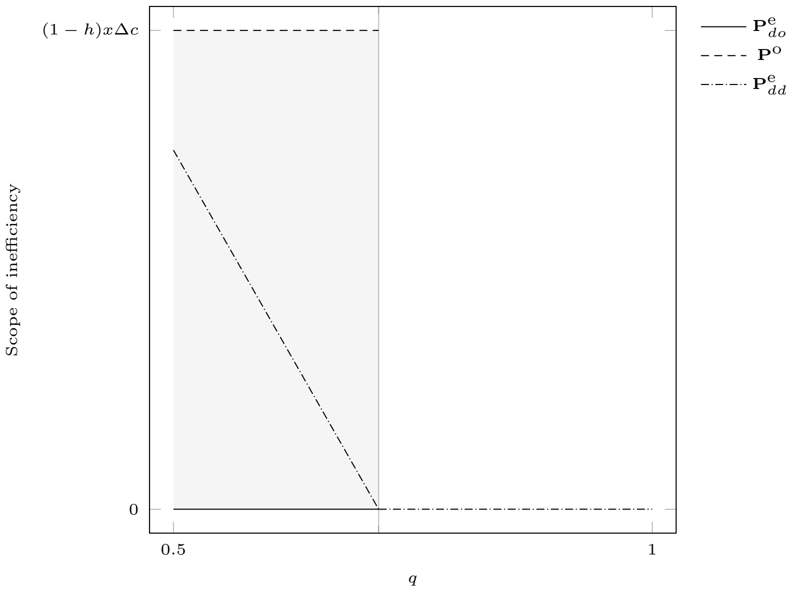


Note: The size of the gray area (that is, combinations of q and h) is determined by customers' off-equilibrium beliefs when observing higher prices than those to be charged in the respective equilibria. The figure shows the largest possible area when higher-than-equilibrium prices lead customers to believe that they face a low-ability expert type with certainty.

Figure 1.5: Market (in)efficiency (compared to the most efficient equilibrium) when a major problem occurs with sufficiently high probability ($h > (1+x)\Delta c/((1-x)v+2x\Delta c)$), and when off-equilibrium beliefs equal zero.

diagnosis. The efficiency of these equilibria increase as the low-ability type's diagnosis becomes more accurate. If customers and the expert coordinate on the major-treatment equilibrium, the increase in diagnostic precision again does not change efficiency. For high values of q, only the two equal-markup equilibria exist and coincide. Hence, an increase in diagnostic precision does not change efficiency.

In the case with a medium probability for the major problem, the major-treatment equilibria and the equal-markup equilibria in which experts follow their diagnosis when they are indifferent exist also for low values of q. *Figure 1.6* displays this case. Starting from a low value of q, an increase in the diagnostic precision leads to a lower inefficiency in the equal-markup equilibria in which experts follow their diagnosis. This does not hold for the major-treatment equilibria. There, the inefficiency persists. When q is sufficiently high, both equal-markup equilibria coincide.



Note: The size of the gray area (that is, combinations of q and h) is determined by customers' off-equilibrium beliefs when observing higher prices than those to be charged in the respective equilibria. The figure shows the largest possible area when higher-than-equilibrium prices lead customers to believe that they face a low-ability expert type with certainty.

Figure 1.6: Market (in)efficiency (compared to the most efficient equilibrium) when a major problem occurs with medium probability ($h \in (\Delta c/v, (1+x)\Delta c/((1-x)v + 2x\Delta c))$), and when off-equilibrium beliefs equal zero.

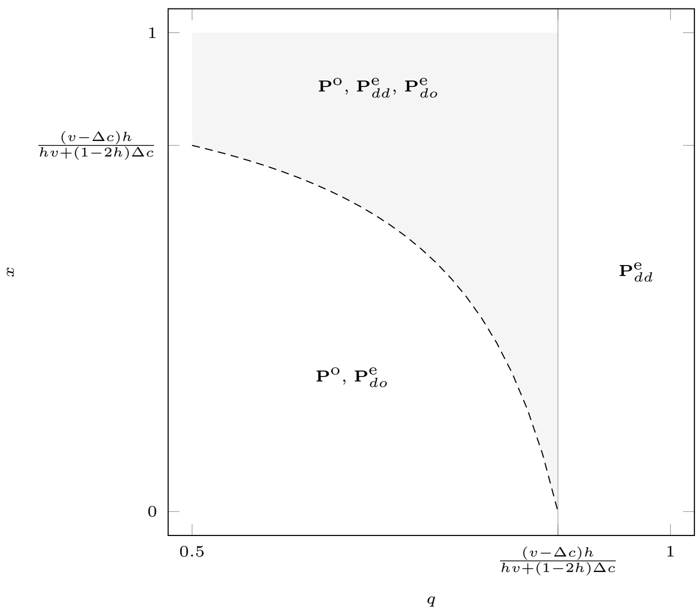
The case of a low probability for the major problem is analogous to the case of a high probability. We can thus summarize our findings in the following straightforward proposition:

Proposition 1.6. *When both types do not choose an equal-markup price vector for $h \in (h^{u}_{dd}, h^{u}_{L})$ or $h \in (h^{o}_{L}, h^{o}_{dd})$, better diagnostic abilities of the low-ability expert type have no effect on efficiency. If $q > (\max\{hv, \Delta c\} - h\Delta c)/(hv + (1-2h)\Delta c)$, however, an increase in q increases efficiency.*

Thus, better diagnostic abilities do not necessarily lead to higher efficiency. Naturally, if improving diagnostic abilities comes at any cost, this may decrease welfare. If the diagnostic ability of the low-ability type becomes large enough, however, such that there does not exist a major-treatment or a minor-treatment equilibrium anymore, an increase in that ability is efficiency enhancing. Consequently, a sufficiently strong increase in the diagnostic ability of the low-ability type can robustly increase welfare.

1.5.2.2 Increase in probability of high-ability expert

The second dimension that may be important for a policymaker is the share of high-ability experts in the market. This section analyzes how such a higher share affects efficiency in the market.



Note: The size of the gray area (that is, combinations of q and h) is determined by customers' off-equilibrium beliefs when observing higher prices than those to be charged in the respective equilibria. The figure shows the largest possible area when higher-than-equilibrium prices lead customers to believe that they face a low-ability expert type with certainty.

Figure 1.7: Equilibrium pricing for combinations of q and x (for $h > \Delta c/v$).

Figure 1.7 illustrates the existence of the different equilibria depending on the diagnostic precision and the probability for a high-ability expert type. A first observation is that for relatively precise diagnoses ($q > (\max\{hv, \Delta c\} - h\Delta c)/(hv + (1-2h)\Delta c)$), only equal-markup equilibria exist. The two equal-markup equilibria coincide. For a lower diagnostic precision ($q \leq (\max\{hv, \Delta c\} - h\Delta c)/(hv + (1-2h)\Delta c)$), multiple equilibria that actually lead to different behaviors exist: For lower values of q and high values of x, the major-treatment equilibria and the two types of equal-markup equilibria exist. For lower values of q and x, only the major-treatment equilibria and the efficient equal-markup equilibria exist.

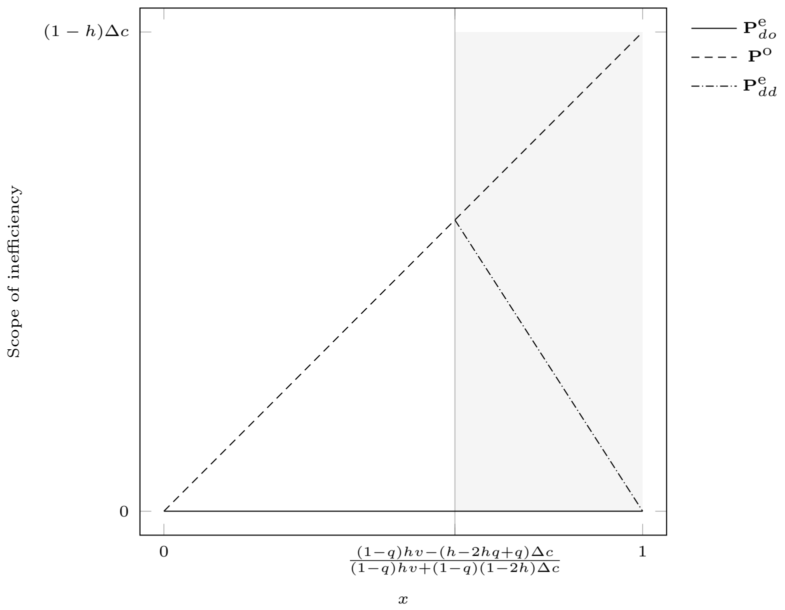
With regard to the impact of an increase in the probability for a high-ability expert, efficiency increases for high values of q ($q > (\max\{hv, \Delta c\} - h\Delta c)/(hv + (1-2h)\Delta c)$), where only equal-markup equilibria exist. For lower values of q ($q \leq (\max\{hv, \Delta c\} - h\Delta c)/(hv + (1-2h)\Delta c)$) and low values of x, an increase in the probability for a high-ability expert type leads to an increase in the surplus under the efficient equilibrium. In the major-treatment equilibria, high-ability experts stick to providing a major treatment, although they could provide the appropriate treatment, which does not affect social welfare. For higher values of x, the equilibria in which experts follow their diagnosis also exist.

An increase in x leads to a lower inefficiency as the probability for an incorrect diagnosis by low-ability experts decreases. *Figure 1.8* illustrates the case for lower values of q.

Note that increasing neither x nor q actually decreases efficiency if there is no direct cost of doing so. If increasing either is not free, a policymaker should not make use of this option if players coordinate on the major- or the minor-treatment equilibria, unless in combination with other policies that have the potential to get rid of those equilibria, such as price regulation or increasing transparency. A further important exception is the following: As *Figure 1.7* illustrates, if the policymaker increases q not only marginally but by sufficiently much, those equilibria do not exist anymore. Increasing x to a value smaller than one does not have such an effect.

Proposition 1.7. *When both types do not choose an equal-markup price vector for $h \in (h^{u}_{dd}, h^{u}_{L})$ or $h \in (h^{o}_{L}, h^{o}_{dd})$, a higher probability of the high-ability expert type does not decrease inefficiencies.*

Whereas a sufficiently large increase of the low-ability type's diagnostic abil-



Note: The size of the gray area (that is, combinations of q and h) is determined by customers' off-equilibrium beliefs when observing higher prices than those to be charged in the respective equilibria. The figure shows the largest possible area when higher-than-equilibrium prices lead customers to believe that they face a low-ability expert type with certainty.

Figure 1.8: Market (in)efficiency (compared to the most efficient equilibrium) when major problem occurs with sufficiently high probability ($h > \Delta c/v$), when diagnostic quality of the low-ability expert type is sufficiently low ($q < (v - \Delta c)h/(hv + (1 - 2h)\Delta c)$), and when off-equilibrium beliefs equal zero.

ity guarantees an increase in welfare, an increase of the probability of the high-ability expert type does not (unless the probability becomes one).

1.5.3 Effort

In our basic model, we have assumed that diagnostic ability is exogenous. Our results, however, extend to several important situations in which the expert can exert effort to influence the precision of a diagnosis. First, if effort is not observable or too costly, the expert does not have an incentive to exert any effort. Our exogenous diagnostic ability could be interpreted as the exogenous baseline diagnostic ability (for exerting no effort) in this case.[29] Second, if effort is observable, but both types face the same effort costs, they choose the same effort because they make the same profit.[30] Moreover, this is also the case if the costs are not the same but similar enough, such that the low-ability type wants to imitate the high-ability type. In either case, our exogenously given diagnostic abilities could be interpreted as endogenous total diagnostic abilities, no matter whether the heterogeneity stems from different baseline diagnostic abilities, different translations of effort into diagnosis improvements, or a combination of the two. This reasoning also applies, of course, if the different expert types choose different effort levels in equilibrium (for example, because they do not have the same effort levels to choose from), but those different levels cannot be told apart.

1.5.4 Competition

So far, we have assumed that the expert is a monopolist. This section demonstrates that our results are robust to competition. There is a shift of surplus from experts to customers, but the equilibrium treatment strategies continue to exist, and, hence, efficiency remains unchanged. In the following, we consider a situation in which at least two experts compete à la Bertrand.

When the experts' types are observable, we have to consider three different cases. First, if there are at least two experts with a high diagnostic ability, at least two high-ability experts charge prices as in Section 1.4.1, the only difference being that the prices of both treatments are reduced by their expected profit as given in Section 1.4.1. Customers only visit those experts, and those experts follow their diagnosis. Other experts charge prices that are not attractive for customers. Thus, all experts make zero profits, and no one has an incentive to deviate.

Second, if all experts have a low ability, at least two of them charge prices as in Section 1.4.1, with the only difference being that the prices of both treatments are reduced by their expected profit as given in Section 1.4.1. Customers only

[29]Recall that our results do not depend on the high-ability type having perfect ability.

[30]Our results for unobservable types apply as long as experts do not end up with the same diagnostic ability. If they end up with the same diagnostic ability, we are essentially back to a situation in which types are observable, and our results of Section 1.4.1 apply.

visit those experts, and those experts employ the treatment strategy of Section 1.4.1. Other experts charge prices that are not attractive for customers. Again, all experts make zero profits, and no one has an incentive to deviate.

Third, if there is exactly one expert with a high ability, at least one low-ability expert charges prices as in Section 1.4.1, the only difference being that the prices of both treatments are reduced by the low-ability type's expected profit given in Section 1.4.1. The high-ability expert reduces his prices from Section 1.4.1 by the same amount, such that customers are indifferent between visiting him and the low-ability expert. In equilibrium, however, all customers visit the high-ability expert who follows his diagnosis. All other experts charge prices that are not attractive for customers. Thus, all low-ability experts make zero profits, and no one has an incentive to deviate. The high-ability expert makes positive profits, but does not have an incentive to deviate either.

We can thus summarize experts' treatment decisions for the case with observable types as follows:

Proposition 1.8. *Assume expert types are observable. Given any parameter values, if an expert's treatment strategy is part of an equilibrium in the monopoly case, it is also part of an equilibrium in the competition case.*

When the experts' types are not observable, low-ability experts can – as in the monopoly case – imitate a high-ability expert at no cost because they have the same profit function.[31] Thus, all equilibria derived in Section 1.4.2 have a treatment-equivalent equilibrium, the only difference being that the prices of both treatments are reduced by experts' expected profit in the corresponding equilibrium as given in Section 1.4.1. At least two experts charge those prices, customers only visit those experts, and other experts charge unattractive prices. Experts make zero profits, and no one has an incentive to deviate. If q is large and h is intermediate, however, there are additional equal-markup equilibria in which experts make positive profits as long as they charge only moderate prices: If there is no profitable major-treatment or minor-treatment vector that would also appeal to customers, customers may also hold the belief that a deviating expert posting an equal-markup price vector provides a diagnosis-independent treatment, which is not attractive to customers. If prices were too high, an

[31] Hence, it also does not matter whether experts can observe each others' types.

expert could deviate by posting a major-treatment and minor-treatment price vector. This means that the threat of major-treatment and minor-treatment price vectors can provide commitment against high prices.

We can summarize our analysis of competition with unobservable types analogously to Proposition 1.2:[32]

Proposition 1.9. *Assume expert types are not observable. In the case of Bertrand competition with at least two experts, the existence of equilibria with price pooling is characterized as follows:*

(i) for $h \in [0, h_L^{u}]$, there exist equilibria with minor-treatment price vectors;

(ii) for $h \in [h_L^{o}, 1]$, there exist equilibria with major-treatment price vectors;

(iii) for $h \in [0, 1]$, there exist equilibria with equal-markup price vectors.

Thus, because the treatments under competition are the same as with a monopolistic expert, the results with regard to efficiency remain unchanged.

1.5.5 Fines and warranties

In this section, we assume that the expert is liable and has to pay a fine $f > 0$ whenever the treatment is insufficient. A compensation that the expert has to pay to the customer if the treatment is insufficient (warranty) would work in the same way.[33]

Introducing a fine implies that the major-treatment equilibria no longer exist: Because the high-ability type of expert knows better when he can recommend a minor treatment without risking a fine, there exists a price vector, such that the high-ability expert type has a strict incentive to recommend the appropriate treatment, and the low-ability expert type has a strict incentive to always recommend the major treatment to avoid the potential fine (such a price vector would have a slightly smaller profit margin for the major treatment when not taking into account the fine). Because this is the efficient thing to do for a

[32] The results of Propositions 1.3 and 1.4 extend analogously.

[33] Note that fines and compensations are similar to what the literature calls liability. In contrast to liability, however, the expert may (and, depending on parameters, sometimes will) provide an insufficient treatment. For efficient liability design in credence goods markets, see Chen et al. (2022).

low-ability expert type in that parameter region, customers' willingness to pay would increase, resulting in a higher profit margin for both treatments, and, hence, giving the high-ability expert type the opportunity to profitably deviate.

Moreover, introducing a fine implies that the minor-treatment equilibria no longer exist. Because the high-ability type of expert knows better when he has to recommend a major treatment and should not risk the fine, there exists a price vector, such that the high-ability expert type has a strict incentive to recommend the appropriate treatment, and the low-ability expert type has a strict incentive to always recommend the minor treatment (if the fine is not large), while risking the fine (such a price vector would have a slightly smaller profit margin for the major treatment when not taking into account the fine, even slightly smaller than in the deviation price vector in the above paragraph). Because this is the efficient thing to do for a low-ability expert in that parameter region, customers' willingness to pay would increase, resulting in a higher profit margin for both treatments, and, hence, giving the high-ability expert type the opportunity to profitably deviate.

Note also that for all of the efficient equal-markup equilibria that we derived for the case without fines, there exist equilibria in which the expert employs the same treatment strategy, and customers always visit for the case with fines. By contrast, the inefficient equal-markup equilibria are not robust because there is always a profitable deviation price vector that unambiguously determines either expert type's treatment strategy. Thus, (even small) fines and warranties are adequate policy tools for implementing efficient market outcomes.

1.6 Conclusion

We present a credence goods model with expert types that differ in their diagnostic ability. Whereas a high-ability expert type always performs a correct diagnosis with regard to the customer's problem, a low-ability expert type sometimes makes mistakes when diagnosing problems.

In our benchmark case with observable expert types, both expert types post equal-markup prices to signal that they have no incentive to overtreat or undertreat (on purpose). The high-ability expert type posts higher prices than the low-ability type because the customers' valuation for receiving a correct diagnosis (and treatment) is higher than for a possibly incorrect one. Furthermore, profits are higher for the high-ability type than for the low-ability type.

Under unobservable expert types, we find that efficient market outcomes always exist. Nevertheless, expert types may also coordinate on inefficient equilibria. In both – efficient and inefficient – equilibria, the two expert types post equal prices. This is the case because the low-ability expert type could always mimic the high-ability expert type when the high-ability expert type deviates from equal prices. Hence, markups and profits are identical for both expert types, which also implies that there are no private benefits to improving one's diagnostic ability. Increasing transparency through (perfect) certification, that is, making expert types observable, would weakly increase efficiency in our set-up.[34] This is especially important in settings in which experts' investments in their diagnostic ability are essential.

Relative to the efficiency under efficient equilibria, a marginal increase in the low-ability type's diagnostic ability does not necessarily improve social welfare. Welfare depends on the probability that customers need a major treatment and on the equilibrium experts coordinate on. We find that efficiency do not improve if the probability for a major problem is sufficiently high or sufficiently low. Only for an intermediate likelihood, an increase in efficiency results if the expert types post equal-markup prices and follow their own diagnosis.

We observe that an infinitesimally costly increase in the share of the high-ability type can even decrease social welfare because the equilibrium outcomes do not change, but costs must be incurred. For example, if expert types coordinate on an equilibrium in which both expert types always provide the major treatment, increasing the probability for a high-ability expert does not change the behavior of expert types, although the high-ability expert type would be able to provide a correct diagnosis.

Whereas a sufficiently large increase in the low-ability type's diagnostic ability can guarantee an efficient equilibrium, increasing the share of high-ability experts would only do so if there was no low-ability type left at all. This suggests that increasing minimum standards for experts can be a more successful

[34]Note that imperfect certification – often the only feasible option in practice – does not necessarily render our other insights obsolete. There can still be substantial variation in diagnoses, even among highly qualified experts; see, for example, Botvinik-Nezer et al. (2020), Huntington-Klein et al. (2021), and Menkveld et al. (2021).

policy than increasing the share of excellent experts.

If the success or failure of a treatment is verifiable, warranties or fines for an insufficient treatment appear to be useful policy tools. Without such verifiability, the optimal policy is not as straightforward.

Our results suggest that a regulation that obliges experts to follow the diagnostic results can be detrimental to social welfare. Such a regulation supports the efficient equilibrium only if diagnostic precision is sufficiently high. Moreover, it is never optimal to require both expert types to always provide a certain treatment. However, if the policy maker can differentiate expert types, requiring the low-ability type to always provide a certain treatment is optimal if this type's ability is sufficiently low. Overall, our results show that a careful design of expert markets is necessary to attain the social optimum.

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Chapter 2

Spatial Competition with Network Effects

2.1 Introduction

In this paper, I study the competition of platforms which offer differentiated products à la Hotelling in the presence of network effects when the location choices are endogenous. My research mainly shows that the equilibrium locations depend on the specified pricing policies and competition modes. Under *mill pricing policy* and *unbalanced competition* (in which platforms can choose their locations on only one side), in contrast to the *principle of maximum differentiation* in the standard Hotelling model, a tendency of agglomeration emerges in equilibrium when the difference of cross-sided network externalities is sufficiently high. Given this pricing policy, the *principle of maximum differentiation* still holds under *balanced competition* (in which platforms' location choices apply to both sides). With *discriminatory delivered pricing policy*, the tendency of agglomeration emerges in equilibrium under both *unbalanced* and *balanced* competition.

Competition among platforms differs from traditional one-sided markets in several aspects. The most distinctive ones are the price structure and the interdependency of prices on difference sides. Using a Hotelling specification with cross-sided network effects, Armstrong (2006) provides a theory of platform competition and shows that with single-homing agents and membership fees, the equilibrium prices are given by the prices in the standard Hotelling model adjusted downward by cross-sided network externalities. More precisely, agents on each side receive a subsidy, of which the amount corresponds to how much the agents on the other sides value network size. This price structure actually implies a kind of interdependence of prices on different sides, namely the price on one side depends on the level of the aggregate network effects associated to it. As discussed by Rochet and Tirole (2003) and Weyl (2009), there is a *see-saw effect* among the prices on different sides. The *see-saw effect* basically tells a fact that when there is a downward pressure (due to competition or regulation) on the prices on one side, the prices on the other side(s) may increase. Because the decrease in price can lead to a higher demand on this side. Since market agents on the other side(s) value network size, their willingness to pay increases. Therefore, platforms can charge a higher price on these side(s).

To study how this *see-saw effect* affects platforms' decisions of location choice, I extend the model of platform competition with fixed locations in Armstrong (2006) to a two-stage game, in which platforms select their locations in the first stage and compete in prices in the second. This is a very interesting research question because this very effect of price movement on different sides implies that a more intensified competition on one side does not necessarily reduce platforms' profits, as the lost of profit on this side can be compensated by the increased price(s) on other side(s). The most interesting result in my research is that, when agents' (individual users and sellers) valuations of the cross-sided network effects are sufficiently heterogeneous, platforms tend to approach each other in equilibrium under some specific combinations of pricing policies and competition modes. The product differentiation level in equilibrium could be even lower than the socially optimal one.

Besides mill pricing policy, discriminatory delivered pricing is also studied in this paper. Under this pricing policy, platforms pay the transportation costs and can discriminate the market agents based on their locations. My results show that, different from mill pricing policy, a tendency of agglomeration emerges under both unbalanced and balanced competition.

The remainder of this paper is structured as follows. In Section 2.2 the relevant literature is discussed. In Section 2.3 I introduce the basic setup and assumptions of the model. In Section 2.4 and Section 2.5 I come to the derivation of the results under the two different pricing policies respectively. In Section 2.6 I conclude and discuss some possible policy implications.

2.2 Literature

This paper mainly contributes to the literature of platform competition. In the paper by Armstrong (2006), the author provides a basic framework of pricing schemes in two-sided markets. Using a discrete choice model with within-sided and cross-sided network externalities, Tan and Zhou (2021) provide a general framework of platform competition with n sides and arbitrary number of platforms and show that the price structure of platform competition basically follows a similar pattern as in Armstrong (2006) when there is full market coverage. As mentioned before, Rochet and Tirole (2003) and Weyl (2009) identify and discuss a *see-saw effect* in platform pricing, which is also considered as the core of the price interdependency in this paper. As shown in these papers, prices charged by platforms may vary across different groups, because market agents from different sides may value network size heterogeneously. Besides the asymmetry in prices, my research shows that platforms also respond to this kind of heterogeneity by their incentives of location choices (product selection).

As studied by d'Aspremont et al. (1979), firms will choose to locate at the different end-points in the standard Hotelling model with quadratic transportation costs. This is often referred to as the *principle of maximum differentiation.* But having the maximum level of product differentiation may not be profitable anymore with cross-sided network effects, since a more intensified competition on one side may result in a higher price on the other side. Aiming at studying platforms' incentive of location choices with network effects, a location game is incorporated into platform competition in this paper.

In my research, it is essential to derive the conditions for a market-sharing equilibrium, in which both platforms are active. Because when network effects are fairly strong, there may be an equilibrium outcome with market tipping. For example, Arthur (1989) studies the market standardization outcome when consumers entering the markets sequentially. By treating the consumer choice as a stochastic process, it is proved that the whole market will be locked in a specific standard when this standard achieves its *critical mass.* This explains why some inferior standards finally prevail in the markets even if there are better ones. Sometimes, market agents may find it optimal to adopt a *wait-and-see* strategy in order to be able to utilize the maximum network size. Take the paper by Farrell and Saloner (1985) as an example. They study a sequential game of technology adoption and find that there exits a unique *bandwagon equilibrium* for some specific types of agents. Weyl (2010) provides a monopoly pricing theory in which platforms can adopt *insulating tariffs* to prevent market agents from misallocating. Throughout my analysis, the conditions for a market sharing equilibrium are assumed to hold and equilibria with market tipping are not considered.

It has been shown in the early literature that the market outcomes vary significantly with agents' expectations of network size. Katz and Shapiro (1985) incorporate within-sided network effects into a standard Cournot game and show that asymmetric equilibrium can exists, in which only a fraction of firms are active, if consumes' expectations are assumed to be self-fulfilling. In two-sided markets, Jullien (2011) defines a *divide and conquer strategy* for the second-mover in a Stackelberg price game when consumers are pessimistic. For the second-mover, its price has to be so favorable that an agent will choose a unilateral switch to it. In this paper, all market agents are assumed to be fully rational and they always coordinate on the platform which provides a higher utility to them.

In addition to uniform pricing policy, discriminatory delivered pricing is also studied in this paper. Hoover (1937) studies spatial price discrimination and provides explainations for why prices are not necessarily increasing with distance. Holahan (1975) proves that spatial discriminatory pricing may induce higher net benefits than uniform pricing and it will bring consumers from afar in attraction. What is more, the adopted pricing policies have crucial influence on location choice as well. Focusing only on firms' location choices, Greenhut et al. (1986) conclude that spatial discriminatory pricing policy generally induces more product differentiation than uniform delivered pricing. Hamilton et al. (1989) study firms' location choices with spatial discrimination and compare the equilibrium outcomes under Cournot and Bertrand competition. They find that firms tend to choose the locations which minimize the total transportation costs given their demand schedules. Anderson et al. (1992) show in a location-then-price model that socially optimal locations can be sustained in equilibrium under discriminatory delivered pricing. Anderson and De Palma (1988) study this pricing policy with heterogeneous products and find that complete agglomeration is possible in equilibrium when the degree of product heterogeneity is sufficiently high. In this paper, I consider a location-then-price game under discriminatory delivered pricing with network effects and find that insufficient differentiation levels are possible in equilibrium when the difference of cross-sided network effects is high enough.

2.3 The Model

This section mainly introduces the setup of the model that exists as a two-stage Hotelling model with network effects. There are two platforms (A and B) competing for market agents from two sides: Individual users (denoted by U)

and sellers (denoted by S). Assume that market agents are uniformly distributed in the agent space I. On each side there is a continuum of agents with measure 1. For simplicity, the cost of serving each agent is assumed to be zero. Only single-homing agents are considered here. The utility of a user (locating at x) from joining platform i is

$$u_U^i = v - p_U^i + \alpha_U n_S^i + \beta_U n_U^i - t_U(x - x^i)^2, \tag{2.1}$$

and the utility of a seller (locating at x) from joining platform i is

$$u_S^i = v - p_S^i + \alpha_S n_U^i + \beta_S n_S^i - t_S(x - x^i)^2, \tag{2.2}$$

where $i \in \{A, B\}$. v is the stand-alone utility of an agent from joining a platform. This value is assumed to be homogeneous across agents on different sides and sufficiently high, such that all market agents are active. p_U^i and p_S^i denote the prices (in the form of membership fees) charged by platform i on the user and seller sides respectively. $\alpha_U > 0$ and $\alpha_S > 0$ are the parameters of the cross-sided network externalities. β_U and β_S denote the parameters of the within-sided network externalities. Note that the parameters of the cross-sided network externalities are strictly positive, whereas the parameters of the within-sided externalities could be negative. In other words, there may be congestion effects within agent groups. n_U^i and n_S^i represent the demand of platform i on the user and seller sides respectively. The last term represents the transportation cost from joining a platform locating at x^i. With parameters t_U and t_S, the transportation cost takes a quadratic form.

The timing of the game is as follows: In the first stage, platforms choose their locations $\{x^A, x^B\}$ in the agent spaces. Without loss of generality, it is assumed that $x^A \leq x^B$. In this stage, two different scenarios are discussed. The first one is *(potentially) unbalanced competition*. In this scenario, platforms choose their locations for only one side. On the other side, they are assumed to be located at the two extremes. The second one is defined as *balanced competition*, namely x^i applies on both sides.[1] In stage two, platforms compete in prices by setting $\boldsymbol{p^i} = (p_U^i, p_S^i)$. Two different pricing policies are considered here:

[1] Weyl (2009) also uses the terms *unbalanced* and *balanced competition*, but his is a notion that mainly describes price compititon, while the terms here are extended onto platforms' location choices.

Mill pricing and *discriminatory delivered pricing*. With *mill pricing policy*, the transportation costs are paid by the agents and platforms are only allowed to set a uniform price on each side. Whereas with *discriminatory delivered pricing*, platforms pay the transportation costs and they are allowed to discriminate their agents at different locations. In next sections, I will discuss platform competition under the two pricing policies respectively.

2.4 Mill Pricing

Under *mill pricing policy*, market agents pay the transportation costs and platforms set a constant membership fee on each side. It has been shown in the early litertature that without network effects, the equilibrium locations under this pricing policy involve platforms locating at the two extremes (*principle of maximum differentiation*, see d'Aspremont et al. (1979)). However, the equilibrium locations with network effects may be different from it. The discussion here is undertaken in the two above mentioned scenarios: *(potentially) unbalanced competition* and *balanced competition*. Note that in both scenarios, each platform has only one location variable x^i.

2.4.1 Unbalanced competition

It is often observed in the market that the competition intensity is asymmetric across different sides. This phenomenon is more obvious in the markets in which there is significant heterogeneity across different sides. Therefore, platforms may select products in different patterns in order to cater to the heterogeneous preferences across different groups. In this subsection, I assume unbalanced competition and platforms can only select locations on the user side. On the seller side, they are simply located at different extremes in the agent space, meaning that $\boldsymbol{x^i_U} = (x^A, x^B)$ and $\boldsymbol{x^i_S} = (0, 1)$.

2.4.1.1 Price equilibrium

In the second stage, platforms compete in prices after observing the location choices in the previous stage. Given the utilities in (2.1) and (2.2), the number of agents buying from platform i on side U is to be formulated by the following pattern:

$$n_U^i = \frac{\alpha_U(n_S^i - n_S^j) + \beta_U(n_U^i - n_U^j) - (p_U^i - p_U^j) - t_U((x^A)^2 - (x^B)^2)}{2t_U(x^B - x^A)}, \quad (2.3)$$

and the number of agents of platform i on side S is given by

$$n_S^i = \frac{\alpha_S(n_U^i - n_U^j) + \beta_S(n_S^i - n_S^j) - (p_S^i - p_S^j) + t_S}{2t_S}, \quad (2.4)$$

where $i, j \in \{A, B\}$ and $i \neq j$. Equation (2.3) and (2.4) actually define a system of equations. In Lemma 2.1, I derive the conditions for a unique solution of this system of equations.

Lemma 2.1. *For any pair of location choices* (x^A, x^B)*, there exist a unique solution of the equation system defined by (2.3) and (2.4) if*

$$\beta_U < 0, \quad \beta_S < 2t_S. \quad (2.5)$$

Proof. Define the system of equations above as $n_k^i = f(n_k^i)$, where $k \in \{U, S\}$. Note that n_k^i is defined on a closed area $[0, 1]$ and $f(n_k^i)$ is a continuous function. So, according to *Brouwer's fixed point theorem*, the system of equations above has at least one solution. As long as $\frac{\partial f(n_k^i)}{\partial n_k^i} < 1$, this system of equations has a unique solution. Solving $\frac{\partial f(n_k^i)}{\partial n_k^i} < 1$, we get the conditions in (2.5) in this lemma. □

Solving the system of equations defined by (2.3) and (2.4), we get the demand functions of platform A on the two sides:

$$n_U^A = \frac{\alpha_U\alpha_S + \alpha_U(p_S^A - p_S^B) - \Omega_S(p_U^A - p_U^B) - \Omega_S(\beta_U + t_U((x^A)^2 - (x^B)^2))}{2(\alpha_U\alpha_S - \Omega_U\Omega_S)},$$

$$n_S^A = \frac{\alpha_U\alpha_S + \alpha_S(p_S^A - p_S^B) - \Omega_U(p_U^A - p_U^B) - \Omega_U\Omega_S + \alpha_S t_U(x^A - x^B)(x^A + x^B - 1)}{2(\alpha_U\alpha_S - \Omega_U\Omega_S)},$$

where $\Omega_U := \beta_U + t_U(x^A - x^B)$, and $\Omega_S := \beta_S - t_S$. The demand of platform B on each side is $n_k^B = 1 - n_k^A$. Given the demand function of each platform on each side, the profit of platform i, $\pi_{M,un}^i$ (M for *Mill pricing* and *un* for *unbalanced competition*), can be written as

$$\pi^i_{M,un} = p^i_U \cdot n^i_U + p^i_S \cdot n^i_S.$$

Before proceeding to solve the equilibrium prices, it is worthwhile to discuss the necessary and sufficient conditions for a market-sharing equilibrium. When platforms locate sufficiently near to each other, agents may find it optimal to coordinate on only one platform to enjoy the whole network size. In order to avoid the situation of multiple equilibria, the conditions in Lemma 2.2 must be satisfied throughout the analysis.

Lemma 2.2. *Under mill pricing policy and unbalanced competition, for any pair of locations* (x^A, x^B)*, the necessary and sufficient conditions for a market-sharing equilibrium are*

$$\beta_U < 0 \tag{2.6}$$

$$4\beta_U(\beta_S - t_S) > (\alpha_U + \alpha_S)^2. \tag{2.7}$$

Proof. Since the profit function may not be continuous in prices, the approach discussed by Tan and Zhou (2019) is introduced to help deriving the conditions: The profit function of each platform is transformed from prices into quantities, while keeping the prices of the other platform fixed. The Hessian matrix of the profit of platform i is then given by

$$H_i = 2 \cdot \begin{bmatrix} 2(\beta_U + t_U(x^A - x^B)) & \alpha_U + \alpha_S \\ \alpha_U + \alpha_S & 2(\beta_S - t_S) \end{bmatrix}.$$

For a maximized profit of platform i, the Hessian matrix must be negative semidefinite for any pair of location choices, which means the conditions in (2.6) and (2.7) must be satisfied. □

Keeping the location choices in the first stage fixed, the equilibrium prices must satisfy the first-order conditions and can be solved by a system of equations $\frac{\partial \pi^i_{M,un}}{\partial p^i_k} = 0$. The precise expressions of equilibrium prices given locations x^A and x^B are given in Appendix A.

The price structure of platform competition has been analyzed in early literature with various settings. With symmetric platforms and full market coverage under fixed market volume, the papers by Armstrong (2006) and Tan and Zhou (2021) prove that the equilibrium prices on each side actually can be decomposed by the following rule: The prices equal to the equilibrium prices in the standard Hotelling model (the market power generated by product differentiation plus the operating cost) adjusted downward by the network externalities associated to this side. In this two-stage model, the prices listed in Appendix A also follow the price structure identified in the previously mentioned literature. For symmetric locations, the price on each side is given by:

$$p_U^i = t_U(1 - 2x^A) - \alpha_S - \beta_U,$$

$$p_S^i = t_S - \alpha_U - \beta_S.$$

Note that the first term in p_U^i, $t_U(1 - 2x^A)$, represents the market power of platform i on the user side given the locations. One can find out that as the two platforms moving towards each other, they are losing their market power associated with product differentiation. When their locations coincide at the market center, they could end up with negative prices. One can find out in the next part that platforms will move closer to each other in equilibrium if the difference of cross-sided network effects is high enough. But a complete agglomeration can never be an equilibrium. The reason can be found right here. Since the prices may drop too severely and even become negative when the distance between the two platforms shrinks, they will never find it optimal to locate together.

Different from traditional markets, platforms must take the interdependency of their prices on different sides into consideration when maximizing their profits. With this Hotelling specification and linear externalities, a price change on one side of a platform leads to the following effect on its price on the other side:

$$\frac{\partial p_U^i}{\partial p_S^i} = \frac{\alpha_U + \alpha_S}{2(\beta_S - t_S)}, \tag{2.8}$$

$$\frac{\partial p_S^i}{\partial p_U^i} = \frac{\alpha_U + \alpha_S}{2(\beta_U + t_U(x^A - x^B))}. \tag{2.9}$$

Equation (2.8) and (2.9) show that there is indeed a *see-saw effect* on equilibrium prices from different sides. As long as the conditions for a unique demand

and a market-sharing equilibrium hold for any pair of locations (x^A, x^B), the expressions in (2.8) and (2.9) are strictly negative. This means that a decrease in price on one side does not only increase the demand on this side, but also leads to a higher equilibrium price on the other side. It is worthwhile to notice that the effects of a price change are asymmetric on different sides. Keeping the parameters of network effects and transportation cost fixed, the effect of a price change on the sellers side does not depend on platforms' location choices. However, as shown in equation (2.9), the effect of a change in p_U^i on p_S^i depends on the distance between the two platforms. When $(x^A - x^B)$ increases, $\frac{\partial p_S^i}{\partial p_U^i}$ decreases, which means that when the distance between the competing platforms becomes smaller, the *see-saw effect* on the user side gets stronger. We know from the standard two-stage Hotelling model that firms tend to locate at the two end-points of the consumer space, since the loss from a decreased price cannot be compensated by the gain from an increased demand from they moving closer to each other. However, this principle may lose its power with cross-sided network effects. When a platform moves towards its competitor, alongside its demand being increasing, it encounters higher benefits from the other side, of which the agents are willing to pay more due to cross-sided network effects. Therefore, it is not so straightforward to tell the effect of a tendency of agglomeration on platforms' profits. The following analysis illustrates that this effect depends mainly on the difference of cross-sided network externalities of the two sides.

2.4.1.2 Spatial competition

Because the equilibrium prices on different sides move in opposite directions, moving towards the center of the agent space has an ambiguous effect on platforms' profits. Since the product differentiation level on the seller side remains maximized, platforms may have incentive to move closer to each other in the user market in order to extract more rent from the sellers when the difference of cross-sided network effects is sufficiently high. Considering only symmetric locations (i.e., $x^B = 1 - x^A$), this intuition is proved by the analytical results, and the equilibrium of the spatial game in the first stage is summarized in the following proposition.

Proposition 2.1. *For the location-then-price game with mill pricing and un-*

balanced competition, platforms do not locate at the extremes if $\alpha_U > \alpha_U^* := \frac{\alpha_S^2+(\beta_S-t_S)(\alpha_S-3(\beta_U-t_U))}{2\alpha_S-\beta_S+t_S}$ *and the equilibrium location of platform A* (x^{A^*}) *is the smaller root that solves* $\frac{\partial \pi^A_{M,un}}{\partial x^A} = 0$*, while the equilibrium location of platform B is* $x^{B^*} = 1 - x^{A^*}$*. Otherwise, platforms choose to locate at different extremes.*

See Appendix B for a detailed proof. The equilibrium locations are illustrated in Figure 2.1. The lower curve represents the equilibrium locations of platform A and the upper one, which is symmetric to the lower one, represents the equilibrium locations of platform B. It is worthwhile to notice that although platforms have an incentive to move towards the market center when the cross-sided network effect on the user side is sufficiently high, complete agglomeration will never be an equilibrium. Actually since the conditions for a market-sharing equilibrium must be fulfilled, the two platforms will still maintain certain distance.

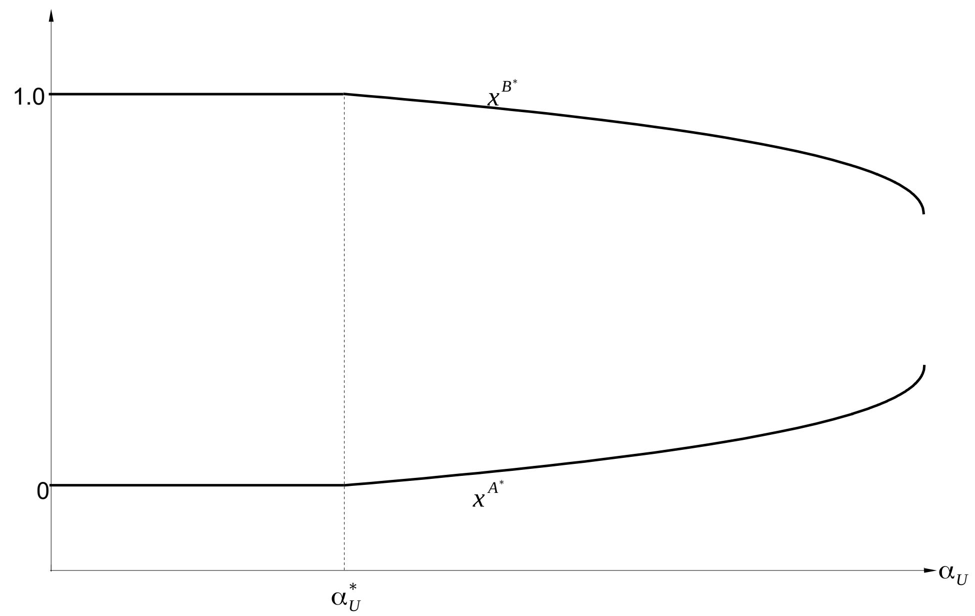

Figure 2.1: Equilibrium locations under mill pricing and unbalanced competition.

2.4.1.3 Social welfare

We know from the conclusion in the standard Hotelling model that firms' desired differentiation level is over-sufficient compared to the social optimum. In the standard location-then-price game, the socially optimal differentiation level involves firms locating at the first and third quartiles in the consumer space, which correspond to the locations that minimize the total transportation costs. However, the results are still some way from being clear with network effects, since platforms have incentive to move towards the center. The comparison is summarized in the following proposition.

Proposition 2.2. *For the location-then-price game with mill pricing policy and unbalanced competition, the socially optimal locations involve platforms locating at* $x^A = \frac{1}{4}$ *and* $x^B = \frac{3}{4}$*. The equilibrium differentiation level is higher than the social optimum if* $\alpha_U < \alpha_U^{**}$*, where* α_U^{**} *is the bigger root of* $(\alpha_S + 2\alpha_U)(3\alpha_S + \alpha_U) + (\beta_S - t_S)(\alpha_S - \alpha_U - 6(2\beta_U - t_U)) = 0$*. Otherwise, the differentiation level is lower than the socially optimal one.*

See Appendix C for a detailed proof. The comparison between the equilibrium and socially optimal locations is illustrated in Figure 2.2, in which the dashed curves represent the locations which maximize social welfare.

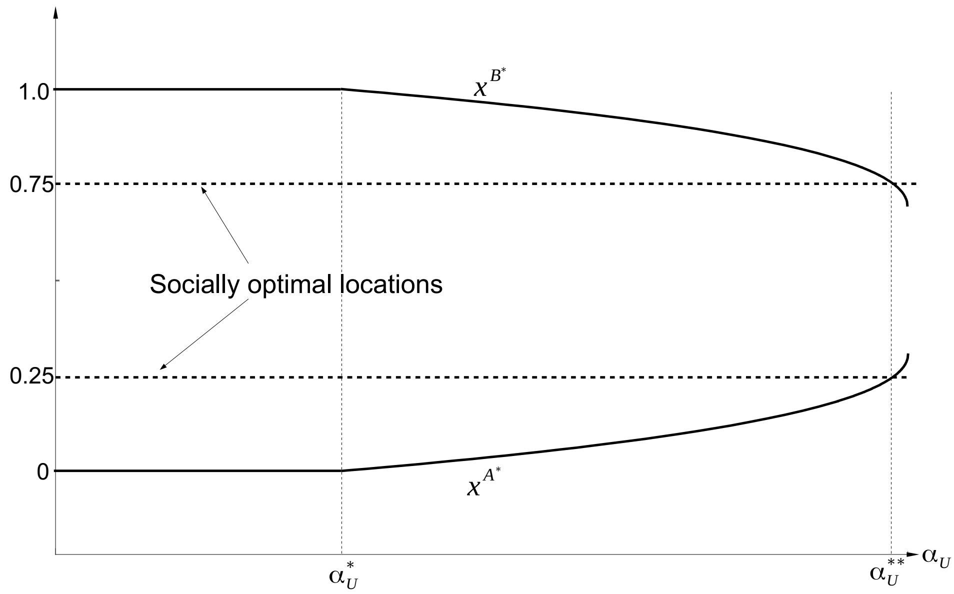

Figure 2.2: Comparison between the equilibrium and socially optimal locations under mill pricing and unbalanced competition.

In this case, the socially optimal locations correspond to the locations which minimize the total transportation costs. One can infer from the comparison that when the cross-sided network effect on the user side is sufficiently high, platforms voluntarily choose to have more intensified competition on this side. But in this case, the agents on the seller side suffer from the increased price due to the *see-saw effect*.

2.4.2 Balanced competition

This subsection discusses *mill pricing policy* with balanced competition. $\boldsymbol{x_k^i} = (x^A, x^B)$ denotes the location choices of the two competing platforms, respectively. Given the utilities in (2.1) and (2.2), the demands of agents buying from platform i on the user and seller sides satisfy

$$n_U^i = \frac{\alpha_U(n_S^i - n_S^j) + \beta_U(n_U^i - n_U^j) - (p_U^i - p_U^j) - t_U((x^A)^2 - (x^B)^2)}{2t_U(x^B - x^A)}, \quad (2.10)$$

$$n_S^i = \frac{\alpha_S(n_U^i - n_U^j) + \beta_S(n_S^i - n_S^j) - (p_S^i - p_S^j) - t_S((x^A)^2 - (x^B)^2)}{2t_S(x^B - x^A)}, \quad (2.11)$$

where $i, j \in \{A, B\}$ and $i \neq j$.

2.4.2.1 Price equilibrium

Similar as unbalanced competition, Lemma 2.3 states the condition for a unique demand in this case.

Lemma 2.3. *For any pair of location choices (x^A, x^B), there exist a unique solution of equations (2.10) and (2.11) if*

$$\beta_k < 0.$$

The proof is similar as in Lemma 2.1 and is omitted here. The demand of platform i on side U is

$$n_U^i = \frac{\alpha_U\alpha_S - \beta_U\beta_S + \alpha_U(p_S^i - p_S^j) - \Theta_S(p_U^i - p_U^j) + \Phi_U}{2(\alpha_U\alpha_S - \Theta_U\Theta_S)},$$

and the demand of platform i on side S is

$$n_S^i = \frac{\alpha_U\alpha_S - \beta_U\beta_S + \alpha_S(p_U^i - p_U^j) - \Theta_U(p_S^i - p_S^j) + \Phi_S}{2(\alpha_U\alpha_S - \Theta_U\Theta_S)},$$

where $\Theta_U := \beta_U + t_U(x^i - x^j)$, $\Theta_S := \beta_S + t_S(x^i - x^j)$, $\Phi_U := ((x^i - x^j)(\alpha_U t_S(x^i + x^j - 1) - \beta_U t_S - \Theta_S t_U(x^i + x^j))$ and $\Phi_S := ((x^i - x^j)(\alpha_S t_U(x^i + x^j - 1) - \beta_S t_U - \Theta_U t_S(x^i + x^j))$. The demand of the other platform is given by $n_k^j = 1 - n_k^i$. Given the demand function of each platform on each side, the profit of platform i, $\pi^i_{M,ba}$ (*ba* for *balanced competition*), can be written as

$$\pi^i_{M,ba} = p^i_U \cdot n^i_U + p^i_S \cdot n^i_S.$$

The necessary and sufficient conditions for a market-sharing equilibrium are provided in Lemma 2.4.

Lemma 2.4. *Under mill pricing policy and balanced competition, for any pair of locations* (x^A, x^B)*, the necessary and sufficient conditions for a market-sharing equilibrium are*

$$\beta_U < 0 \tag{2.12}$$

$$4\beta_U\beta_S > (\alpha_U + \alpha_S)^2. \tag{2.13}$$

Proof. Here is the same approach as used in Lemma 2.2. In this case, the Hessian matrix of the profit of platform i is given by

$$H_i = 2 \cdot \begin{bmatrix} 2(\beta_U + t_U(x^A - x^B)) & \alpha_U + \alpha_S \\ \alpha_U + \alpha_S & 2(\beta_S + t_S(x^A - x^B)) \end{bmatrix}.$$

□

Given the conditions for a market-sharing equilibrium, we get the equilibrium outcome of the price competition in this stage. Similar as in the previous analysis, the equilibrium prices can be derived by solving the first-order conditions.

2.4.2.2 Spatial competition

In the first stage, platforms choose their locations simultaneously taking the price competition into consideration. Again, only symmetric location equilibrium will be considered here. Proposition 2.3 summarizes the equilibrium in the location game. A detailed proof is in Appendix D.

Proposition 2.3. *For the location-then-price game with mill pricing policy and balanced competition, platforms locate at opposite extremes in equilibrium, namely* $x^{A^*} = 0$ *and* $x^{B^*} = 1$.

2.4.2.3 Social welfare

The above analysis proves that the results derived in the standard two-stage Hotelling model are still true in the case with network effects under balanced competition. A comparison between the equilibrium and socially optimal locations is summarized in Proposition 2.4.

Proposition 2.4. *For the location-then-price game with mill pricing policy and balanced competition, the socially optimal locations involve platforms locating at* $x^A = \frac{1}{4}$ *and* $x^B = \frac{3}{4}$. *This means that there is always excess differentiation between the competing platforms in the market.*

A detailed proof is provided in Appendix E. Figure 2.3 shows the comparison between the equilibrium and socially optimal locations in this case. Comparing to the results under unbalanced competition, the equilibrium locations under balanced competition are largely driven by the assumption that platforms' location choices apply to both sides simultaneously. Given the locations of their competitors, moving towards the center intensifies competition on both sides. Therefore the *principle of maximum differentiation* remains in effect.

2.5 Discriminatory Delivered Pricing

Other than *mill pricing* policy, it is also often observed in the market that transportation costs are paid by the platforms. In this section, the analysis comes to another pricing policy: *Discriminatory delivered pricing.* Similar as in the previous section, both unbalanced and balanced competition are discussed.

2.5.1 Equilibrium price without network effects

Before proceeding to the analysis with network effects, the case of price competition without network effects is briefly discussed here. With this pricing policy, it is assumed that transportation costs are paid by the platforms. What is

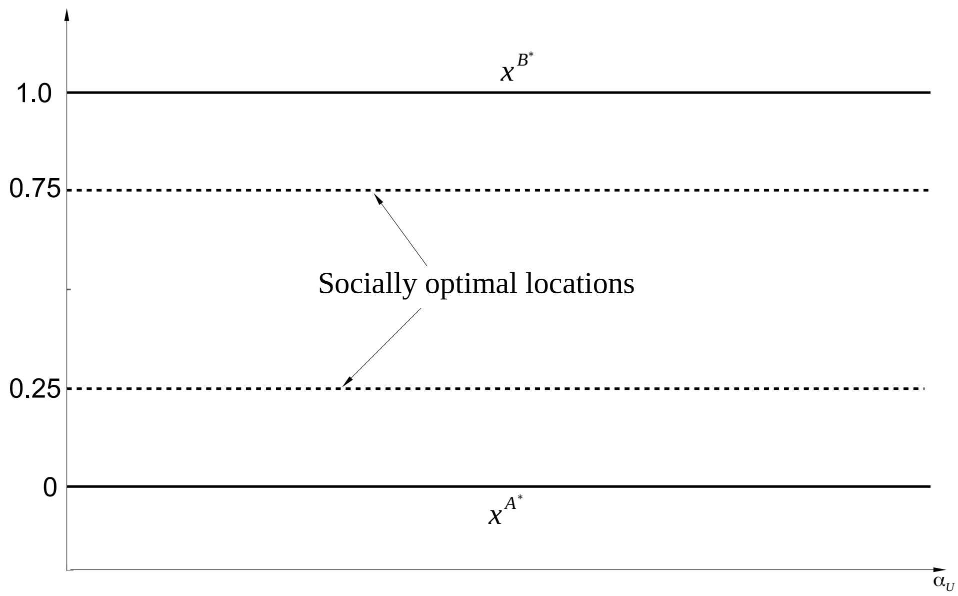

Figure 2.3: Comparison between the equilibrium and socially optimal locations under mill pricing and balanced competition.

more, platforms can discriminate the agents based on their locations. Such a case has already been analyzed in previous research, for example, in Anderson et al. (1992). It has been proved that with these assumptions, the price competition at each point in the agent space is similar to the case in which these two platforms compete with asymmetric costs. Figure 2.4 (a reduced version of that in Anderson et al. (1992), Chapter 8) illustrates the equilibrium prices without network effects. The equilibrium prices are represented by the bold curve in this figure.

I briefly introduce some relevant results in Anderson et al. (1992) here. First, at each point in the agent space, the platform with the lowest transportation cost wins the agent and it charges the price which equals to the second lowest transportation cost in the market. One can find out in this figure that platforms make zero profit at the margin. Second, although the transportation costs are paid by the platforms, equilibrium prices are not necessarily increasing with distance. This is because the two platforms have to compete more severely in the area between them. Anderson et al. (1992) also analyze a location-then-price game under this pricing policy and they prove that the socially optimal locations can be sustained in equilibrium.

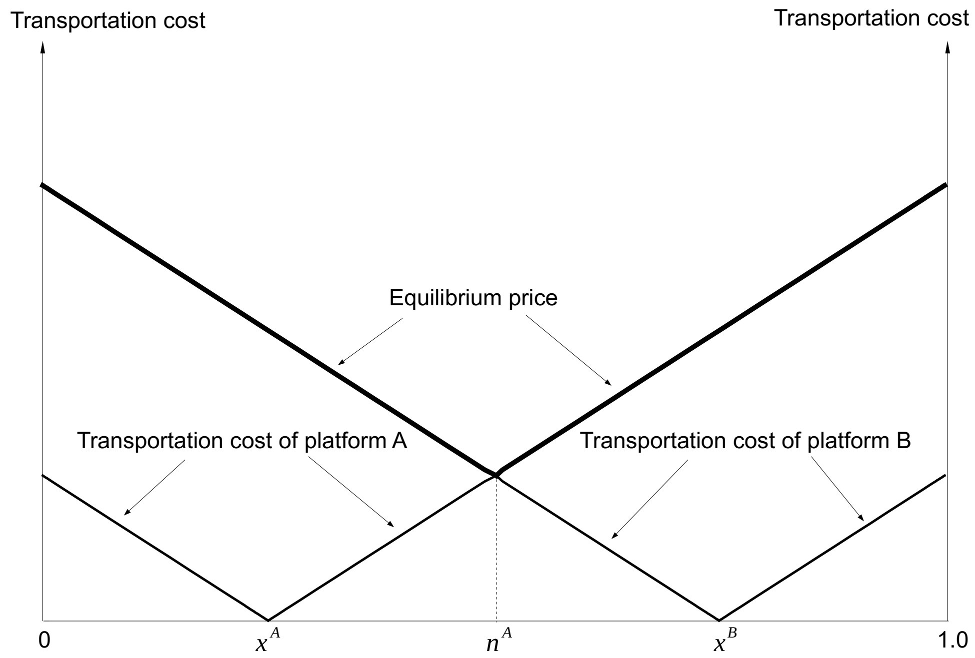

Figure 2.4: Discriminatory delivered pricing without network effects.

2.5.2 Price competition with network effects

With network externalities, the utility of an agent on the user side from joining platform i can be written as

$$u_U^i = v - p_U^i + \alpha_U n_S^i + \beta_U n_U^i.$$

The utility of a seller from joining platform i is

$$u_S^i = v - p_S^i + \alpha_S n_U^i + \beta_S n_S^i.$$

For the platforms, the transportation cost on each side is assumed to be linear in distance in this case, i.e., $t_k|x_k^i - x|$.[2]

Given the utility functions of the agents, the equilibrium prices can be derived

[2]It has been proved that, in the standard Hotelling model with linear transportation cost, a pure strategy equilibrium does not exist when firms locate close enough to each other (See d'Aspremont et al. (1979)). Nevertheless, such an equilibrium always exists with discriminatory delivered pricing. So linear transportation cost is assumed here to simplify the analysis.

by shifting the cost curve of one of the platforms as shown in Figure 2.5. Here $d = \alpha_k(n_g^i - n_g^j) + \beta_k((n_k^i - n_k^j)$.

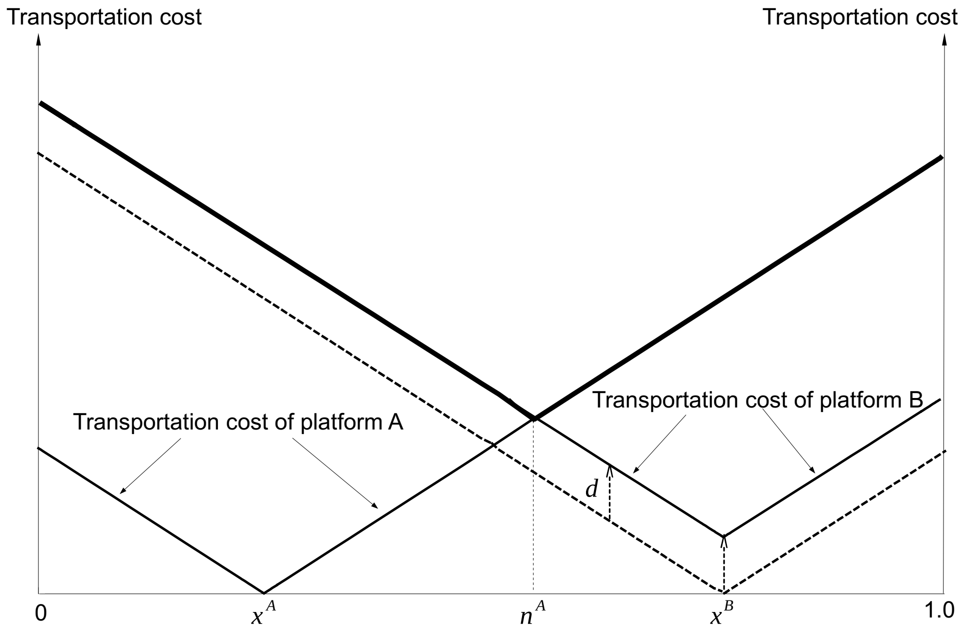

Figure 2.5: Discriminatory delivered pricing with network effects.

2.5.3 Unbalanced competition

Under discriminatory delivered pricing policy, the network effects can be considered as platforms' cost advantage if one platform has larger network size on a specific side. This advantage can be too high to fade away when reaching even the farthest agent and thus make the other platform driven out. Therefore, the conditions for a market-sharing equilibrium must be satisfied under this pricing policy as well and are given in the next lemma.

Lemma 2.5. *For any pair of locations, the location-then-price game under discriminatory delivered pricing with unbalanced competition has a unique market-sharing equilibrium if* $\alpha_k < \frac{1}{2}t_k - \beta_k$.

See Appendix F for a sketch of proof. Given the utility functions of the agents, the demand functions of platform A are given by

$$n_U^A = \frac{\alpha_U\alpha_S - (\beta_S - t_S)(\beta_U - t_U(x^A + x^B))}{2\alpha_U\alpha_S - 2(\beta_S - t_S)(\beta_U - t_U)}, \tag{2.14}$$

$$n_S^A = \frac{\alpha_S(\alpha_U - t_U(x^A + x^B - 1)) - (\beta_S - t_S)(\beta_U - t_U)}{2\alpha_U\alpha_S - 2(\beta_S - t_S)(\beta_U - t_U)}. \tag{2.15}$$

The demand functions for platform B are $n_k^B = 1 - n_k^A$. Proposition 2.5 states the corresponding equilibrium locations.

Proposition 2.5. *Under discriminatory delivered pricing and unbalanced competition, the (symmetric) equilibrium locations are given by*

$$x^{A^*} = \frac{\beta_S t_U - t_S(\alpha_S + t_U)}{4(\alpha_S\alpha_U - (\beta_S - t_S)(\beta_U - t_U))}, \tag{2.16}$$

$$x^{B^*} = 1 - \frac{\beta_S t_U - t_S(\alpha_S + t_U)}{4(\alpha_S\alpha_U - (\beta_S - t_S)(\beta_U - t_U))}. \tag{2.17}$$

Proof. Given the demand functions, the profit of platform A, $\pi_{D,un}^A$ (D for *Discriminatory delivered pricing*), can be derived as

$$\begin{aligned}\pi_{D,un}^A = &\int_0^{x^A} [t_U(x_B - x) + \alpha_U(n_S^A - n_S^B) + \beta_U(n_U^A - n_U^B) - t_U(x^A - x)]\,dx \\ &+ \int_{x^A}^{n_U^A} [t_U(x_B - x) + \alpha_U(n_S^A - n_S^B) + \beta_U(n_U^A - n_U^B) - t_U(x - x^A)]\,dx \\ &+ \int_0^{n_S^A} [t_S(1 - x) + \alpha_S(n_U^A - n_U^B) + \beta_S(n_S^A - n_S^B) - t_S x]\,dx.\end{aligned}$$

The profit of platform B can be written in a symmetric form. Taking the first derivative of the profit of platform A with respect to its location variable x^A and considering only the symmetric locations, we get

$$\frac{t_U(\beta_S t_U - t_S(\alpha_S + t_U))}{2\alpha_S\alpha_U - 2(\beta_S - t_S)(\beta_U - t_U)} - 2t_U x^A. \tag{2.18}$$

The expression in (2.18) is strictly positive at $x^A = 0$ when the conditions for a market-sharing equilibrium hold, which means that the profit of platform A is increasing at this point. It is also true that the first derivative of $\pi_{D,un}^A$ with respect to x^A is negative at the point $x^A = \frac{1}{2}$ with the conditions for a market-sharing equilibrium being satisfied. This means that the optimal location for platform A is within $[0, \frac{1}{2}]$ and, analogously, that for platform B is within $[\frac{1}{2}, 1]$. Setting expression (2.18) equal to zero we get the optimal location for platform

A, which is given in expression (2.16). The equilibrium location for platform B is given by $x^{B^*} = 1 - x^{A^*}$. □

It is worthwhile to notice that, as long as the conditions for a market-sharing equilibrium hold, the equilibrium location of platform A is increasing with higher cross-sided network effect on the user side α_U and that of platform B is decreasing in it, meaning that the following relationships always hold:

$$\frac{\partial x^{A^*}}{\partial \alpha_U} = \frac{4\alpha_S(t_S(\alpha_S + t_U) - \beta_S t_U)}{(4\alpha_S\alpha_U - (\beta_S - t_S)(\beta_U - t_U))^2} > 0,$$

$$\frac{\partial x^{B^*}}{\partial \alpha_U} = -\frac{4\alpha_S(t_S(\alpha_S + t_U) - \beta_S t_U)}{(4\alpha_S\alpha_U - (\beta_S - t_S)(\beta_U - t_U))^2} < 0.$$

The results further confirm the intuition that platforms are willing to have more competition when the cross-sided network effect on the user side increases. Whether the sufficiency of equilibrium differentiation reaches the level required by the social optimum is summarized in the following proposition.

Proposition 2.6. *Under discriminatory delivered pricing and unbalanced competition, the socially optimal locations are still $x^A = \frac{1}{4}$ and $x^B = \frac{3}{4}$, which minimize the total transportation costs. The equilibrium differentiation level is smaller than the socially optimal one if $\alpha_U > \bar{\alpha_U} := \frac{\beta_S\beta_U - (\alpha_S + \beta_U)t_S}{\alpha_S}$.*

See Appendix G for a sketch of proof. Figure 2.6 demonstrates the equilibrium locations as well as a comparison with the social optimum.

2.5.4 Balanced competition

Similar as unbalanced competition, the necessary and sufficient conditions for a market-sharing equilibrium in this case are given in the following lemma.

Lemma 2.6. *For any pair of locations, the location-then-price game under discriminatory delivered pricing with balanced competition has a unique market-sharing equilibrium if $\alpha_k < \frac{1}{2}t_k - \beta_k$.*

See Appendix F for a sketch of proof. Under balanced competition, the demand functions for platform A look slight different from that under unbalanced

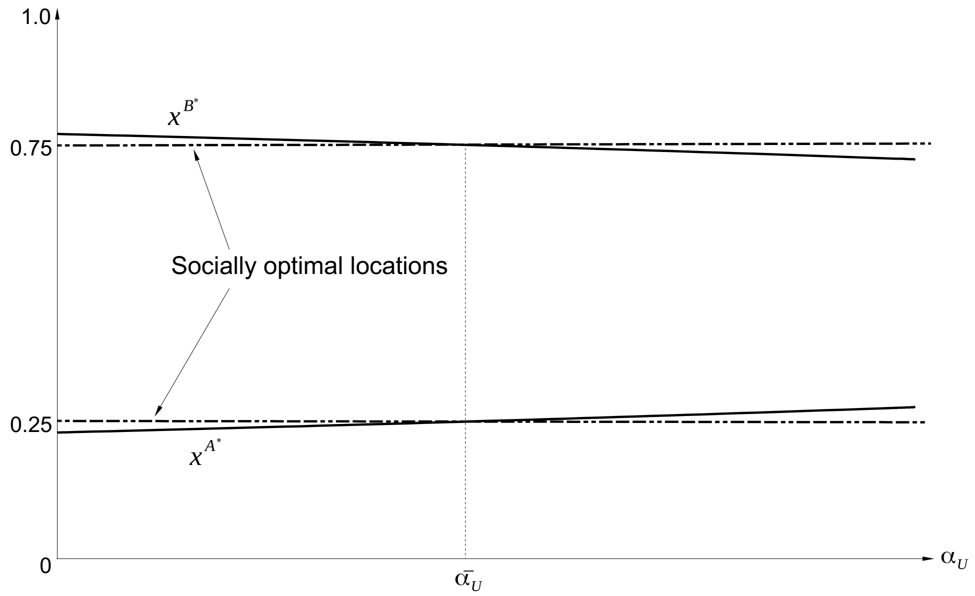

Figure 2.6: Comparison between the equilibrium and socially optimal locations under discriminatory delivered pricing and unbalanced competition.

competition and are given by

$$n_U^A = \frac{\alpha_S(\alpha_U - t_U(x^A + x^B - 1)) - (\beta_U - t_U)(\beta_S - t_S(x^A + x^B))}{2\alpha_U\alpha_S - 2(\beta_U - t_U)(\beta_S - t_S)},$$

$$n_S^A = \frac{\alpha_U(\alpha_S - t_S(x^A + x^B - 1)) - (\beta_S - t_S)(\beta_U - t_U(x^A + x^B))}{2\alpha_S\alpha_U - 2(\beta_S - t_S)(\beta_U - t_U)}.$$

The demand functions for platform B on side k is $1 - n_k^A$. Therefore, the profit of platform A is

$$\begin{aligned}\pi_{D,ba}^A = &\int_0^{x^A} [t_U(x_B - x) + \alpha_U(n_S^A - n_S^B) + \beta_U(n_U^A - n_U^B) - t_U(x^A - x)]\,dx \\ &+ \int_{x^A}^{n_U^A} [t_U(x_B - x) + \alpha_U(n_S^A - n_S^B) + \beta_U(n_U^A - n_U^B) - t_U(x - x^A)]\,dx \\ &+ \int_0^{x^A} [t_S(x_B - x) + \alpha_S(n_U^A - n_U^B) + \beta_S(n_S^A - n_S^B) - t_S(x^A - x)]\,dx \\ &+ \int_{x^A}^{n_S^A} [t_S(x_B - x) + \alpha_S(n_U^A - n_U^B) + \beta_S(n_S^A - n_S^B) - t_S(x - x^A)]\,dx.\end{aligned}$$

The profit of platform B can be put in a symmetric form. The equilibrium outcome in the first stage in this case is summarized in the following proposition.

Proposition 2.7. *Under discriminatory delivered pricing and balanced competition, the equilibrium location for platform A is given by*

$$x^{A^*} = \frac{\beta_U t_S^2 + t_U(\beta_S t_U - t_S(\alpha_S + \alpha_U + t_S + t_U))}{4(\alpha_S \alpha_U - (\beta_S - t_S)(\beta_U - t_U))(t_U + t_S)}. \tag{2.19}$$

The equilibrium location for platform B is $x^{B^*} = 1 - x^{A^*}$.

Proof. Considering again only symmetric locations, the first derivative of the profit of platform A with respect to x^A can be written as

$$\frac{\beta_U t_S^2 + t_U(\beta_S t_U - t_S(\alpha_S + \alpha_U + t_S + t_U))}{2\alpha_S \alpha_U - 2(\beta_S - t_S)(\beta_U - t_U)} - 2(t_S + t_U)x^A. \tag{2.20}$$

At the point $x^A = 0$, the expression in (2.20) is positive when the conditions for a market-sharing equilibrium hold, meaning an increasing profit function at this point. One can check that the profits of the two platforms are driven down to zero if they locate at the market center. Solving the function by settign expression (2.20) equal to zero we get the optimal location for platform A. □

Similar as before, as long as the conditions for a market-sharing equilibrium are satisfied, the following relationships always hold:

$$\frac{\partial x^{A^*}}{\partial \alpha_U} = \frac{((\alpha_S + t_S)t_U - (\beta_U t_S))((\alpha_S + t_U)t_S - (\beta_S t_U))}{4(\alpha_S \alpha_U - (\beta_S - t_S)(\beta_U - t_U))^2(t_U + t_S)} > 0,$$

$$\frac{\partial x^{B^*}}{\partial \alpha_U} = -\frac{((\alpha_S + t_S)t_U - (\beta_U t_S))((\alpha_S + t_U)t_S - (\beta_S t_U))}{4(\alpha_S \alpha_U - (\beta_S - t_S)(\beta_U - t_U))^2(t_U + t_S)} < 0.$$

This means that the equilibrium location of platform A is increasing with higher cross-sided network effect on the user side α_U and that of platform B is decreasing in it.

Comparing to the results under mill pricing policy, the tendency of agglomeration holds even with balanced competition under discriminatory delivered pricing. Proposition 2.8 states the comparison between the equilibrium outcome and social welfare.

Proposition 2.8. *Under discriminatory delivered pricing and balanced competition, the socially optimal locations involve the two platforms locating at* $x^A = \frac{1}{4}$ *and* $x^B = \frac{3}{4}$*. What is more, the equilibrium differentiation level is smaller than the social optimum if* $\alpha_U > \tilde{\alpha_U} := \frac{\beta_S\beta_U(t_S+t_U)-(\alpha_S+\beta_S+\beta_U)t_St_U}{t_St_U+\alpha_S(t_S+t_U)}$.

In Appendix H a sketch of proof is provided. The equilibrium as well as socially optimal locations are illustrated in Figure 2.7.

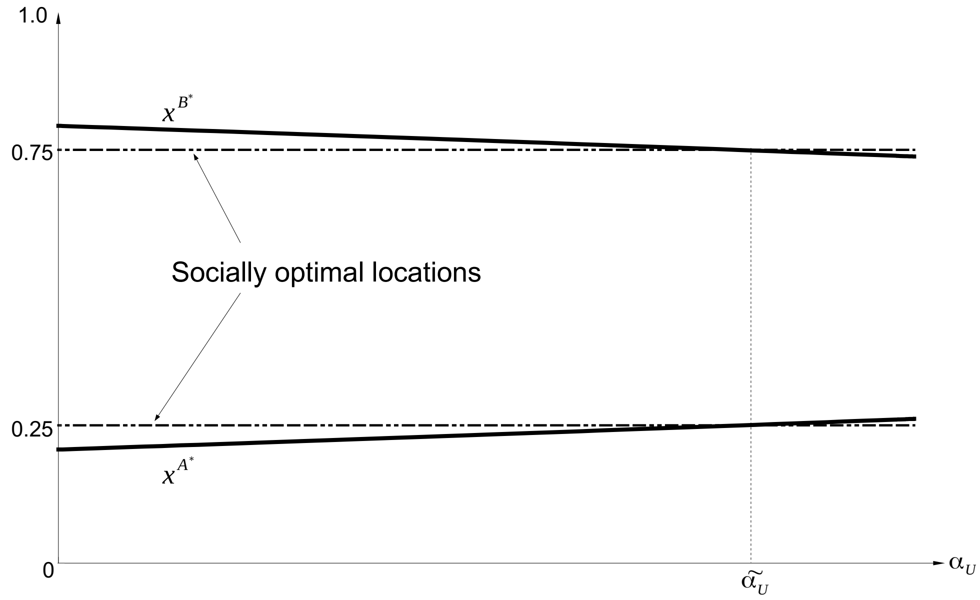

Figure 2.7: Comparison between the equilibrium and socially optimal locations under discriminatory delivered pricing and balanced competition.

2.6 Conclusions and Policy Implications

In this paper, I consider a location-then-price model with both within-sided and cross-sided network effects. By assuming different pricing policies and competition modes, I find that under *mill pricing policy* and *unbalanced competition*, competing platforms are willing to locate less distantly in equilibrium on one side, when there is significant heterogeneity in the valuations of network size among different groups. Given this pricing policy, the *principle of maximum differentiation* still holds under *balanced competition*. With *discriminatory delivered pricing policy*, the tendency of agglomeration emerges in equilibrium under both *unbalanced* and *balanced* competition. This effect becomes increasingly evident when the difference of cross-sided network externalities increases.

Comparing to the socially desirable locations, insufficient differentiation is possible in equilibrium, when the difference of cross-sided network externalities is sufficiently high. This effect is more obvious in unbalanced competition than in balanced competition under mill pricing policy. Because when platforms can select locations on only one side, they can extract more rent from the other side due to the *see-saw effect* as they move towards each other.

These results have important policy implications. First, policy makers should pay special attention to the potentially unbalanced spatial competition among platforms. When platforms voluntarily choose more intense competition on one side, it is possible that the prices on the other sides are too high and the total social welfare is impeded. Second, besides price regulation, balancing the degree of competition on all of the sides should be taken into consideration when making regulating policies, especially when platforms can choose the level of differentiation flexibly. Since a price decrease due to regulation on one side may cause dramatic prices increase on many other sides and this may not be socially optimal. Last but not least, welfare maximizing locations are not sustainable any more under discriminatory delivered pricing policies when network externalities are considered in the model. This deserves some special attention, since it has been shown that there could be insufficient differentiation in the markets with network effects both under balanced and unbalanced competition.

Appendices

A Equilibrium prices given x^A and x^B

Under mill pricing and unbalanced competition, the equilibrium prices given location choices are given by

$$p_U^A = \frac{2\alpha_S^3 + \alpha_S^2 M_1^U + \alpha_S(2\alpha_U^2 + 5\alpha_U\beta_U - M_2 + M_3) + (\beta_U + t_U(x^A - x^B))M_4^U}{M_2 - (2\alpha_S + \alpha_U)(\alpha_S + 2\alpha_U)}$$

$$p_S^A = \frac{2\alpha_U^3 + \alpha_U^2 M_1^S + \alpha_U(2\alpha_S^2 + 5\alpha_S(\beta_S - t_S) - (\beta_S - t_S)M_5) + (\beta_S - t_S)M_4^S}{M_2 - (2\alpha_S + \alpha_U)(\alpha_S + 2\alpha_U)}$$

$$p_U^B = \frac{2\alpha_S^3 + \alpha_S^2 N_1^U + \alpha_S(2\alpha_U^2 + 5\alpha_U\beta_U - M_2 - N_3) + (\beta_U + t_U(x^A - x^B))N_4^U}{M_2 - (2\alpha_S + \alpha_U)(\alpha_S + 2\alpha_U)}$$

$$p_S^B = \frac{2\alpha_U^3 + \alpha_U^2 N_1^S + \alpha_U(2\alpha_S^2 + 5\alpha_S(\beta_S - t_S) - (\beta_S - t_S)N_5) + (\beta_S - t_S)N_4^S}{M_2 - (2\alpha_S + \alpha_U)(\alpha_S + 2\alpha_U)}$$

where $M_1^U = 5\alpha_U + 2\beta_U + t_U(x^A - x^B)(x^A + x^B + 1)$, $M_1^S = 5\alpha_S + 2\beta_S - 2t_S$, $M_2 = 9(\beta_S - t_S)(\beta_U + t_U(x^A - x^B))$, $M_3 = \alpha_U t_U(x^A - x^B)(3 + 2x^A + 2x^B)$, $M_4^U = 2\alpha_U^2 - 3(\beta_S - t_S)(3\beta_U + t_U(x^A - x^B)(x^A + x^B + 2))$, $M_4^S = 2\alpha_S^2 - M_2 + \alpha_S t_U(x^A - x^B)(x^A + x^B - 1)$, $M_5 = 9\beta_U + t_U(x^A - x^B)(x^A + x^B + 8)$ and $N_1^U = 5\alpha_U + 2\beta_U - t_U(x^A - x^B)(x^A + x^B - 3)$, $N_1^S = 5\alpha_S + 2\beta_S - 2t_S$, $N_3 = \alpha_U t_U(x^A - x^B)(2x^A + 2x^B - 7)$, $N_4^U = 2\alpha_U^2 - 3(\beta_S - t_S)(3\beta_U - t_U(x^A - x^B)(x^A + x^B - 4))$, $N_4^S = 2\alpha_S^2 - M_2 - \alpha_S t_U(x^A - x^B)(x^A + x^B - 1)$, $N_5 = 9\beta_U - t_U(x^A - x^B)(x^A + x^B - 10)$.

B Proof of Proposition 2.1

Taking the first derivative of the equilibrium profit of platform A with respect to its location variable x^A and setting $x^A = 0$, $x^B = 1$ we get the following expression

$$\left.\frac{\partial \pi_{M,un}^A}{\partial x^A}\right|_{x^A=0,x^B=1} = \frac{(\alpha_S^2 + \alpha_S(2\alpha_U + \beta_S - t_S) - (\beta_S - t_S)(\alpha_U + 3\beta_U - 3t_U))t_U}{2(9(\beta_S - t_S)(\beta_U - t_U) - (2\alpha_S + \alpha_U)(\alpha_S + 2\alpha_U))}.$$

As long as the conditions for a market-sharing equilibrium hold, the denominator is always positive. The numerator is non-negative if $\alpha_U \geq \alpha_U^* :=$

$\frac{\alpha_S^2+(\beta_S-t_S)(\alpha_S-3(\beta_U-t_U))}{2\alpha_S-\beta_S+t_S}$. This means that if $\alpha_U \geq \alpha_U^*$ is true, the profit of platform A is increasing in x^A at $x^A = 0$. When the two platforms jointly locate at the market center, the first-derivate is given by $\left.\frac{\partial \pi_{M,un}^A}{\partial x^A}\right|_{x^A=\frac{1}{2},x^B=\frac{1}{2}} = -\frac{t_U}{2} < 0$. Given the continuity of the first derivate, the optimal location of platform A must be within $[0, \frac{1}{2}]$ and solves $\frac{\partial \pi_{M,un}^A}{\partial x^A} = 0$. The equilibrium location is actually the smaller root that solves $\frac{\partial \pi_{M,un}^A}{\partial x^A} = 0$. For platform B, the optimal location can be derived in a symmetric manner.

C Proof of Proposition 2.2

Under mill pricing and unbalanced competition, the aggregate consumer surplus $CS_{M,un}$ can be calculated as

$$\begin{aligned} CS_{M,un} = &\int_0^{n_U^A} [v - p_U^A + \alpha_U n_S^A + \beta_U n_U^A - t_U(x - x^A)^2]\, dx \\ &+ \int_{n_U^A}^1 [v - p_U^B + \alpha_U n_S^B + \beta_U n_U^B - t_U(x - x^B)^2]\, dx \\ &+ \int_0^{n_S^A} [v - p_S^A + \alpha_S n_U^A + \beta_S n_S^A - t_S x^2]\, dx \\ &+ \int_{n_S^A}^1 [v - p_S^B + \alpha_S n_U^B + \beta_S n_S^B - t_S(1-x)^2]\, dx. \end{aligned}$$

The social welfare in this scenario is given by $SW_{M,un} = CS_{M,un} + \pi_{M,un}^A + \pi_{M,un}^B$. Taking the first derivate of $SW_{M,un}$ with respect to x^A and assuming that location choices of the two platforms are symmetric in equilibrium we obtain the socially optimal locations: $x^A = \frac{1}{4}$ and $x^B = \frac{3}{4}$.

When $x^A = \frac{1}{4}$ and $x^B = \frac{3}{4}$, the first derivate of the profit of platform A with respect to its location choice can be written as

$$\frac{\partial \pi_{M,un}^A}{\partial x^A} = \frac{(3\alpha_S^2 + 2\alpha_U^2 + \alpha_S(7\alpha_U + \beta_S - t_S) + \alpha_U(t_S - \beta_S) - 6(\beta_S - t_S)(2\beta_U - t_U))t_U}{18(\beta_S - t_S)(2\beta_U - t_U) - 4(2\alpha_S + \alpha_U)(\alpha_S + 2\alpha_U)}.$$

The above expression is non-negative if $\alpha_U \geq \alpha_U^{**}$, where α_U^{**} is the bigger root of $(\alpha_S + 2\alpha_U)(3\alpha_S + \alpha_U) + (\beta_S - t_S)(\alpha_S - \alpha_U - 6(2\beta_U - t_U)) = 0$. The situation of platform B is symmetric to that of platform A. This means that platforms tend to move too close to each other when the cross-sided network effect on the user side is sufficiently high.

D Proof of Proposition 2.3

In this section, the proof of Proposition 2.3 is provided. If the platforms' optimal location choices are $x^A = 0$ and $x^B = 1$, we must have $\frac{\partial \pi^A_{M,ba}}{x^A}\Big|_{x^A=0,x^B=1} \leq 0$ and $\frac{\partial \pi^B_{M,ba}}{x^B}\Big|_{x^A=0,x^B=1} \geq 0$.

Taking first derivative of platform A's equilibrium profit with respect to its location x^A and assuming that platforms locate at different extremes of the agent space, the following expression is obtained:

$$\frac{\alpha_U^2 t_S + \alpha_S^2 t_U - 3\Psi_1 + \alpha_U \Psi_2 + \alpha_S(2\alpha_U(t_S + t_U) - \Psi_2)}{2(9(\beta_S - t_S)(\beta_U - t_U) - (2\alpha_S + \alpha_U)(\alpha_S + 2\alpha_U))}$$

where $\Psi_1 = (\beta_S - t_S)(\beta_U - t_U)(t_S + t_U)$, $\Psi_2 = \beta_U t_S - \beta_S t_U$. The above expression is always non-positive as long as the conditions for a market-sharing equilibrium hold. The equilibrium location of platform B can be proved in a symmetric manner. Therefore, it can be concluded that the equilibrium locations for the two competing platforms are $x^A = 0$ and $x^B = 1$.

E Proof of Proposition 2.4

In this scenario, the total consumer surplus is given by

$$\begin{aligned} CS_{M,ba} = &\int_0^{n_U^A} [v - p_U^A + \alpha_U n_S^A + \beta_U n_U^A - t_U(x - x^A)^2]\, dx \\ &+ \int_{n_U^A}^1 [v - p_U^B + \alpha_U n_S^B + \beta_U n_U^B - t_U(x - x^B)^2]\, dx \\ &+ \int_0^{n_S^A} [v - p_S^A + \alpha_S n_U^A + \beta_S n_S^A - t_S(x - x^A)^2]\, dx \\ &+ \int_{n_S^A}^1 [v - p_S^B + \alpha_S n_U^B + \beta_S n_S^B - t_S(x - x^B)^2]\, dx. \end{aligned}$$

The social welfare is $SW_{M,ba} = CS_{M,ba} + \pi^A_{M,ba} + \pi^B_{M,ba}$. Taking the first derivatives of $SW_{M,ba}$ with respect to x^A and considering only symmetric locations we obtain

$$\frac{\partial SW_{M,ba}}{\partial x^A} = -\frac{1}{4}(t_S + t_U)(4x^A - 1).$$

Setting the above expression equal to zero we get $x^A = \frac{1}{4}$. The socially optimal location of platform B is given by $x^B = \frac{3}{4}$. These are the location configurations that maximizes the social welfare in this scenario.

F Proof of Lemma 2.5 and Lemma 2.6

Under discriminatory delivered pricing, the advantage provided by network size can be considered as a shift of the cost curve of each platform. Taking platform A as an example, one can find out that if the aggregate network size of it is too large, the cost curve of platform B keeps shifting upward until there is no intersection point of the two curves. In that case platform B is driven out of the market completely. Because now platform A is sufficiently efficient such that even the cost of serving the farthest agent ($x = 1$) is lower than that of platform B. To avoid this situation, the increasing part of platform A's cost curve must be strictly lower than that of platform B, which means that the conditions in Lemma 2.5 and Lemma 2.6 must be satisfied.

G Proof of Proposition 2.6

The aggregate consumer surplus is

$$\begin{aligned} CS_{D,un} = &\int_0^{n_U^A} [v - t_U(x^B - x) + \alpha_U n_S^A + \beta_U n_U^A]\, dx \\ &+ \int_{n_U^A}^1 [v - t_U(x - x^A) + \alpha_U n_S^B + \beta_U n_U^B]\, dx \\ &+ \int_0^{n_S^A} [v - t_S(1 - x) + \alpha_S n_U^A + \beta_S n_S^A]\, dx \\ &+ \int_{n_S^A}^1 [v - t_S x + \alpha_S n_U^B + \beta_S n_S^B]\, dx. \end{aligned}$$

Adding up the profits of the two platforms and the consumer surplus we get the social welfare in this scenario: $SW_{D,un} = CS_{D,un} + \pi_{D,un}^A + \pi_{D,un}^B$. The socially optimal locations are still the ones that minimize the total transportation costs, namely $x^A = \frac{1}{4}, x^B = \frac{3}{4}$.

Taking the first derivate of the profit of platform A with respect to its location x^A at the point $x^A = \frac{1}{4}, x^B = \frac{3}{4}$ we get

$$\left.\frac{\partial \pi^A_{D,un}}{\partial x^A}\right|_{x^A=\frac{1}{4},x^B=\frac{3}{4}} = \frac{\alpha_S((\alpha_U + t_S) + \beta_U(t_S - \beta_S))t_U}{2((\beta_S - t_S)(\beta_U - t_U) - \alpha_S\alpha_U)}.$$

The expression above is nonnegative if $\alpha_U \geq \bar{\alpha_U} := \frac{\beta_S\beta_U - (\alpha_S+\beta_U)t_S}{\alpha_S}$, which means that platforms tend to have more intensified competition than the socially optimal level if the cross-sided network effect on the user side is high enough.

H Proof of Proposition 2.8

The aggregate consumer surplus is

$$\begin{aligned} CS_{D,ba} = &\int_0^{n^A_U} [v - t_U(x^B - x) + \alpha_U n^A_S + \beta_U n^A_U]\, dx \\ &+ \int_{n^A_U}^1 [v - t_U(x - x^A) + \alpha_U n^B_S + \beta_U n^B_U]\, dx \\ &+ \int_0^{n^A_S} [v - t_S(x^B - x) + \alpha_S n^A_U + \beta_S n^A_S]\, dx \\ &+ \int_{n^A_S}^1 [v - t_S(x - x^A) + \alpha_S n^B_U + \beta_S n^B_S]\, dx. \end{aligned}$$

The social welfare in this scenario is given by $SW_{D,ba} = CS_{D,ba} + \pi^A_{D,ba} + \pi^B_{D,ba}$. One can check that the optimal locations are still $x^A = \frac{1}{4}, x^B = \frac{3}{4}$.

At the point $x^A = \frac{1}{4}, x^B = \frac{3}{4}$ we have

$$\frac{\partial \pi^A_{D,ba}}{\partial x^A} = \frac{\alpha_U\alpha_S t_S + \beta_S t_S t_U + (\alpha_U + \beta_U)t_S t_U + \alpha_S t_U(\alpha_U + t_S) - \beta_S\beta_U(t_S + t_U)}{2((\beta_S - t_S)(\beta_U - t_U) - \alpha_S\alpha_U)}.$$

The expression above is nonnegative if $\alpha_U \geq \tilde{\alpha_U} := \frac{\beta_S\beta_U(t_S+t_U) - (\alpha_S+\beta_S+\beta_U)t_S t_U}{t_S t_U + \alpha_S(t_S+t_U)}$.

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Chapter 3

Capacity Precommitment and Price Competition — the Case of Inelastic Demand

3.1 Introduction

In this paper, I study a modification of the model in Kreps and Scheinkman (1983) by assuming perfectly inelastic demand. The characterization and efficiency of the equilibrium are studied under both constant and increasing marginal costs of capacity installation. In the analysis of price competition, I provide a full characterization of the Bertrand-Edgeworth price equilibrium given firms' capacity choices. The results mainly show that under any given cost functions, monopoly outcome can always be sustained in equilibrium. While most of the equilibria involve firms choosing their aggregate capacity equal to the market volume, insufficient capacity can also occur in equilibrium.

The paper by Kreps and Scheinkman (1983) implies that the result to an oligopoly game depends not only on the strategic variables which are chosen in the game but also on the timing in which these variables are employed. They introduce a two-stage game in which the firms choose their capacities in the first stage and compete in prices in the second. With a downward-sloping demand function, this two-stage game finally yields Cournot outcome.

The objective of this paper is to introduce a modification of perfectly inelastic demand to the Kreps-Scheinkman model and provide a complete characterization of the equilibrium. As argued in some other literature, the results in Kreps and Scheinkman (1983) are mainly driven by the assumption that demand is rationed *efficiently*. However, Davidson and Deneckere (1986) show that this result may not be true when using some alternative rationing rules, and even *overcapacity* can emerge in equilibrium. By assuming perfectly inelastic demand, the equilibrium outcome does not depend on the rationing rule anymore and we can concentrate on comparing the effect of different capacity installation costs.

The remainer of the paper is organized as follows. In Section 3.2 the related literature will be discussed. In Section 3.3, I introduce the basic setup of the model. Section 3.4 provide the analysis with constant marginal capacity installation cost. The model with increasing marginal installation cost is discussed in Section 3.5. Finally, the conclusions and interpretation of the results are provided in Section 3.6.

3.2 Literature

My study mainly builds on the work by Kreps and Scheinkman (1983), in which the authors show that the two-stage game finally yields the unique Cournot outcome, with the demand allocated as the *efficient* rationing rule. However, Davidson and Deneckere (1986) argue that this result is not robust when using alternative rationing rules, and excessive capacity and asymmetric equilibrium are also possible. While Madden (1998) proves that the problem regarding the rationing rules studied by Davidson and Deneckere (1986) vanishes and the Cournot outcome is restored, if the demand is assumed to be uniformly elastic and all the costs are sunk before price competition. Instead of modeling a Bertrand-like price competition in the second stage, Moreno and Ubeda (2006) prove that the Cournot equilibrium prevails if firms set a reservation price after building their capacities. What is more, the robustness of Kreps-Scheinkman results also prevails to some extent under demand uncertainty. For example, Lepore (2012) establishes a model in which firms build their capacities before the state of demand is realized. The author proves that the Cournot outcome can emerge under certain conditions of the demand distribution. As a commitment device, capacity commitment is also proved as a barrier to entry. For example, Allen et al. (2000) provide another kind of modification in which firms (incumbents and entrants) make capacity decisions sequentially and compete in price simultaneously afterwards. In such a model, capacity precommitment can serve as entry deterrence and the incumbent may even find it optimal to hold excessive capacity in order to prevent the entrant from choosing a large capacity. While the Kreps-Scheinkman model assumes symmetric production costs for firms, Deneckere and Kovenock (1996) show that Cournot outcome may not emerge in equilibrium when firms have asymmetric production costs. Especially, there may be only mixed-strategy capacity equilibrium when the cost for capacity is significant.

Some related results with constant marginal capacity installation cost have been found also by Acemoglu et al. (2009) and De Frutos and Fabra (2011). Acemoglu et al. (2009) characterize the equilibria in a similar game with potentially asymmetric linear capacity installation cost. They characterize a continuum of pure-strategy equilibria in the capacity stage by proving their sufficiency and necessity. Differently, my approach in the first stage is to fully characterize the profit functions and the best responses given the capacity decisions of their competitors. They also investigate the difference in efficiency among the equilibria by distinguishing *Price of Anarchy* and *Price of Stability.* De Frutos and Fabra (2011) also study a similar capacity-then-price game with perfectly inelastic demand. They focus on the effect of demand uncertainty on the potentially asymmetric market outcomes. As a benchmark situation, a two-player model with deterministic demand is first discussed without providing a full characterization of the price competition in the second stage.

An essential part in the analysis in this paper is that, within a certain range of capacity choices, firms engage in a Bertrand-Edgeworth competion (see Edgeworth (1925)) and adjust their prices randomly within a specific price interval. With a downward-sloping demand, De Francesco and Salvadori (2009) generalize the features of mixed-strategy price equilibrium under duopoly to oligopoly and provide a full characterization for triopoly market. (See also De Francesco and Salvadori (2022)). Compte et al. (2002) study the Bertrand-Edgeworth price competition with n firms and examine the relationship between the asymmetry in capacity distributions and tacit collusion. Hirata (2009) also studies the characterization of the mixed-strategy price equilibrium given different capacities of firms and applies the results to merger analysis. Deneckere and Kovenock (1992) study a game of price leadership with capacity constraints. Interestingly, when the capacity configurations lead to no pure-strategy equilibrium in the simultaneous game, the large firm can become price leader by endogenous timing choices with *efficient* rationing rule. Furth and Kovenock (1993) further prove that an endogenously determined price leader can emerge with differentiated products within a certain range of capacity constraints. By varying firms excess capacity, Fonseca and Normann (2008) test the influence of different capacities on price behaviors in a repeated Bertrand-Edgeworth setting in a laboratory experiment. They show that increasing capacity levels indeed impose downward pressure on average market prices. However, the decline in prices is less pronounced than theoretical prediction.

3.3 The Model

Consider the Kreps-Scheinkman model with perfectly inelastic demand. There are M consumers and each of them is to buy one unit of goods as long as the price does not exceed their reservation price p^m, which is also the monopoly price in this game. There are two firms in the market. Consumers, at first, buy from the firm with the lowest price. After the capacity of this firm is exhausted, they switch to the other firm. The equilibrium concept used in this model is subgame-perfect Nash equilibrium.

As for the timing, it is specified as: In the first stage, firms make their capacity decisions and production takes place. The capacity decisions of the firms are denoted by x_i ($i \in \{1, 2\}$), which can be observed at the coming stage. Without loss of generality, it is assumed that $x_1 \leq x_2$. For simplicity, production cost is assumed to be zero. But there is still capacity installation cost for the firms, which is denoted by $C(x_i)$, $C(0) = 0$, with the condition $\frac{\partial C(x_i)}{\partial x_i} \geq 0$. In the second stage, firms initiate their competition in price, and their prices are denoted by p_i. Following the setup in Kreps and Scheinkman (1983), the demand of a firm is specified as follows: If $p_1 < p_2$, firm 1's demand is

$$s_1 = \min(x_1, M). \tag{3.1}$$

This equation represents that the firm with the lower price can sell its whole capacity as long as it does not exceed the market volume. In this situation, firm 2's demand is

$$s_2 = \min(x_2, \max(M - x_1, 0)). \tag{3.2}$$

Here the term $M - x_1$ is the residual demand in the market. Since firm 2 has a higher price, the demand of it must be related to the residual demand, in other words, related to the capacity of its rival. The equations take a symmetric form if $p_1 > p_2$. If $p_1 = p_2 = p$, the demand of firm i is

$$s_i = \min(x_i, \frac{M}{2} + \max(0, \frac{M}{2} - x_j)) = \min(x_i, \max(\frac{M}{2}, M - x_j)). \tag{3.3}$$

In all the above mentioned situations, the profit for firm i is $\pi_i = p_i s_i - C(x_i)$.

I analyze the model with two types of capacity installation costs here. First is the situation with constant marginal capacity installation cost. Here I mainly discuss the case in which the marginal cost is positive. The model with zero marginal cost is analyzed as a subcase of it. On top of that, the model with increasing marginal capacity installation cost is also to be discussed.

3.4 Constant Marginal Capacity Installation Cost

In this section, I discuss the model with constant capacity installation cost. I mainly analyze the influence of positive (constant) capacity installation cost on firms' best responses. Then a subcase with zero marginal capacity installation cost will be briefly discussed.

3.4.1 Positive (constant) marginal capacity installation cost

In this case, a constant cost $c > 0$ exists for each unit of capacity installed. In the second stage, firms engage in a Bertrand-like price competition and, given firms' capacity decisions, three cases are discussed. Then, I analyze firms' best responses in the capacity setting stage.

3.4.1.1 Price competition

With the fact that, the profits generated for the firms depend on x_1 and x_2, three forms of price competition are analyzed here. Table 3.1 contains a summary of all the cases of price competition.

Case 1.1	Case 1.2	Case 1.3 (a)	Case 1.3 (b)
$x_1 \geq M$ $x_2 \geq M$	$x_1 + x_2 \leq M$	$x_i < M$, $x_1 + x_2 > M$	$x_1 < M$, $x_2 \geq M$

Table 3.1: Summary of price competition in the second stage.

Case 1.1. $x_1 \geq M$ and $x_2 \geq M$. First, the view is on the case, where both firms choose enough large capacities that can cover the entire market.

This makes it the same situation as the standard Bertrand competition without capacity constraints. The subgame equilibrium in this case is $p_i = 0$, $s_i = \frac{M}{2}$, and $\pi_i = -cx_i$.

Case 1.2. In this case, we have $x_1 + x_2 \leq M$. Hence the competition is absent and both firms can set the monopoly price $p_1 = p_2 = p^m$ and sell $s_1 = x_1$, $s_2 = x_2$. The profit of firm i is $\pi_i = (p^m - c)x_i$.

Case 1.3(a). In this case, we have $x_i < M$, $x_1 + x_2 > M$. While the total capacity of the two firms exceeds the market volume, neither of them can satisfy the whole market all by itself. This is the case of the known Bertrand-Edgeworth game (see Tirole (1988), pp. 211-212). Since no pure-strategy price equilibrium exists here, only the mixed-strategy equilibrium remains, namely the case where firms set prices randomly from the interval $[\underline{p}, p^m]$. In a mixed-strategy Nash equilibrium, firm 2 is indifferent between setting the highest and lowest price and therefore we have

$$(\underline{p} - c)x_i = p^m(M - x_j) - cx_i. \tag{3.4}$$

Given $x_1 \leq x_2$ and solving this equation for $\underline{p}$ we get $\underline{p}(x_2 < M) = \frac{p^m(M-x_1)}{x_2}$, which is the infimum of the price interval. The expected profit of each firm is given by

$$\pi_1 = \frac{p^m(M - x_1)x_1}{x_2} - cx_1 \tag{3.5}$$

and

$$\pi_2 = p^m(M - x_1) - cx_2. \tag{3.6}$$

Let $G_i(p)$ denote the probability that firm i charges the price no higher than p. We have

$$p[G_1(p)(M - x_1) + (1 - G_1(p))x_2] = p^m(M - x_1), \tag{3.7}$$

so,

$$G_1(p) = \begin{cases} 0, & \text{if } p < \underline{p}(x_2 < M) \\ \frac{p^m(M-x_1)-px_2}{p(M-x_1-x_2)}, & \text{if } \underline{p}(x_2 < M) \leq p \leq p^m \\ 1, & \text{if } p > p^m. \end{cases} \tag{3.8}$$

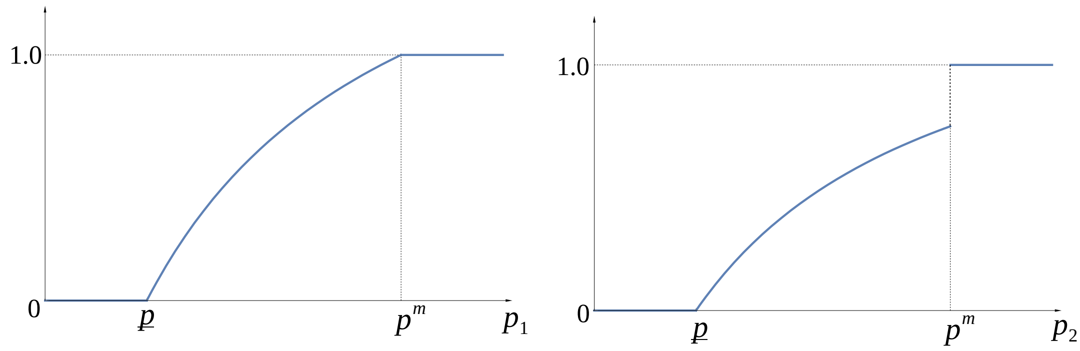
And for firm 2 we have

$$p[G_2(p)(M - x_2) + (1 - G_2(p))x_1] = \frac{p^m(M - x_1)x_1}{x_2}, \tag{3.9}$$

therefore

$$G_2(p) = \begin{cases} 0, & \textit{if } p < \underline{p}(x_2 < M) \\ \frac{x_1(p^m(M-x_1)-px_2)}{px_2(M-x_1-x_2)}, & \textit{if } \underline{p}(x_2 < M) \leq p \leq p^m \\ 1, & \textit{if } p > p^m. \end{cases} \tag{3.10}$$

The cumulative distribution functions are shown in Figure 3.1a and 3.1b. It is clear that the distribution function G_2 has a mass at p^m.



(a) The distribution function G_1. (b) The distribution function G_2.

Figure 3.1: The distribution functions of prices in Case 1.3 (a).

Case 1.3 (b). In this case, we have $x_1 < M$, and $x_2 \geq M$. The price competition takes the similar form as before. Even so, the infimum of price interval as well as the profits are similar as that in *Case 1.3(a)* except that x_2 should be replaced by M in the analysis. As shown before, the lower bound of the price interval must make firm 2 indifferent between getting the residual demand and serving the whole market. So, we have

$$\underline{p}(x_2 \geq M) = \frac{p^m(M - x_1)}{M}. \tag{3.11}$$

The expected profits of the two firms are

$$\pi_1 = p^m(M - x_1)\frac{x_1}{M} - cx_1 \tag{3.12}$$

and

$$\pi_2 = p^m(M - x_1) - cx_2. \tag{3.13}$$

In this case, the cumulative distribution functions are

$$G_1^b(p) = \begin{cases} 0, & \textit{if } p < \underline{p}(x_2 \geq M) \\ \frac{Mp - p^m(M - x_1)}{px_1}, & \textit{if } \underline{p}(x_2 \geq M) \leq p \leq p^m \\ 1, & \textit{if } p > p^m. \end{cases} \tag{3.14}$$

$$G_2^b(p) = \begin{cases} 0, & \textit{if } p < \underline{p}(x_2 \geq M) \\ \frac{Mp - p^m(M - x_1)}{pM}, & \textit{if } \underline{p}(x_2 \geq M) \leq p \leq p^m \\ 1, & \textit{if } p > p^m. \end{cases} \tag{3.15}$$

The distributions have the same patterns as in Figure 3.1a and 3.1b.

3.4.1.2 Capacity decisions

In this part, I discuss the best responses of firms in the first stage. Taking the price comptition into consideration, four different scenarios are considered here.

Scenario 1.1: $x_j \geq M$**.** If firm j's capacity is larger than the market volume, the profit of firm i is given by

$$\pi_i = \begin{cases} \frac{p^m(M - x_i)x_i}{M} - cx_i, & \textit{if } 0 < x_i < M \\ \\ -cx_i, & \textit{if } x_i \geq M. \end{cases} \tag{3.16}$$

Here, the profit of firm i depends only on its own capacity. If firm i also chooses a capacity level higher than the whole market, negative profit is left for it as analyzed in *Case 1.1.* Otherwise, if $x_i < M$, the game is as shown in *Case 1.3 (b)*, generating a profit as in equation (3.13) for firm i. The profit is shown in Figure 3.2. Here, the best response of firm i is to choose a capacity level which satisfies the first-order condition $\frac{\partial \pi_i(x_j \geq M)}{\partial x_i} = 0$. So, the optimal capacity of firm

i is

$$x_i = \frac{(p^m - c)M}{2p^m}. \tag{3.17}$$

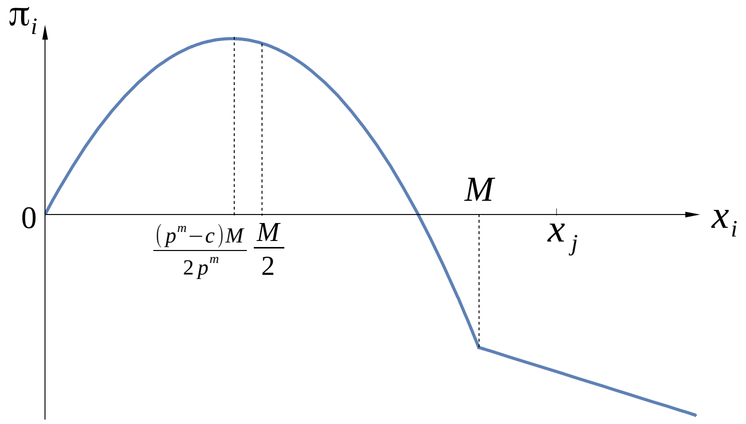


Figure 3.2: The profit of firm i in Scenario 1.1.

Scenario 1.2: $\frac{Mp^m}{2p^m-c} < x_j < M$. In this scenario, firm i's profit can be summarized as

$$\pi_i = \begin{cases} (p^m - c)x_i, & \textit{if } 0 < x_i \le M - x_j \\ \frac{p^m(M-x_i)x_i}{x_j} - cx_i, & \textit{if } M - x_j < x_i \le x_j \\ p^m(M - x_j) - cx_i, & \textit{if } x_i > x_j. \end{cases} \tag{3.18}$$

Here, firm j's capacity alone is unable to serve all the consumers in the market. If firm i chooses $x_i \ge x_j$, the market is completely covered and firm i can always expect its profit to be positive, even if it sets the highest price in the market. Its profit in this case is given by $\pi_i = p^m(M - x_j) - cx_i$. By choosing $M - x_j \le x_i < x_j$, the situation is as shown in *Case 1.3(a)* and firm i has a concave profit function in this interval with a unique maximum point. The first-order condition yields $x_i = \frac{p^m M - cx_j}{2p^m}$. If $x_i < M - x_j$, the subgame of the second stage is down to the monopoly case (*Case 1.2*) and firm i's profit, which is given by $\pi_i = (p^m - c)x_i$, increases with higher capacity. The profit of firm i is illustrated in Figure 3.3. The best response of firm i is to choose $x_i = \frac{p^m M - cx_j}{2p^m}$.

Scenario 1.3: $\frac{M}{2} < x_j \le \frac{Mp^m}{2p^m-c}$. The profit of firm i has the identical expression as in (3.18). The difference between the profit here and that in *Sce-*

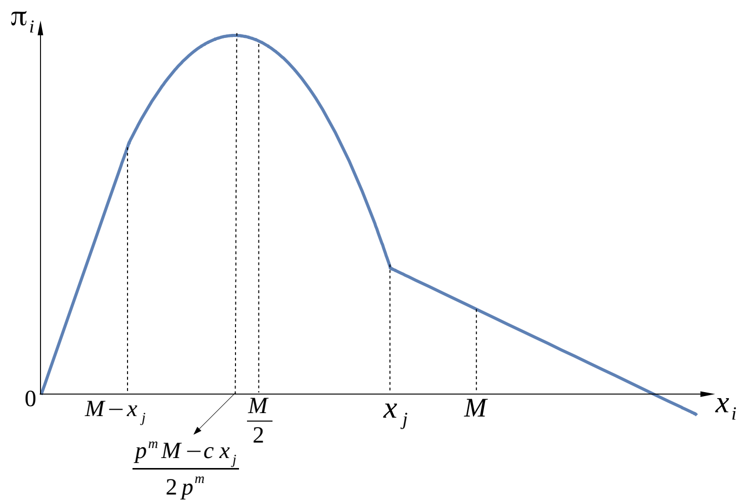


Figure 3.3: The profit of firm i in Scenario 1.2.

nario 1.2 is that $M - x_j > \frac{p^m M - cx_j}{2p^m}$ is true. This implies that the quadratic part of the profit curve is strictly decreasing and the best response in this situation is $x_i = M - x_j$. Figure 3.4 shows the profit of firm i in this scenario.

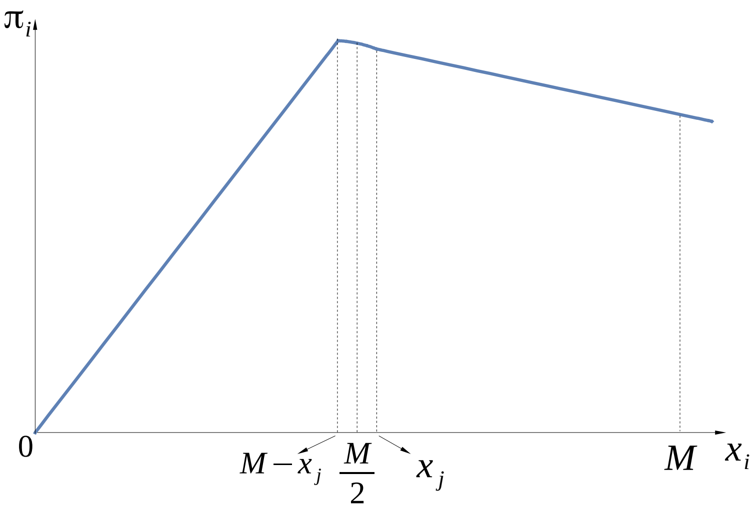


Figure 3.4: The profit of firm i in Scenario 1.3.

Scenario 1.4: $0 \le x_j \le \frac{M}{2}$**.** In this scenario, firm i's profit is given by

$$\pi_i = \begin{cases} (p^m - c)x_i, & \textit{if } 0 < x_i \le M - x_j \\ \\ p^m(M - x_j) - cx_i, & \textit{if } x_i > M - x_j. \end{cases} \tag{3.19}$$

As shown in Figure 3.5, the best response of firm i is $x_i = M - x_j$.

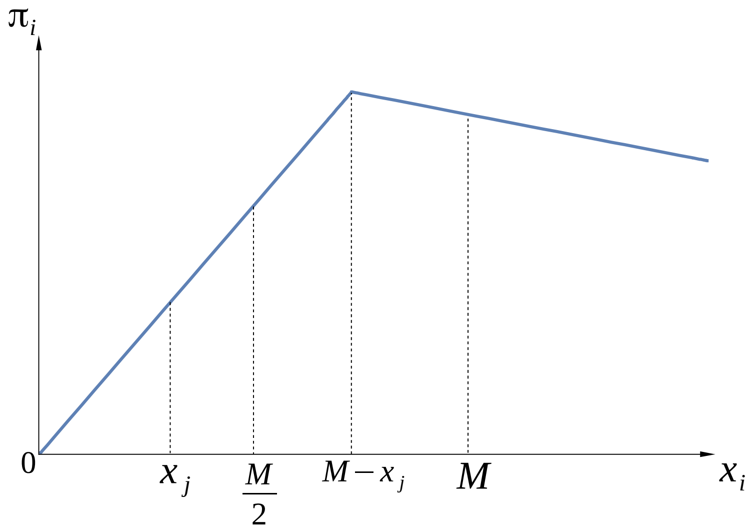


Figure 3.5: The profit of firm i in Scenario 1.4.

So far, all the scenarios in the capacity stage have been analyzed. Proposition 3.1 summarizes the equilibrium in the full game.

Proposition 3.1. *In the game with positive (constant) marginal cost of capacity installation, the subgame-perfect equilibrium involves firms choosing their capacities which satisfy*

$$x_1 + x_2 = M,$$
$$x_i \in [\frac{M(p^m - c)}{2p^m - c}, \frac{Mp^m}{2p^m - c}], \; i \in \{1, 2\}.$$

Firms set $p_i = p^m$ *in equilibrium and the complete best responses in the second stage are as in section 3.4.1.1.*

Proof. Summarizing the analysis above we get the best responses of firm i:

$$BR_i(x_j) = \begin{cases} M - x_j, & \textit{if } 0 < x_j \leq \frac{Mp^m}{2p^m - c} \\ \frac{p^m M - cx_j}{2p^m}, & \textit{if } \frac{Mp^m}{2p^m - c} < x_j < M \\ \frac{(p^m - c)M}{2p^m}, & \textit{if } x_j \geq M. \end{cases} \tag{3.20}$$

Figure 3.6 illustrates the best response functions. Solving the best response functions simultaneously we get the continuum of equilibria. □

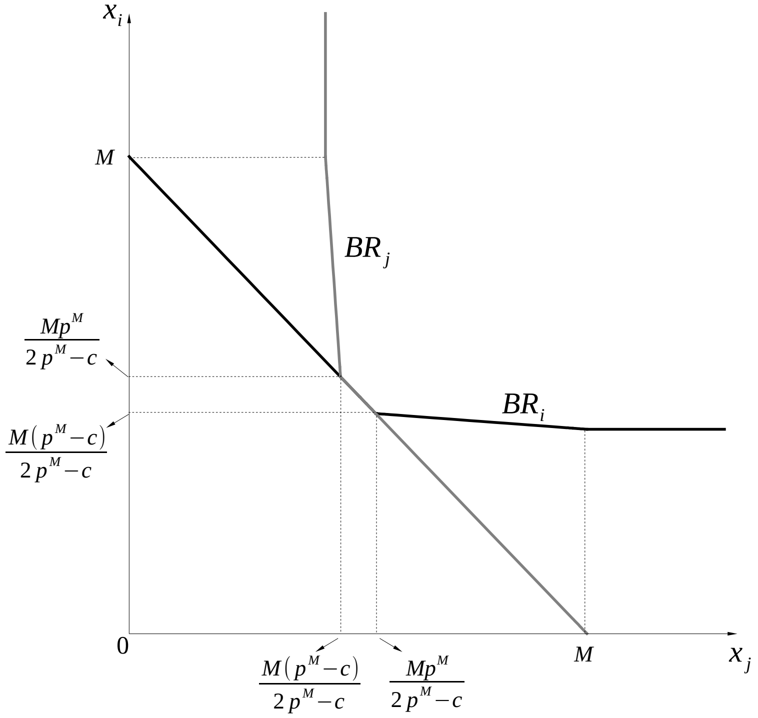


Figure 3.6: The best responses and the equilibrium capacities with positive (constant) marginal capacity installation cost.

Given the best responses, the game has infinitely many equilibria in pure strategies. This equilibrium outcome provides several implications. First, in equilibrium, firms are willing to choose their capacities equal to the residual demand, since holding excessive capacity is a pure loss and is harmful to their profits. In addition, the length of the overlapping part in Figure 3.6 depends on the level of cost c. The higher c is, the longer is the overlapping part and firms are thus more willing to take the residual demand. For example, when c is slightly higher than 0, the best response functions have a unique intersection point. If $c = p^m$, firm i chooses $x_i = M - x_j$ as long as $x_j < M$ and 0 if $x_j \geq M$. What is more, asymmetric capacities are possible in equilibrium. The market is always fully covered and the sum of firms' profits equals the monopoly profit, despite of this asymmetry. It is worthwhile to notice that the asymmetry among equilibria does not affect their efficiency.

3.4.2 Zero marginal capacity installation cost

In this case, the marginal capacity installation cost is assumed to be zero. With this assumption, the analysis shows that there is a unique symmetric equilibrium, in which firms share the market equally, as well as asymmetric equilibria, in which the total capacity is higher than M.

3.4.2.1 Price competition

Similar as the analysis before, three cases in the stage of price competition are discussed here.

Case 2.1. $x_1 \geq M$ and $x_2 \geq M$. This is the case of perfect competition and firms set $p_1 = p_2 = 0$ and obtain $\pi_1 = \pi_2 = 0$.

Case 2.2. $x_1 + x_2 \leq M$. Firms charge $p_i = p^m$ and make a profit of $\pi_i = p^m x_i$.

Case 2.3 (a). $x_i < M$, $x_1 + x_2 > M$. In this case, firms set prices randomly from the interval $[\underline{p}, p^m]$.

$$\underline{p}(x_2 < M) = \frac{p^m(M - x_1)}{x_2} \tag{3.21}$$

is the infimum of the price interval. The expected profit of each firm is given by

$$\pi_1 = p^m(M - x_1)\frac{x_1}{x_2}, \tag{3.22}$$

$$\pi_2 = p^m(M - x_1). \tag{3.23}$$

Case 2.3 (b). $x_1 < M$, and $x_2 \geq M$. Here, the lower bound of the price interval is

$$\underline{p}(x_2 \geq M) = \frac{p^m(M - x_1)}{M}. \tag{3.24}$$

The expected profit function of firm 2 is the same as in (3.23), and that of firm 1 is given by

$$\pi_1 = p^m(M - x_1)\frac{x_1}{M}. \tag{3.25}$$

3.4.2.2 Capacity decisions

In the analysis of firms' capacity decisions, three different scenarios are considered.

Scenario 2.1: $x_j \geq M$**.** In this scenario, the expected profit of firm i is

$$\pi_i = \begin{cases} \frac{p^m(M-x_i)x_i}{M}, & \textit{if } 0 < x_i < M \\ \\ 0, & \textit{if } x_i \geq M. \end{cases} \tag{3.26}$$

Figure 3.7 shows the relationship between x_i and π_i in this scenario. The first-order condition yields $x_i = \frac{M}{2}$. If $x_j \geq M$, firm i will choose $x_i = \frac{M}{2}$ as best response.

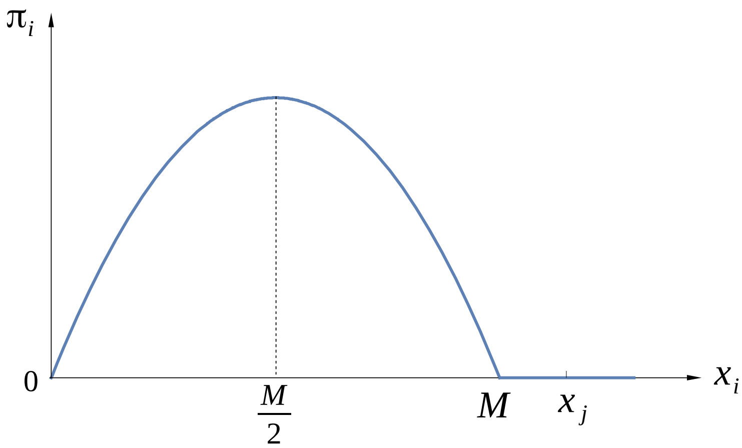


Figure 3.7: The profit of firm i in Scenario 2.1.

Scenario 2.2: $\frac{M}{2} \leq x_j < M$. In this scenario, firm i's expected profit is

$$\pi_i = \begin{cases} p^m x_i, & \textit{if } 0 < x_i < M - x_j \\ p^m (M - x_1)\frac{x_1}{x_2}, & \textit{if } M - x_j \leq x_i < x_j \\ p^m (M - x_j), & \textit{if } x_i \geq x_j. \end{cases} \tag{3.27}$$

The complete relationship between x_i and π_i in this scenario is shown in Figure 3.8. The first-order condition yields $x_i = \frac{M}{2}$. As illustrated, it is optimal for firm i to set $x_i = \frac{M}{2}$.

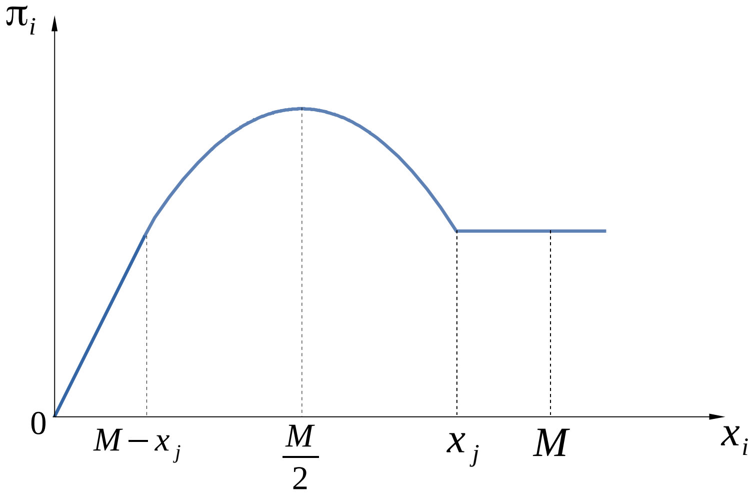


Figure 3.8: The profit of firm i in Scenario 2.2.

Scenario 2.3: $0 \leq x_j < \frac{M}{2}$. The expected profit of firm i is

$$\pi_i = \begin{cases} p^m x_i, & \textit{if } 0 < x_i < M - x_j \\ \\ p^m (M - x_j), & \textit{if } x_i \geq M - x_j. \end{cases} \tag{3.28}$$

As shown is Figure 3.9, the best response is $x_i \geq M - x_j$.

So far all the best responses of firm i have been discussed. The situation is symmetric for firm j. The complete best response for firm i and the equilibrium are summarized as follows:

Lemma 3.1. *When the marginal cost of capacity installation is normalized to*

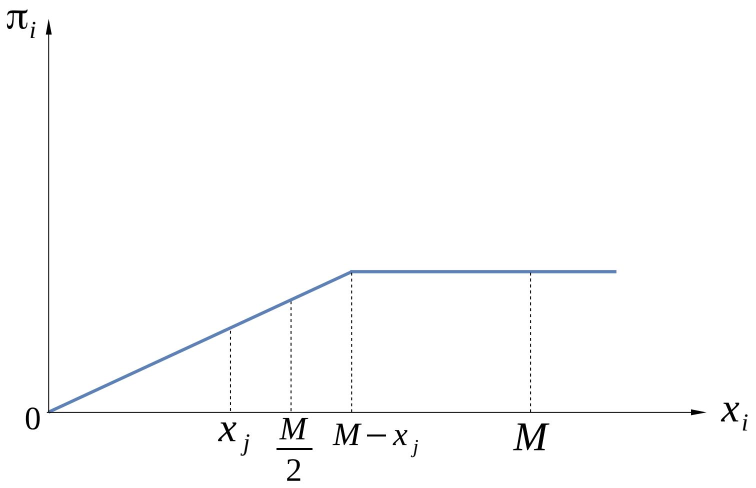


Figure 3.9: The profit of firm i in Scenario 2.3.

zero, the best response of firm i is

$$BR_i(x_j)\begin{cases} x_i \geq M - x_j, & \text{if } 0 \leq x_j < \frac{M}{2} \\ \\ x_i = \frac{M}{2}, & \text{if } x_j \geq \frac{M}{2}. \end{cases} \tag{3.29}$$

Proposition 3.2. *With zero marginal capacity installation cost, the subgame-perfect equilibrium involves $\{x_i = \frac{M}{2},\ x_j \geq \frac{M}{2}\}$, $i, j = 1, 2$, $i \neq j$, with the complete price best responses as in section 3.4.2.1.*

Proof. Figure 3.10 illustrates the best reply functions of the two firms. We can find out that the equilibrium capacities are $\{x_i = \frac{M}{2},\ x_j \geq \frac{M}{2}\}$. □

Corollary 3.1. *In the game with zero marginal capacity installation cost, the only capacity equilibrium in which firms' joint profit is maximized is $\{x_1 = \frac{M}{2}, x_2 = \frac{M}{2}\}$.*

In this game, there are infinitely many equilibria. Since zero capacity installation cost is assumed here, excessive capacity is possible in equilibrium. The only symmetric capacity equilibrium here is $\{x_1 = \frac{M}{2}, x_2 = \frac{M}{2}\}$ and this is Pareto efficient from the firms' perspective, i.e., firms' joint profit is maximized in this equilibrium. Only in this equilibrium, the monopoly outcome is sustained as firms set $p_1 = p_2 = p^m$. For other asymmetric equilibria, the expected

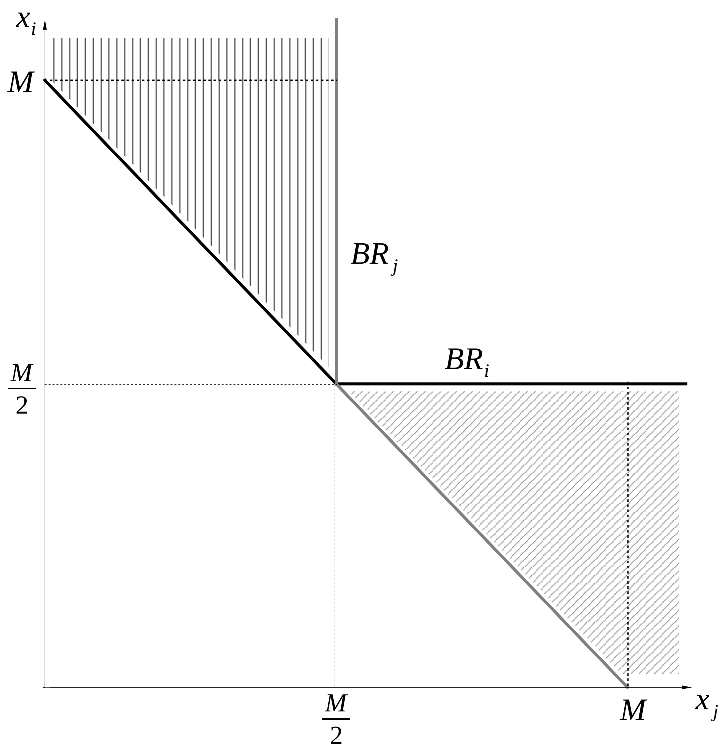


Figure 3.10: The best reply functions and the equilibrium with zero marginal capacity installation cost.

profit for the larger firm is the same as that in the symmetric one, because the residual demand is always $\frac{M}{2}$. The smaller firm, however, is worse off. It gets an expected profit as shown in equation (3.22) or (3.25), which are strictly smaller than the monopoly profit.[1] Note that these equilibria are equally efficient from the perspective of social welfare.

3.5 Increasing Marginal Capacity Installation Cost

With positive (constant) marginal capacity installation cost, infinitely many equilibria are found in the two-stage game and firms are, to some extend, willing to take the residual demand in order to avoid competition. Therefore, asym-

[1]Those asymmetric equilibria can be considered as *Spiteful equilibria*. Because one firm can deviate from the symmetric equilibrium by increasing its capacity in order to squeeze out some profit of its rival. See Saijo and Nakamura (1995) and Wobker (2015).

metric capacities are possible in equilibrium. However, this asymmetric result may be driven by the assumption of constant marginal installation cost. If it is the case, firms may not have incentive to choose a relatively high capacity and compete aggressively with increasing marginal installation cost. Therefore, the model with increasing marginal capacity installation cost is assumed in this section. Same basic setup is taken as before and the capacity installation cost is assumed to be $C(x_i) = \frac{1}{2}\hat{c}x_i^2$. Two different situations are discussed in this section. The first is the situation of *full market coverage*, in which the marginal cost is sufficiently low (or the market volume is sufficiently small) and all the consumers will be served in equilibrium. The second situation refers to *partial market coverage*, in which only a fraction of consumers will be served as the installation cost is too high to have the marginal consumer attended.

3.5.1 Full market coverage

The first situation studied here is *full market coverage*. The most important assumption imposed under this situation is that the parameter of marginal installation cost satisfies $\hat{c} < \frac{2p^m}{M}$.

The procedure of analyzing price competition is similar as before (see Table 3.1). Given the capacity decisions of firms, three different forms of price competition will be considered: the case of perfect competition, monopoly competition and Bertrand-Edgeworth competition. Taking the different price competition forms into consideration, five scenarios of capacity decisions will be analyzed.

Scenario 3.1 $x_j \geq M$. In this scenario, the profit of firm i is given by

$$\pi_i(x_j \geq M) = \begin{cases} \frac{p^m(M-x_i)x_i}{M} - \frac{1}{2}\hat{c}x_i^2, & \textit{if } 0 < x_i < M \\ \\ -\frac{1}{2}\hat{c}x_i^2, & \textit{if } x_i \geq M. \end{cases} \tag{3.30}$$

Figure 3.11 shows how firm i's profit changes with its capacity. The optimal capacity satisfies the first-order condition of the first part of the profit function and is given by

$$x_i = \frac{Mp^m}{\hat{c}M + 2p^m}.$$

Note that the optimal capacity here is still smaller than $\frac{M}{2}$ and the value is constant.

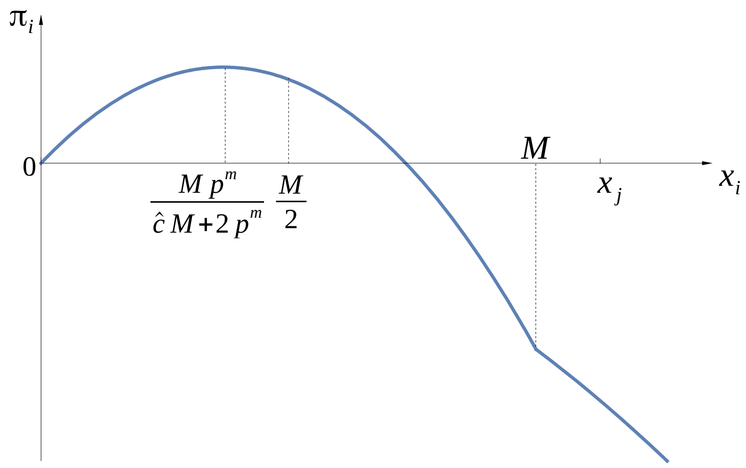


Figure 3.11: The profit of firm i in Scenario 3.1.

Scenario 3.2 $\hat{x} < x_j < M$, where $\hat{x} = \frac{\hat{c}M - 2p^m + \sqrt{\hat{c}^2 M^2 + 4(p^m)^2}}{2\hat{c}}$. In this scenario, the profit of firm i is

$$\pi_i(\hat{x} < x_j < M) = \begin{cases} p^m x_i - \frac{1}{2}\hat{c}x_i^2, & \textit{if } 0 < x_i \leq M - x_j \\ \frac{p^m(M - x_i)x_i}{x_j} - \frac{1}{2}\hat{c}x_i^2, & \textit{if } M - x_j < x_i \leq x_j \\ p^m(M - x_j) - \frac{1}{2}\hat{c}x_i^2, & \textit{if } x_i > x_j. \end{cases} \tag{3.31}$$

The profit of firm i is shown in Figure 3.12. The optimal capacity solves the first-order condition in the second part of the profit function, and is given by

$$x_i = \frac{Mp^m}{\hat{c}x_j + 2p^m}.$$

Scenario 3.3 $\frac{M}{2} < x_j \leq \hat{x}$**.** In this scenario, the profit function of firm i is the same as in Equation (3.31), but the curve exhibits itself slightly different from the previous one. Figure 3.13 shows the profit curve of firm i. Since x_j is relatively smaller than that in the previous scenario, the best response of firm i is to take the residual demand and set $x_i = M - x_j$.

Scenario 3.4 $M - \frac{p^m}{\hat{c}} < x_j \leq \frac{M}{2}$**.** The profit of firm i in this scenario can

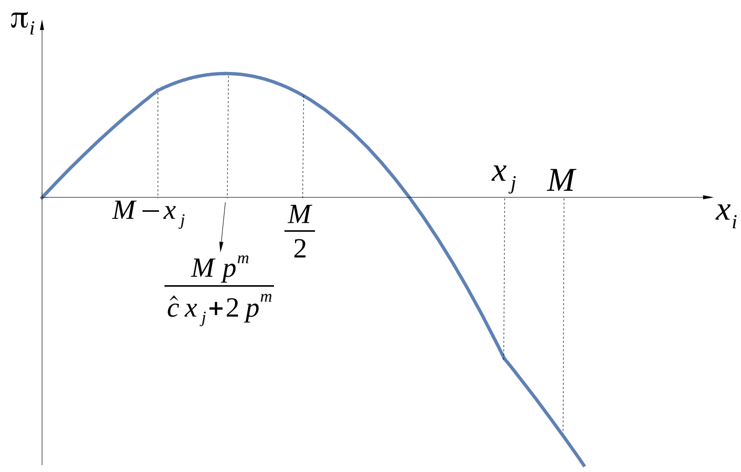


Figure 3.12: The profit of firm i in Scenario 3.2.

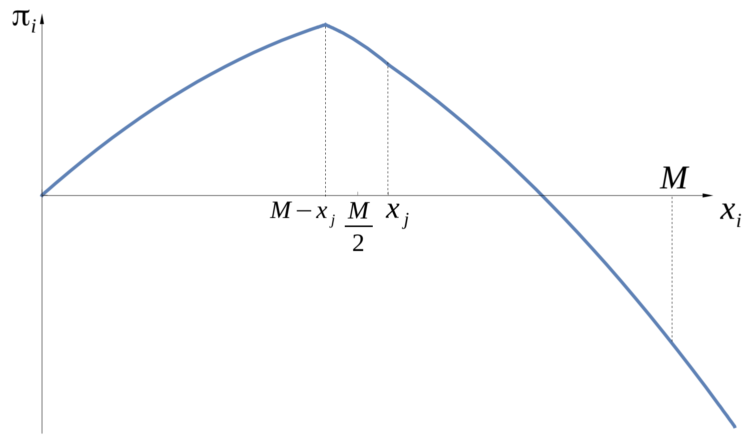


Figure 3.13: The profit of firm i in Scenario 3.3.

be summarized as follows:

$$\pi_i(M - \frac{p^m}{\hat{c}} < x_j \leq \frac{M}{2}) = \begin{cases} p^m x_i - \frac{1}{2}\hat{c}x_i^2, & \textit{if } 0 < x_i \leq M - x_j \\ \\ p^m(M - x_j) - \frac{1}{2}\hat{c}x_i^2, & \textit{if } x_i > M - x_j. \end{cases} \tag{3.32}$$

The profit curve is shown in Figure 3.14. In this scenario, since x_j is still relatively small, the best response of firm i is still to take the rest of the market and set $x_i = M - x_j$.

Scenario 3.5 $x_j \leq M - \frac{p^m}{\hat{c}}$**.** The profit function of firm i has the identical

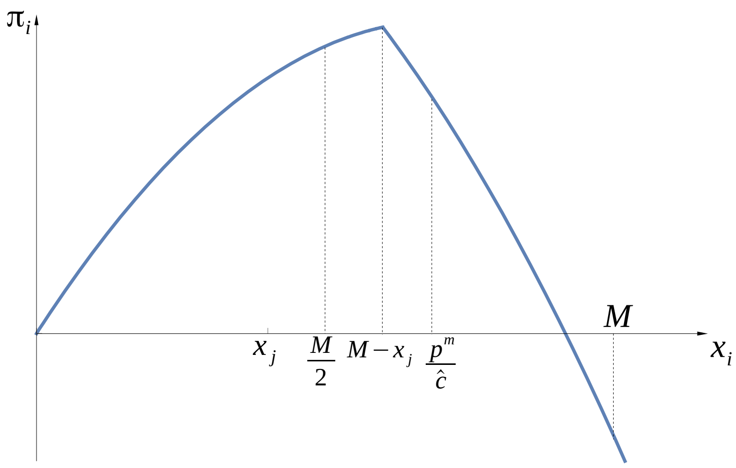


Figure 3.14: The profit of firm i in Scenario 3.4.

expression as that in *Scenario 3.4*. However, the profit curve, which is illustrated in Figure 3.15, is slightly different from the previous one. Since x_j is too small in this scenario, firm i has no incentive to take the residual demand as the installation cost would be too high at the margin. Therefore, the best response of firm i in this scenario is constant and is given by $x_i = \frac{p^m}{\hat{c}}$. This is the optimal capacity which a monopolist would choose in the market.

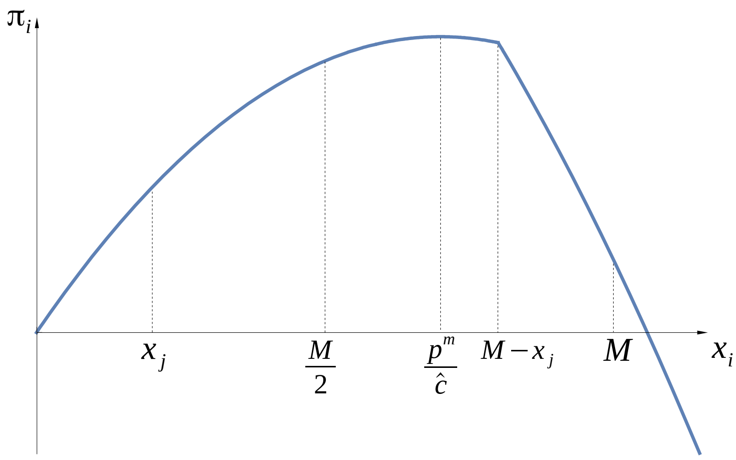


Figure 3.15: The profit of firm i in Scenario 3.5.

So far, all the best response functions of firm i have been characterized. The next lemma summarizes the best response of firm i.

Lemma 3.2. *In the model with increasing marginal cost of capacity installation* *and when $\hat{c} < \frac{2p^m}{M}$ holds, firm i's best response function is*

$$BR_i(x_j) = \begin{cases} \frac{p^m}{\hat{c}}, & \text{if } 0 \le x_j \le M - \frac{p^m}{\hat{c}} \\ M - x_j, & \text{if } M - \frac{p^m}{\hat{c}} < x_j \le \hat{x} \\ \frac{p^m M}{2p^m + \hat{c}x_j}, & \text{if } \hat{x} < x_j < M \\ \frac{p^m M}{2p^m + \hat{c}M}, & \text{if } x_j \ge M. \end{cases} \tag{3.33}$$

Proposition 3.3. *In the model with increasing marginal cost of capacity installation, and provided that $\hat{c} < \frac{2p^m}{M}$, there exits a continuum of equilibria all of which exhibit $x_1 + x_2 = M$ in the stage of capacity decision, when $\tilde{x} \le x_i \le \hat{x}$ holds, where $\tilde{x} = \frac{\hat{c}M + 2p^m - \sqrt{\hat{c}^2 M^2 + 4(p^m)^2}}{2\hat{c}}$. In equilibrium, firms set $p_i = p^m$. The complete pricing strategies is the same as that under constant marginal installation cost.*

Proof. The best responses of the two competing firms are shown in Figure 3.16. Solving the best reponses simultaneously we get the equilibria in the stage of capcacity decisions. The infimum of the support of the range $\tilde{x}$ is the smaller root of the equation $\frac{p^m M - 2p^m x_i}{\hat{c}x_i} = M - x_i$. Here, only the smaller root of the equation is feasible since the bigger one, which is given by $\frac{\hat{c}M + 2p^m + \sqrt{\hat{c}^2 M^2 + 4(p^m)^2}}{2\hat{c}}$, is obviously greater than M. □

Similar as the case with positive (constant) marginal installation cost, there are infinitely many equilibria in this game. Firms choose their capacities which just satisfy the market demand and neither of them holds excessive capacity. Interestingly, in this situation, the equilibrium capacities here are not equally efficient both from the perspective of the firms and from that of social welfare. The efficiency comparison is given in Proposition 3.4.

Proposition 3.4. *In the model with increasing marginal capacity installation cost, and provided that $\hat{c} < \frac{2p^m}{M}$, the most efficient capacity equilibrium is the one at $x_i = x_j = \frac{M}{2}$.*

Proof. Given the assumption of perfectly inelastic demand, consumer surplus is fully extracted by firms. Social welfare in this situation is given by

$$SW = p^m x_1 - \frac{1}{2}\hat{c}x_1^2 + p^m x_2 - \frac{1}{2}\hat{c}x_2^2.$$

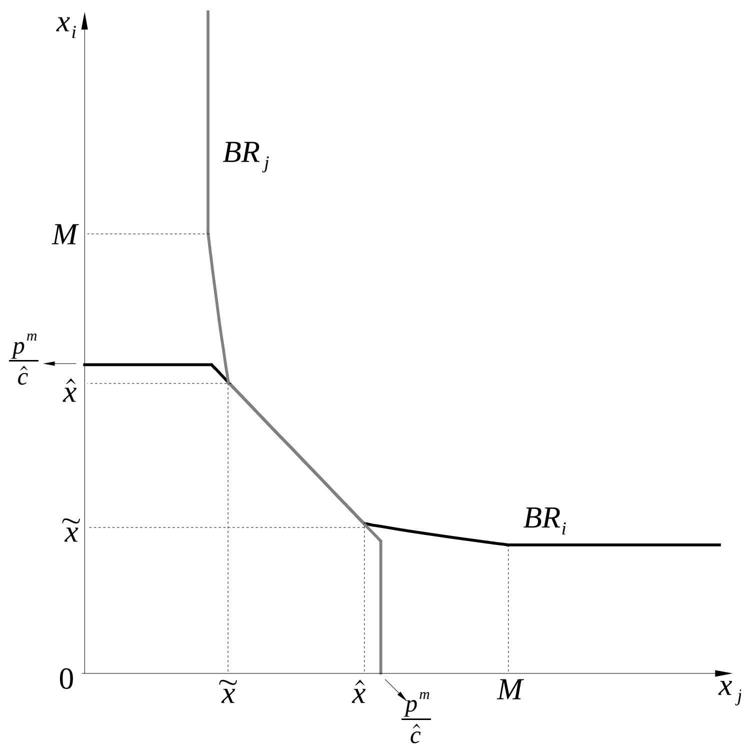


Figure 3.16: The equilibrium capacities with increasing marginal installation cost when $\hat{c} < \frac{2p^m}{M}$.

Since $x_1 + x_2 = M$ in equilibrium, the socially optimal capacity is $\frac{M}{2}$. Figure 3.17 shows the concavity of social welfare. □

Intuitively speaking, the socially optimal capacity is exactly the point, at which firms have the same marginal cost. Because the marginal cost is increasing in firms' capacity.

3.5.2 Partial market coverage

One can imagine that when the capacity installation cost is too high at the margin, firms may find it optimal to refuse some consumers and only cover a fraction of the market. This situation, in which $\hat{c} \geq \frac{2p^m}{M}$ holds, is discussed here. The analysis of price competition is the same as the case with constant marginal installation cost (see Table 3.1) and therefore is omitted here.

Proposition 3.5. *In the model with increasing marginal capacity installation cost and when $\hat{c} \geq \frac{2p^m}{M}$ holds, firms' best response functions are the same as that*

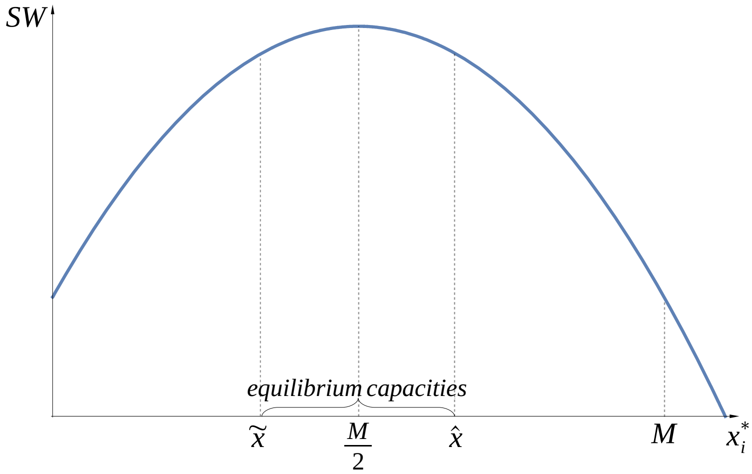


Figure 3.17: Social welfare with increasing marginal capacity installation cost when $\hat{c} < \frac{2p^m}{M}$.

in Equation (3.33).

Proof. There are in total five scenarios to discuss here. The first two scenarios, *Scenario 4.1* and *4.2*, are the same as *Scenario 3.1* and *3.2*, respectively. The other scenarios are discussed below.

Scenario 4.3 $M - \frac{p^m}{\hat{c}} < x_j \leq \hat{x}$**.** In this scenario, the profit of firm i is

$$\pi_i = \begin{cases} p^m x_i - \frac{1}{2}\hat{c}x_i^2, & \textit{if } 0 < x_i \leq M - x_j \\ \frac{p^m(M-x_i)x_i}{x_j} - \frac{1}{2}\hat{c}x_i^2, & \textit{if } M - x_j < x_i \leq x_j \\ p^m(M - x_j) - \frac{1}{2}\hat{c}x_i^2, & \textit{if } x_i > x_j. \end{cases} \tag{3.34}$$

The profit curve is shown in Figure 3.18 and the optimal capacity here is $x_i = M - x_j$.

Scenario 4.4 $\frac{M}{2} < x_j \leq M - \frac{p^m}{\hat{c}}$**.** Firm i's profit has the same expression as the one in *Scenario 4.3*. However, since $M - x_j > \frac{p^m}{\hat{c}}$, the curve and the optimal capacity look differently. With a profit shown in Figure 3.19, the best response in this scenario is $x_i = \frac{p^m}{\hat{c}}$.

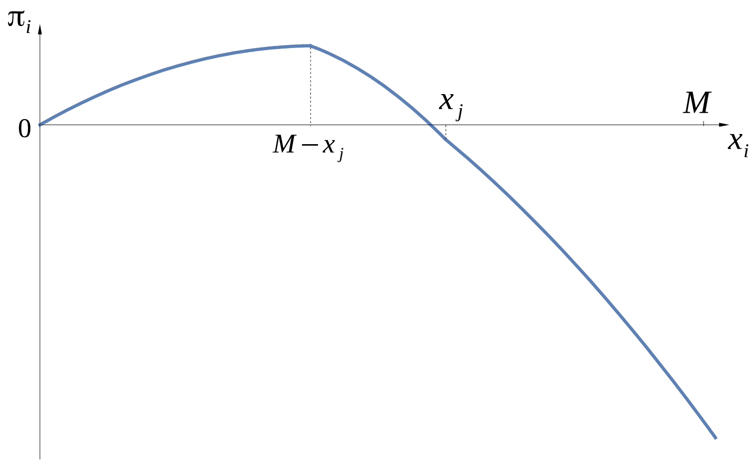


Figure 3.18: The profit of firm i in Scenario 4.3.

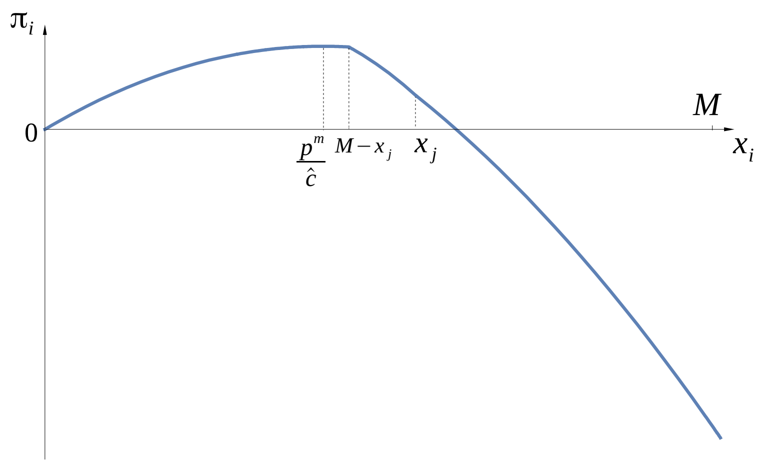


Figure 3.19: The profit of firm i in Scenario 4.4.

Scenario 4.5 $0 < x_j \leq \frac{M}{2}$**.** The profit of firm i is

$$\pi_i = \begin{cases} p^m x_i - \frac{1}{2}\hat{c}x_i^2, & \textit{if } 0 < x_i \leq M - x_j \\ \\ p^m(M - x_j) - \frac{1}{2}\hat{c}x_i^2, & \textit{if } x_i > M - x_j. \end{cases} \tag{3.35}$$

As shown in Figure 3.20, the optimal capacity lies in the first part of the curve and is given by $x_i = \frac{p^m}{\hat{c}}$.

□

Although the best responses in the first stage are the same as previous,

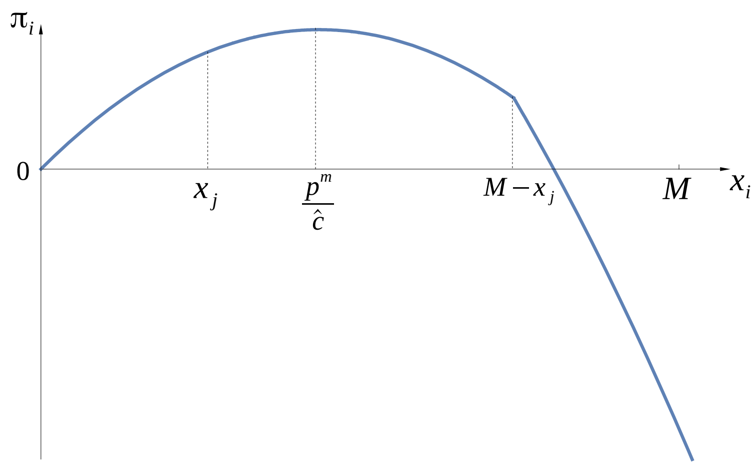


Figure 3.20: The profit of firm i in Scenario 4.5.

the equilibrium is different. The next proposition characterizes the equilibrium when the parameter of marginal capacity installation cost is sufficiently high.

Proposition 3.6. *In the game with increasing marginal installation cost and provided that* $\hat{c} \geq \frac{2p^m}{M}$*, there exits a unique pure-strategy subgame-perfect Nash equilibrium which involves both firms choosing* $x_i = x_j = \frac{p^m}{\hat{c}}$ *and setting* $p_i = p^m$*. The full characterization of price strategies is the same as the case with constant marginal installation cost.*

Proof. Given the best responses and the assumption on $\hat{c}$, the equilibrium in the capacity decision stage is illustrated in Figure 3.21. In this case, there is a unique capacity equilibrium in pure strategy. Solving the best response functions simultaneously we get the intersection point of the two best response curves: $x_i = x_j = \frac{p^m}{\hat{c}}$. □

When the parameter of the marginal cost of building capacity is high enough, firms would find it optimal to choose a constant capacity which actually maximizes the monopoly profit in the market. It is worthwhile to notice that the market is only partially covered with the equilibrium strategies. Because the total capacity supplied in the market is $\frac{2p^m}{\hat{c}}$, which is strictly smaller than M if $\hat{c} < \frac{2p^m}{M}$ is true. Only at the point $\hat{c} = \frac{2p^m}{M}$, all the consumers will be served. Note that although some consumers are rejected, this equilibrium is still socially optimal.

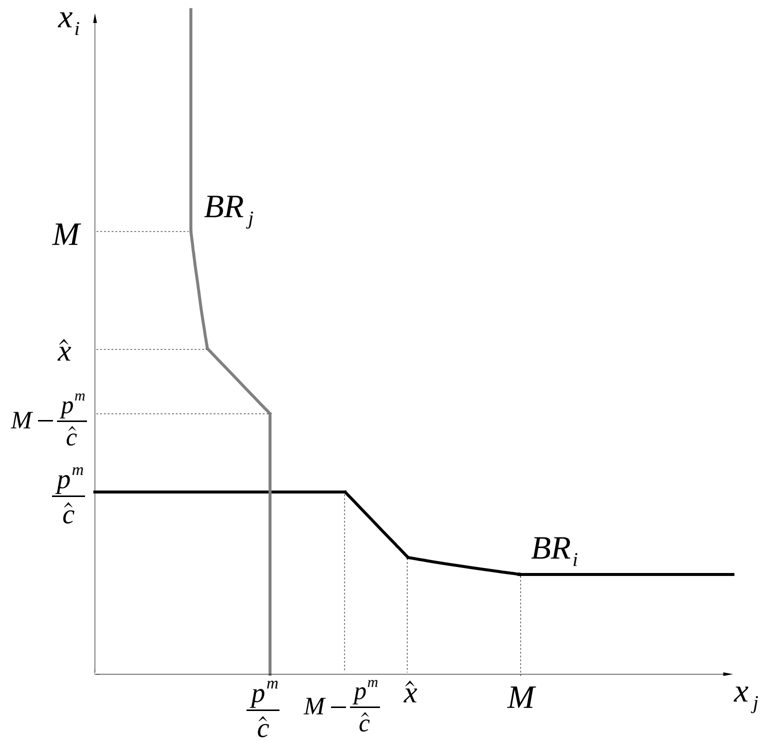


Figure 3.21: The equilibrium capacities with increasing marginal installation cost when $\hat{c} \geq \frac{2p^m}{M}$.

3.6 Conclusion

In this paper, I characterize the equilibrium in a capacity-then-price game with perfectly inelastic demand. In the analysis, I provide complete characterizations of the best responses in price competition and capacity decisions. The results in my research show that the monopoly outcome can always be sustained in equilibrium in this non-cooperative game. In addition, the effects of different types of capacity installation costs on equilibrium are also studied. With positive (constant) marginal cost, there is a continuum of capacity equilibria in which the sum of firms' capacities equals the total market volume. With zero marginal cost for capacity installation, the symmetric subgame-perfect Nash equilibrium involves firms sharing the market volume equally. This is the only equilibrium in which there is no excessive capacity and firms' joint profit is maximized. When the marginal cost is increasing in capacity, the market is fully covered in equilibrium only when the parameter of marginal cost is sufficiently low.

Otherwise, there is a unique capacity equilibrium with partial market coverage.

From the perspective of social welfare, the equilibria under constant marginal cost are equally efficient. However, those under increasing marginal cost may not be the same, especially when the parameter of marginal installation cost is sufficiently low. In this case, only the symmetric equilibrium, in which firms have identical marginal cost, is socially desirable.

In addition, there exists a capacity equilibrium in which only a fraction of consumers are served with increasing marginal cost of capacity installation. Although some consumers are rejected by firms, this result is still the most efficient, since building extra capacity is too costly at the margin.

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Conclusion

In my dissertation, I discuss competition issues in three different market environments using theoretical methods.

In Chapter 1, we discuss market outcomes in credence goods markets when experts are heterogeneous in their diagnostic abilities. We find that when the types of experts are observable to customers, efficient market outcomes can be sustained in equilibrium. However, the efficient outcomes may involve the low-ability expert always providing the major or minor treatment. When the types of experts are unobservable to their customers, multiple equilibria emerge within some certain ranges of parameters. The results have several welfare implications, among which a very interesting one is that, when market agents coordinate on the inefficient equilibria, increasing the share of high-ability experts may not lead to higher efficiency.

In Chapter 2, I analyze platform competition with endogeneous locations. Taking different pricing policies and competition modes into consideration, I find that platforms may choose to have more intensified competition on some certain side(s). If a tendency of agglomeration emerge in equilibrium, the equilibrium differentiation level can be lower than the social optimum. Only with *mill pricing* and *balanced competition*, the *principle of maximum differentiation* stays valid and there is excess differentiation between the competing platforms. These results have important policy implications. For example, insufficient differentiation levels on some certain sides in platform competition deserve special attention from the policy makers. What is more, balancing the competition on different sides should be taken into consideration besides price regulation.

Chapter 3 is about capacity precommitment and price competition in markets with perfectly inelastic demand. In this chapter, complete characterizations of firms' best responses and equilibrium outcomes are provided. My results mainly show that the monopoly outcome can be sustained in equilibrium. While the equilibria are equally efficient with constant marginal cost of capacity installation, there is significant efficiency variation among the equilibria with increasing marginal cost. In addition, when the capacity installation cost is too high at the margin, the most efficient equilibrium outcome may involve some consumers being rejected.