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Inference on Noncooperative Entry Deterrence

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Abstract

This study empirically investigates strategic entry-deterrence behavior under oligopolistic competition. I develop a structural econometric model describing incumbents' entry-deterrence behavior based on the framework of Gilbert and Vives (1986, Review of Economic Studies). I show theoretically that incumbents' marginal costs are interval-identified under the assumption that incumbents deter entry in equilibrium. The structural model is estimated using data from the Japanese aluminum smelting industry. A Vuong-type model selection test utilizing an instrument demonstrates that the entry-deterrence model is more consistent with the data than is an ordinary Cournot competition model without entry threats.

Keywords: Entry threat, Entry deterrence, Identification of marginal cost, Model selection, Vuong-type model selection test, Conduct testing, Aluminum smelting industry

JEL Codes: L13, L71

1 Introduction

Strategic entry deterrence is one of the central research issues that continues to command attention in the field of industrial organization. It is essential to understand comprehensively the process by which firms deter entry and the consequences to devise an effective competition policy to enhance market performance. Therefore, researchers in the industrial organization field have examined theoretically whether various firms' strategies are effective for entry deterrence (Tirole, 1988; Vives, 1999). Antitrust policymakers and researchers have been interested not only in how entry is deterred in theory but also in whether firms undertake entry-deterring strategies in the real world and how such behavior can be detected (Smiley, 1988; Lieberman, 1987). This study empirically investigates strategic entry-deterrence behavior under oligopolistic competition.

Compared with the significant advances in theoretical studies, there are relatively few empirical studies that provide evidence on strategic entry deterrence. One of the reasons why the number of empirical studies is small is that the literature largely focuses on industries in which researchers can clearly identify the emergence of new entry threats; for example, patent expiration in the pharmaceutical industry (see Ellison and Ellison (2011)), entry plans in the casino industry (Cookson (2017)), and Southwest's endpoint operation in the airline industry (Sweeting et al. (2020)). Researchers provide empirical evidence by demonstrating the change of incumbents' strategies around the emergence of such new entry threats. However, the approach limits the examination of an industry where firms may have strategically undertaken entry deterrence, but researchers cannot identify the emergence of the entry threats that firms face.[1] In general, it is difficult for researchers to identify new threats.

Departing from the above approach, this study relies on conduct testing, which is used in the empirical industrial organization literature. Conduct testing is a statistical method for determining which model of firm conduct or competition is appropriate to describe the competition in a particular industry. In the conduct testing literature, researchers construct and estimate various competing

[1] Another reason why the body of empirical studies is relatively small is that "it is inherently difficult to distinguish strategic deterrence motives from other investment rationales" (Cookson, 2017).

models of firm conduct, compare the models, and determine which model has the best explanatory power.[2] More specifically, researchers utilize the Vuong-type model selection test developed by Vuong (1989) and extended by Rivers and Vuong (2002) to statistically compare two competing models of firm conduct.

To adopt the conduct testing approach, I develop a structural econometric model of entry deterrence and present an identification result for firms' marginal costs. Constructing models of firm conduct and thereby identifying firms' markups or marginal costs is a necessary part of the conduct testing method. I show that incumbents' marginal costs are not point-identified but interval-identified under the assumption that incumbents deter entry in equilibrium. Specifically, the upper bounds of the interval-identified marginal costs correspond to the level of costs at which the incumbents are indifferent between deterring or allowing entry, whereas the lower bounds correspond to those identified under the assumption of Cournot competition. Furthermore, I propose a method to numerically calculate the upper bounds of identified marginal costs, as they may not have a closed-form representation depending on the specification of the demand function.

The Japanese aluminum smelting industry in the post-World War II period provides a good case study to examine empirically strategic entry deterrence. The history of the industry indicates that its incumbent firms were threatened by the entry of potential rival firms and that the incumbents were likely to undertake entry-deterring strategies. I focus on the incumbents' commitment to production quantity as an entry-deterrence strategy and develop econometric models based on the industrial economic theory of Gilbert and Vives (1986). I focus on the incumbents' commitment to production quantity because the simple characteristics of aluminum as a product prevent firms in the industry from using certain methods of entry deterrence, such as advertising or brand proliferation. Furthermore, the data on the capacity utilization rate suggest that the overcapacity strategy is not suitable to describe the industry.

The Japanese aluminum industry is suitable for a case study not only because of the suspicion

[2]Although researchers previously used the conduct parameter method to understand the nature of competition in a market, e.g., Bresnahan (1982) and Porter (1983), the difficulties in estimating the conduct parameter are now recognized (Corts, 1999; Puller, 2009).

or likelihood of entry-deterrence behavior but also because of data appropriateness. Recent studies in the conduct testing literature, Backus et al. (2021) and Duarte et al. (2022), propose using generalized method of moments (GMM) objective functions based on excluded instruments for marginal cost as a criterion function in the framework of Rivers and Vuong (2002). This is because Berry and Haile (2014) demonstrate that we can utilize a moment condition constructed from the excluded instruments to falsify a model of firm conduct. Various types of economic variables can be adopted as appropriate excluded instruments in a differentiated product industry, such as the product characteristics of other firms. However, there are limited appropriate excluded instrumental variables in a homogenous product industry. The data on the Japanese aluminum industry include (other) firms' cost-efficiency measures, which provide the basis for an appropriate instrument. Therefore, I can perform the model selection test that does not rely on any instrument and the test that utilizes (other) firms' cost-efficiency measures as excluded instruments.

The results of these tests suggest that the entry-deterrence model is more consistent with the data than is the Cournot competition model. However, the perfect competition model is almost as consistent with the data as the entry-deterrence model. Furthermore, because the data include a sample of firms for which the threat of entry has disappeared, I compare firm conduct with and without entry threats. The result shows that after the threat of entry disappeared, the Cournot competition and perfect competition models are both consistent with the data, with the former being slightly more consistent.

1.1 Related literature

This study is related to two strands of literature in the field of industrial organization. The first strand comprises studies that aim to provide empirical evidence of strategic entry deterrence. Commonly, studies adopt the approach of examining different investment strategies between firms in situations with and without entry threats. The seminal work by Lieberman (1987) investigates whether incumbent firms strategically maintain excess capacity in a rapidly growing chemical industry. If an incumbent has an incentive to deter the entry of potential rivals in a growing industry, the industry growth rate and the capacity utilization rate that are sufficient to elicit new capacity installation will be lower for incumbents than for entrants. However, Lieberman (1987) shows that entrants and incumbents exhibit similar investment strategies. Cookson (2017) examines whether capacity expansion strategies vary between incumbents facing or not facing entry threats. The casino entry plan data on which Cookson (2017) focuses enables him to identify clearly whether an incumbent is threatened by entry plans because the data include information on the planned site of a proposed entrant. By employing a difference-in-difference method, Cookson shows that incumbents expand their capacity with a motive to deter entry. Ellison and Ellison (2011) introduce a novel approach for empirically examining entry deterrence. They prove that there is a non-monotonic relationship between market size (or attractiveness of entry) and strategic investment under entry-deterrence motives and that the relationship is monotonic if firms do not invest for the purpose of entry deterrence. Therefore, they propose testing the monotonicity between market size and incumbents' investment to examine strategic entry-deterrence behavior. Sweeting et al. (2020) adopt Ellison and Ellison (2011)'s approach to examine limit pricing. The present study contributes to this literature by presenting new empirical evidence in environments where the methods adopted in the existing literature are not applicable.

Several studies in this strand of literature rely on a structural econometric approach. To investigate the entry-deterrence impact of code-sharing, which is a form of strategic alliance in airline industries, Gayle and Xie (2018) estimate a dynamic structural model of entry and exit in the tradition of Ericson and Pakes (1995). They show that code-sharing influences potential entrants' market entry costs and thereby effectively functions as a means of entry deterrence. In addition, they demonstrate that entry costs vary according to the form of code-sharing and the identity of entrants. From the perspective of predation differing from entry deterrence, Snider (2009) and Williams (2012) show that incumbent firms in the US domestic airline industry had predatory incentives when they invested in capacity building and thereby induced entrants to exit the market.

The second strand of literature to which this study contributes is concerned with the issue of conduct testing and identifying markup and marginal cost based on model assumptions. Understanding firm conduct is not only of general interest for researchers but also a fundamental component of structural models used for policy evaluation. Therefore, researchers in the industrial organization field have developed and empirically tested various structural models describing firm conduct. Several studies use pair-wise model selection tests for nonnested models originally developed by Vuong (1989) and extended by Rivers and Vuong (2002). The tests have been applied to various economic issues, including collusion (Gasmi et al., 1992; Doi and Ohashi, 2019), vertical relationships (Sudhir, 2001; Bonnet and Dubois, 2010), and common ownership (Backus et al., 2021).[3] [4]

In recent years, new insights have been developed within this strand of literature. Berry and Haile (2014) generalize Bresnahan (1982)'s idea of "demand rotation" to identify the degree of competition and derive testable restrictions to falsify a model of firm conduct. The restriction is a moment condition constructed from an excluded instrument for marginal cost. Building on Berry and Haile (2014)'s arguments, Backus et al. (2021) and Duarte et al. (2022) propose a test using a GMM objective function based on excluded instruments as a criterion in Rivers and Vuong (2002)'s test framework. Furthermore, Backus et al. (2021) propose an optimal instrument for testing when many instruments are available.

Salvo (2010) is one of the studies most relevant to this one because it develops a structural econometric model where incumbents face a threat of imports and tests the model using Vuong's type model selection test. However, there are significant differences between the current study and Salvo (2010) because the way that the threat of entry is modeled is quite different between the two papers and because I employ the excluded instrument, i.e., the other firms' cost-efficiency measure, to test the model. Therefore, this study contributes to this literature by providing a new identification result for marginal costs under the assumption of an entry-deterrence model based

[3]Identification results for firms' marginal costs are presented in the literature for various purposes, not only for the model selection test. Examples include dynamic learning models (Irwin and Klenow (1994); Ohashi (2005)), investment decision models (Pesendorfer (2003)), and price discrimination models (Miller and Osborne, 2014; D'Haultfœuille et al., 2019).

[4]The usefulness of the Vuong-type model selection test is not limited to the testing of firm conduct. For example, Gayle and Luo (2015) provides a simulation study that shows the test has the power in distinguishing between alternate order-of-entry assumptions in an entry game.

on Gilbert and Vives (1986), and by testing the model utilizing the new insights for testing firm conduct.

The remainder of the paper is organized as follows. Section 2 introduces the model describing the entry-deterrence behavior of incumbent firms and presents the identification result for the incumbents' marginal cost. Section 3 provides an overview of the development of the Japanese aluminum smelting industry. Section 4 presents the specification employed for empirical analysis, elaborates on the data set used, and provides estimation and testing results. Section 5 concludes by summarizing the main results and identifying topics for future research.

2 Model and identification of marginal costs

In this section, I first develop a theoretical model of strategic entry deterrence based on Gilbert and Vives (1986), and then show that the marginal costs of incumbents are interval-identified.

2.1 Settings

I consider a two-stage game with complete information. There are M incumbent firms and a potential entrant. Both the incumbents and the entrant produce a homogeneous product. Let i represent a generic incumbent and e represent the entrant. In the first stage of the game, the incumbent firms independently make their respective production decisions. In the second stage, the potential entrant decides whether to enter and, if it does enter, its level of production, given the incumbents' first-stage output.

The entrant incurs a sunk entry cost if it enters. Given the total output, the market-clearing price is realized.

Incumbent firm i's cost function is assumed to be $C_i(x) = c_i x$, where $c_i \geq 0$ is a positive constant that differs between incumbents, and x represents a level of production. The entrant has a cost function of $C_e(x) = c_e x + F$ if $x > 0$, and zero otherwise, where $F \geq 0$ is a sunk entry cost and $c_e \geq 0$ is a constant marginal cost for the entrant.

Let $P(X)$ denote the inverse demand function, where X represents the total industry output. I assume that $P(X)$ is twice continuously differentiable, downward sloping, i.e., $P' < 0$, and concave, i.e., $P'' < 0$, whenever $P(X)$ is positive. In addition, I assume that a value of $\xi > 0$ exists such that $X \geq \xi \Rightarrow P(X) = 0$.

Ignoring entry for a moment, let $r(Z, c)$ be the optimal level of output for an incumbent firm with marginal cost c when the other firms produce a total output of Z. In other words,[5]

$$r(Z, c) = \underset{x}{\operatorname{argmax}}\ P(x + Z)x - cx. \tag{1}$$

The convexity of the response function $r(Z, c)$ in Z is assumed.[6]

The potential entrant actually enters the market if the profit that it earns as a Stackelberg follower exceeds the sunk entry cost; otherwise, it does not enter. Because the profit that the entrant earns as a Stackelberg follower is decreasing in the first-stage total output, there exists a minimum level of first-stage total output that induces the entrant to give up entering the market. It is referred to as the critical limit output, Y, for the oligopoly, and satisfies the following equation:

$$\pi_e\left(r\left(Y, c_e\right), Y\right) = F,$$

where $\pi_e(r(Y, c_e), Y) = (P(r(Y, c_e) + Y) - c_e)r(Y, c_e)$ is the maximum profit that the entrant can earn as a Stackelberg follower.

2.2 Best response function and entry-deterring equilibrium

Gilbert and Vives (1986) analyze the model described above with cost homogeneity between the incumbents and an entrant, derive the best response function for incumbents, and characterize the equilibria of the game according to the level of the critical limit output Y. Let $\phi_i(Z)$ denote the best response of firm i when the other incumbents produce a total output of Z. Depending on the

[5]Thus, $r(Z, c)$ is the Cournot best response.

[6]The convexity is assumed in Gilbert and Vives (1986) because it simplifies the analysis of the incumbents' optimal production decision as a Stackelberg leader.

level of Z, firm i may or may not have an incentive to deter entry.

On the one hand, when Z is sufficiently large to satisfy $r(Z, c_i) + Z \geq Y$, incumbent i produces $r(Z, c_i)$ and entry is blocked because the first-stage total output, $r(Z, c_i) + Z$, exceeds Y. On the other hand, entry cannot be blocked if Z is not sufficiently large to satisfy $r(Z, c_i) + Z \geq Y$. In this case, firm i may either allow entry or prevent it. Firm i can prevent entry by producing $Y - Z$ and making up the difference between Y and Z.[7] However, the smaller Z becomes, the more that firm i needs to produce to make up the difference, and the lower is its incentive to prevent entry. Therefore, when Z is sufficiently small, firm i gives up deterring entry and allows entry. When firm i chooses to allow entry, it behaves as if it were a Stackelberg leader. Therefore, the best response of firm i is summarized in the following equation (2), with the derivation provided in Appendix A.1:

$$\phi_i(Z) = \begin{cases} r(Z, c_i) & \text{if } Z \geq \overline{Z}(Y, c_i), \\ Y - Z & \text{if } \underline{Z}(Y, c_i, c_e) \leq Z < \overline{Z}(Y, c_i), \\ s(Z, c_i, c_e) & \text{if } 0 \leq Z < \underline{Z}(Y, c_i, c_e). \end{cases} \tag{2}$$

Here, $\overline{Z}(Y, c_i)$ and $\underline{Z}(Y, c_i, c_e)$ represent the threshold production levels of the other incumbents at which firm i can block and prevent the potential entrant from entering. More specifically, $\overline{Z}(Y, c_i)$ is the minimum output level produced by the other incumbents at which incumbent i can block entry, and it is the solution of equation $r(Z, c_i) + Z = Y$ for Z. $\underline{Z}(Y, c_i, c_e)$ is the minimum output level at which incumbent i has an incentive to deter entry. When $Z = \underline{Z}(Y, c_i, c_e)$, the profit when firm i prevents entry is equal to the profit when it allows entry and behaves like a Stackelberg leader. The optimal production level when firm i plays the role of a Stackelberg leader is represented by $s(Z, c_i, c_e)$. The following result, presented by Gilbert and Vives (1986), proves the existence of entry-deterring equilibria and is important for the identification of marginal costs.

Proposition 1 (Gilbert and Vives 1986)

[7] Incumbent i has no incentive to produce an amount larger than $Y - Z$ because $Y - Z > r(Z, c_i)$ when $r(Z, c_i) + Z < Y$.

Assume that $c_i = c_e = 0$. Let X^C be the total output in the Cournot equilibrium between incumbents, let $\overline{Y}$ be the largest Y such that the ϕs intersect on the hyperplane $\sum_{i=1}^{M} x_i = Y$, and let X_{-i} be $\sum_{j \neq i} x_j$. If $X^C \leq Y \leq \overline{Y}$, then any $x = (x_i)_{i=1}^{M}$ in the set $\mathcal{E} = \{x \in \mathbb{R}_+^M | \sum_{i=1}^{M} x_i = Y, r(X_{-i}, c_i) \leq x_i \leq Y - \underline{Z}(Y, c_i, c_e),\ \forall i\}$ and the potential entrant remaining out of the market is a subgame perfect equilibrium. Incumbents prevent entry by producing a total output of Y.

Proof. See Gilbert and Vives (1986). ■

Even in the presence of cost heterogeneity, it can be shown that any incumbent i has no incentive to deviate from its equilibrium strategy if $x = (x_i)_{i=1}^{M}$ is in the set $\mathcal{E}$ because the incumbent's best response function remains unchanged even if cost heterogeneity is introduced.[8] In other words, entry-deterring equilibria exist even when cost heterogeneity is introduced. For the marginal cost identification analysis, the equilibria represented by the set $\mathcal{E}$ are focused.

2.3 Identification of marginal cost

To consider the identification problem concerning the incumbents' marginal cost $(c_i)_{i=1}^{M}$, it is first necessary to define the observables for a researcher. A researcher can observe the market price P and the firm-level output $(x_i)_{i=1}^{M}$. The researcher need not observe entry cost F, but it is assumed that the marginal cost of a potential entrant c_e is observable. Although the assumption that c_e is known is strong, it is realistic that a researcher has prior knowledge of the range of possible values for a parameter. That is, a researcher knows that c_e falls into a known interval of $[\underline{c}_e, \overline{c}_e]$. In this case, conservatively to construct an identification region for the incumbents' marginal cost, let c_e be $\underline{c}_e$.[9]

To identify the incumbents' marginal cost, the following proposition is beneficial. The proposition shows that firms with higher marginal costs are less willing to deter entry if other firms do

[8] Taking the incumbent's strategy $(x_i)_{i=1}^{M}$ in an equilibrium, consider whether incumbent i has an incentive to deviate from x_i. Because $r(X_{-i}, c_i) < x_i$ is satisfied, firm i has no incentive to increase its production level. Furthermore, $x_i \leq Y - \underline{Z}(Y, c_i, c_e)$ and $\sum_{i=1}^{M} = Y$ means that $X_{-i} \geq \underline{Z}(Y, c_i, c_e)$. Therefore, firm i has an incentive to deter rather than allow entry given X_{-i}. Moreover, the entrant has no incentive to enter the market because the limit output Y is produced in the first stage.

[9] I clarify why this is sufficient to conservatively construct the identification region for marginal costs in Appendix A.3.

not produce a sufficient amount.

Proposition 2 *When $\underline{Z}(Y, c_i, c_e) > 0$, $\underline{Z}(Y, c_i, c_e)$ is strictly increasing in c_i.*

Proof. See Appendix A.2. ■

Assume that an entry-deterring equilibrium is realized in the data, that is, $(x_i)_{i=1}^M \in \mathcal{E}$. Therefore, the quantity that a researcher observes satisfies:

$$r(X_{-i}, c_i) \leq x_i \leq Y - \underline{Z}(Y, c_i, c_e). \tag{3}$$

Because $\underline{Z}(Y, c_i, c_e)$ is strictly increasing in c_i and $r(X_{-i}, c_i)$ is strictly decreasing in c_i, given the other arguments, both functions have their inverse functions, denoted by $\underline{Z}^{-1}(Y, ., c_e)$ and $r^{-1}(X_{-i}, .)$, respectively. Therefore, equation (3) can be rearranged as:

$$r^{-1}(X_{-i}, x_i) \leq c_i \leq \underline{Z}^{-1}(Y, Y - x_i, c_e). \tag{4}$$

Note that the limit output Y is observable because it corresponds to the incumbents' total output $X = \sum_i x_i$ in any entry-deterring equilibrium. Therefore, both sides of equation (4) are identified from the data.

To apply the data to equation (4), it is necessary to be able to compute the function on both sides. Because the function on the left-hand side is the inverse of the Cournot best response, it can be calculated from the first-order condition of the optimization problem (1), as in previous studies. Conversely, the function $\underline{Z}^{-1}(Y, Y - x_i, c_e)$ may not be solved analytically, depending on the shape of the demand function. Appendix A.3 provides a method to calculate the value of the right-hand side of equation (4) numerically.

3 The Japanese aluminum smelting industry post-World War II

In this section, I describe the post-World War II development of the Japanese aluminum smelting industry. There are several reasons why the postwar industry data are appropriate for empirical research on entry deterrence. First, incumbent firms operating in the industry evidently faced the threat of entry and hence were likely to undertake entry-deterring strategies. Second, because the properties of aluminum are simple, making it difficult to produce differentiated products, firms operating in the industry could not use various methods of entry deterrence, such as brand proliferation or advertisements. Furthermore, during the sample period on which I focus, it is unlikely that overcapacity was employed as an entry barrier. Over the sample period, the average industry operating ratio, defined as the ratio of annual production over annual capacity, was 0.89. Third, because the 1973 oil crisis changed the market environment and profitability of the industry, it is possible to compare firm conduct with and without entry threats by dividing the whole sample into two subsamples, before and after 1973. This section describes the development of the industry and aluminum production to guide the empirical specification in Section 4.[10]

The Japanese aluminum smelting industry experienced both a remarkable rise and decline during the period of analysis. Postwar aluminum smelting in Japan began with three incumbent firms, Nippon Light Metal, Sumitomo Chemical, and Showa Denko. With the rapid growth in demand, these incumbent firms expanded their smelting facilities, and new companies, Mitsubishi Chemical, Mitsui Aluminum, and Sumikei Aluminum, entered the industry. As a result, the total annual capacity grew from about 65,000 tons in 1955 to 1,640,000 tons in 1978. However, the two oil crises of 1973 and 1979 sharply increased the cost of aluminum smelting and deprived the industry of its global competitiveness and prosperity. As a result, by 1987, all except one plant had closed, and almost all domestic aluminum demand since has been satisfied by imports. The focus of this study is on this period of dramatic change.

[10]Goto (1988) provides a good overview of the development of the industry and a description of public policy concerning the industry after the oil crisis.

The postwar Japanese aluminum industry is characterized by a three-level vertical supply chain consisting of (i) aluminum smelting; (ii) processing, including rolling, extrusion, and die casting; and (iii) production of final consumer products. At the first level in the supply chain, firms produce aluminum ingots from raw materials, such as imported bauxite. At the second level, aluminum undergoes processing, for example, rolling and heat treatment to harden it. After processing, aluminum has the properties required to make a final product at the third level of the supply chain. Each level of the supply chain comprises vertically separated companies. The focus of this study is on the first level of the supply chain.

There are two types of aluminum used in the second and third levels of the supply chain: primary aluminum, which is made from bauxite, and secondary aluminum, which is made from aluminum products that have been discarded as waste. Primary and secondary aluminum differ in their levels of purity and uses. Our focus is on primary aluminum, which has purity levels of 99.0%–99.9%.[11]

Although aluminum is used in a variety of applications, an increase in demand from the construction and transportation sectors supported the rapid growth of the industry. Table 1 shows the volume of product shipments in the second level of the supply chain classified by shipping destinations. The table shows that shipments to the transportation and construction sectors increased significantly in the 1960s and 1970s. The increase in shipments to the construction sector is particularly noteworthy, rising from 3% of total shipments in the 1950s to 33% in the 1970s. This was a result of the rapid increase in the popularity and the spread of aluminum window sashes. By contrast, during the 1980s, shipments to the construction sector did not grow as much as previously. Figure 1 shows the volume of demand for aluminum and a measure of construction activity, which is the total floor area of the buildings on which construction had commenced. Demand is represented by the sum of domestic production and imports of primary aluminum. The figure suggests that demand from the construction sector was the main driver of growth in the industry.

[—–Table 1—–]

[11] Suslow (1986)'s empirical analysis shows that the price of secondary aluminum does not influence the demand for primary aluminum.

[——Figure 1——]

The demand for aluminum in postwar Japan continued to increase during the 1970s, but the domestic suppliers began to be replaced by overseas producers (imports). The oil crisis took a heavy toll on the Japanese aluminum smelters. Figure 1 shows that after the 1973 oil shock, domestic production fell, and imports rose. Although imports continued to rise after 1973, domestic production did not increase in the 1970s, and when the second oil shock occurred in 1979, domestic production fell sharply. The reason why the oil crisis hit the domestic smelters so hard relates to the main raw material for aluminum and how it was sourced by domestic smelters.

Although the main raw material for aluminum is bauxite, the production of aluminum is highly electricity-intensive. Aluminum is produced by electrolyzing the intermediate product alumina (or aluminum oxide), employing the Hall–Héroult process, after the alumina is extracted from bauxite by the Bayer process. The electrolyzing process requires a large amount of electricity. Specifically, approximately $15,000$ kWh of electricity is consumed in the Hall–Héroult process to produce a unit ton of aluminum[12] and the electricity costs accounted for about 25% of total costs even before the oil crisis (Miwa, 2016).

In addition, Japanese smelters relied mainly on oil-fired thermal power generation to meet their electric power needs, whereas overseas smelters used low-cost electricity generated by hydropower (Peck, 1988). Therefore, the oil crisis increased the electricity costs of aluminum smelting for Japanese firms in particular. Figure 2 shows crude oil, imported bauxite, and aluminum prices. The 1973 oil shock raised the price of oil threefold and the 1979 shock further increased it to more than seven times the level before the oil crisis. These increased oil prices led to the decline in the share of domestic firms' production shown in Figure 1.

[——Figure 2——]

The presence and disappearance of entry threats Before the oil crisis, the aluminum industry achieved substantial profits, making it attractive to potential new entrants. In October 1960, the first

[12]Because of successive innovations in the smelting process, the electricity intensity declined in the sample period.

entry plan to the industry since the end of the war was reported in a newspaper. Nisso Steel, an open-hearth furnace steel manufacturer and a group company of an integrated steel manufacturer, Yahata Steel Corporation, planned to commercialize aluminum smelting. Yahata Steel had shown interest in aluminum production before the report and it took a leading role in the commercialization of aluminum, expanding and revising Nisso's plan to include aluminum processing as well as smelting. There was fierce opposition from the three existing companies to Yahata's plan to enter the aluminum smelting and processing industry.

In response to this opposition, the Ministry of International Trade and Industry (MITI) postponed approval of the entry. Ultimately, entry into the smelting sector was abandoned, and a new company, Sky Aluminum, which engaged only in the processing business, was established and began operating in 1967.

The threat of entry remained for the three existing firms even after Nisso (and Yahata) withdrew their plans to enter the smelting industry. Mitsubishi Chemical announced its intention to enter the industry in December 1960, about the same time as Nisso's entry plan announcement. A joint venture of the Mitsui group companies, Mitsui Aluminum, was established as an aluminum smelting business in January 1968. As in the case of Nisso, the incumbent companies opposed the entry plans of these companies.[13]. In these cases, despite their opposition, the entry did occur. Mitsubishi commenced operations in May 1963 at Naoetsu City in Nigata Prefecture, and Mitsui Aluminum began to operate in January 1971 at Miike in Fukuoka Prefecture.

The 1973 oil crisis significantly altered Japan's aluminum smelting industry, which relied on oil-fired thermal power generation to produce aluminum. After the oil shock, smelting was no longer a lucrative industry. Indeed, two companies (Kobe Steel and Furukawa Aluminum) had planned to enter the industry, but both abandoned these plans immediately after the oil shock. Thus, after the oil shock, the industry was no longer subject to entry threats.

[13]The existing companies were not as strongly opposed to the entry of Mitsubishi Chemical as they were to the entry of Nisso (Yahata) and Mitsui. This may be because Mitsubishi had stated that it would only supply aluminum ingots to Mitsubishi group companies and that any excess production would be exported (Neo, 2003). Moreover, the three incumbents may have been tolerant of Mitsubishi Chemical as a means of deterring more powerful rivals (Ashiya, 2000).

The change in the competitive environment might have led to a change in firm conduct in the industry. Figure 2 shows that smelting firms were unable to pass through the rising prices of raw materials to aluminum prices after the oil crisis. As a cost pass-through rate of less than 100% is the nature of imperfect competition[14], this observation suggests a change in firm conduct from a competitive one to an uncompetitive one.

Based on the above overview of the industry, I model its structure, including demand and costs, select the variables used in the analysis, and split the whole sample into the two subsamples, before and after the 1973 oil shock. Finally, it is noteworthy that several industrial policies were implemented by MITI after the oil shocks, particularly in the late 1970s and early 1980s, that are not explicitly modeled in the empirical analysis. The objective of the industrial policies was not to aid and sustain the industry[15], but to promote the reduction of excess capacity, which had been brought about by the increased electricity costs. Specifically, from 1978, existing companies could receive an annual sum equivalent to approximately 6% (the annual interest rate) of the book value of their "frozen" capacity[16]. Because the industrial policies would have affected the dynamic incentives of firms in relation to their capacity choices, but would not have influenced static competition, I exclude analysis of the policies from the scope of this study.

4 Empirical analysis

By comparing alternative economic models that describe the competition in the Japanese aluminum industry, it is possible to test whether the incumbent firms attempted to deter entry by committing to excessive production output. The three models of competition tested are: (i) Cournot, (ii) entry-deterrence, and (iii) perfect competition. Because marginal costs are interval-identified under the assumptions of the entry-deterrence model, I use the upper bounds on marginal costs for the entry-deterrence model.

[14]See Ritz (2018) for the relationship between the cost pass-through rate and firm conduct.

[15]The existing businesses requested that the government offer exceptionally low electricity rates as an industrial policy, but their request went unheeded.

[16]Smelting equipment that became technically unusable after a certain period was referred to as "frozen."

Employing the upper bounds has the following two implications[17]. First, employing the upper bounds assumes that a specific equilibrium arises in the data. Although there are multiple equilibria in which entry is deterred, firms taking an entry-deterring strategy produce more than they would produce if no entry threat existed. Because the total output in a Cournot equilibrium is decreasing in firms' marginal costs, the difference between the counterfactual Cournot total output of incumbents with marginal costs equal to the upper bounds and the observed limit output becomes as large as possible. In other words, employing the upper bounds means that the equilibrium arises where the firms' output is maximally affected and increased in response to the threat of entry.

Second, a test using specific values of partially identified parameters, such as in this study, may have implications for the result of a formal test where two partially identified models are compared, when the formal test is infeasible. A formal Vuong-type model selection test where two moment inequality models are compared is developed by Shi (2015). The test is structured to select the model that includes a distribution closer to the true distribution.[18] In other words, the test is structured to compare the best distributions of each of the two models. Given the test structure, when the specific values of partially identified parameters are used and favored over the point-identified model, this may mean that the partially identified model will be favored in a formal model selection test developed for partially identified models. However, this is intuition and not a mathematical result.[19]

[17]It is common to employ a specific value for partially identified parameters in the industrial organization literature to enable the analysis to proceed. For example, Wollmann (2018) uses the midpoints of bounds on partially identified parameters for sunk costs to perform a counterfactual analysis.

[18]The moment inequality conditions yield a set of distributions that are consistent with those conditions.

[19]The test structure of Shi (2015) is not appropriate for this study because the determination of firm conduct should be based on a criterion formed from excluded instruments (Berry and Haile, 2014), whereas the test developed by Shi (2015) prohibits this treatment. To my knowledge, a formal model selection test that enables the treatment has not been developed.

4.1 Demand and cost specification and testing method for firm conduct

Demand function To test firm conduct, it is necessary to estimate a demand function. A log-linear demand function for aluminum demand is specified as follows:

$$\log Q_t = \alpha_0 + \alpha_1 \log P_t + \alpha_2 \log X_t + \epsilon_t^D, \tag{5}$$

where Q_t is the sum of domestic production and imports, P_t is the aluminum ingot price, X_t denotes demand shifters, and ϵ_t^D represents an unobserved demand shock. The shifter X_t includes the total floor areas of buildings on which construction had commenced in a period, a linear time trend, and month fixed effects.

Because there appear to be delays in the effect of the total floor area on aluminum demand, as seen in Figure 1, the 12-month moving averages are used in the demand analysis. The parameters of the demand function are estimated by two-stage least squares (2SLS) using the imported bauxite price, the oil price, and the average electricity intensity as instrumental variables for the aluminum price P_t. The electricity intensity, which is often used as a measure of inefficiency in the industry, can be calculated as the ratio of the consumption of electricity to production output.[20] Because the unobserved demand shock ϵ_t^D may involve serial correlation, the standard errors of estimates are adjusted following Newey and West (1987).[21]

Cost function To proceed with the test, the cost function for a firm engaging in aluminum smelting needs to be estimated. A linear marginal cost function for aluminum smelting is specified as:

$$MC_{jt} = \beta_0 W_t + \beta_1 W_{jt} + \gamma_j + \epsilon_{jt}, \tag{6}$$

[20] Although the electricity intensity is calculated using production quantities, which are endogenous, it is not an endogenous variable because the value does not depend on the utilization rate and only reflects a technological aspect.

[21] Boyd et al. (1995) assume that the unobserved demand shock follows an autoregressive AR(1) process in the case of US primary aluminum demand.

where MC_{jt} is the constant marginal cost for firm j at time t, W_t and W_{jt} are exogenous cost shifters, γ_j is a firm fixed effect, and ϵ_{jt} is an unobserved cost shock. The cost shifter W_t, which is common between firms, includes the bauxite price, a time trend, and month fixed effects, whereas the shifter W_{jt}, which varies between firms, includes the product of the crude oil price and firm-level electricity intensity (rather than just electricity intensity), W_{jt} = oil price$_t$ × electricity intensity$_{jt}$.

In the cost analysis, I use the 12-month moving average for the oil price. This is because not all smelters had their own thermal power generation equipment. In other words, several firms met their power needs by buying electricity. Because the price set by electricity companies does not immediately reflect the rise in oil prices, I assume that oil prices have a delayed effect on firms' marginal costs.[22] I expect the firm fixed effects in the cost function (6) to capture the differences among firms in terms of how they sourced their power needs.

Given that the demand function has already been estimated, it is possible to identify marginal costs under different assumptions for competition. If the Cournot model is assumed to describe the competition in the industry, marginal costs can be identified using the first-order condition and estimated as follows:

$$\widehat{MC}_{jt}^{C} = P_t(1 + \frac{q_{jt}}{Q_t}\frac{1}{\hat{\alpha}_1}). \tag{7}$$

where q_{jt} is each firm's production quantity and $\hat{\alpha}_1$ is the estimated price elasticity of demand. If the entry-deterrence model is assumed to represent industry competition, the upper bounds of the interval-identified marginal costs are estimated as:

$$\widehat{MC}_{jt}^{ED} = \underline{Z}^{-1}(Q_t - q_{jt}, Q_t, c_{et}). \tag{8}$$

In the case of entry deterrence, the marginal cost of potential entrant c_{et} must be known in advance

[22]For the same reason, the oil price used as an instrumental variable in the demand estimation is converted to a 12-month moving average.

to identify the incumbents' marginal costs. Let the entrant's marginal cost be:

$$c_{et} = P_t \times 0.9. \tag{9}$$

Based on accounting data, the net profit margins of Nippon Light Metal[23] in the 1960s ranged from 4% to 6%. As noted in Section 2, to obtain a conservative (or wide) estimate of the identification region, it is necessary to set low marginal costs for the entrant. Therefore, the marginal cost of a potential entrant is set lower than the level analogous to the incumbents' accounting unit cost.[24]

Depending on the form of the demand function specified, the function for estimating the upper bounds, $\underline{Z}^{-1}(.)$, cannot be calculated explicitly. Therefore, in this study, the marginal costs are calculated numerically using the method described in Appendix A.3. Finally, when the aluminum industry is assumed to be characterized by perfect competition, marginal costs can be identified and estimated as:

$$\widehat{MC}_{jt}^{P} = P_t. \tag{10}$$

Testing method Using the different marginal costs estimated by equations (7), (8), and (10), the assumptions of firm conduct can be tested. Pair-wise model selection tests for nonnested models originally developed by Vuong (1989), and further extended by Rivers and Vuong (2002), are beneficial for this exercise. The tests are designed to determine which of the two models being pair-wisely compared is appropriate in explaining the data. A distinctive feature of the test is that both pair-wisely compared models can be misspecified. Furthermore, whereas Vuong (1989) formalized model selection tests based on the criterion of the likelihood of a model, Rivers and

[23] Nippon Light Metal was the only firm specializing in aluminum in the 1960s.

[24] An alternative approach is to refer to engineering costs, which are calculated by building up the cost of raw materials. Tanaka (1969) estimates that the unit cost of aluminum production in 1969 (when the aluminum price was 205,000 yen) was 173,000 yen. Therefore, the cost represented by equation (9) is an intermediate cost falling between the costs inferred from the accounting and engineering data. Several specifications are examined, including (i) $c_{et} = 0.95 \times P_t$, (ii) $c_{et} = 0.85 \times P_t$, and (iii) linear decreases in c_{et} over time from 240 to 180. The third specification reflects the lowering of costs in response to improvements in electricity intensity, which are observed in the data. In all cases, the qualitative results concerning the test of firm conduct are the same as in the case in which equation (9) is assumed.

Vuong (2002) enables a test based on a broad class of criterion functions, including the residual sum of squares or moment-based objective functions.

There are several approaches to the test, depending on the criterion function used in the test. Conduct testing literature using the Vuong-type model selection tests rely mainly on a criterion function such as a likelihood, or the residual sum of squares of an estimated marginal cost function (Gasmi et al., 1992; Bonnet and Dubois, 2010; Doi and Ohashi, 2019). The idea underlying the tests based on these criterion functions is to detect which estimated marginal costs are best correlated to variables that are likely to affect firms' marginal costs (Bonnet and Dubois, 2010). Conversely, Berry and Haile (2014) derive restrictions to empirically distinguish firm conduct. They show that models describing oligopolistic competition are testable using an appropriate instrumental variable. Specifically, if the competition model employed to identify marginal costs is correct, identified cost shocks are independent of the instrument; however, this is not the case when the model is incorrect. Backus et al. (2021) propose using a moment-based criterion function in conduct testing based on Rivers and Vuong (2002)'s framework. They also propose an optimal instrument when there are multiple instrument variables available. Here, the latter approach, which relies on instruments, is employed.

The criterion function that I employ here is represented for model h as:

$$
\begin{aligned}
Q_n^h &= \hat{g}_h' \hat{W} \hat{g}_h, \\
\hat{g}_h &= \frac{1}{n} \sum \hat{\epsilon}_{jt} \hat{z}_{jt}, \\
\hat{W} &= (\frac{1}{n} \sum \hat{z}_{jt} \hat{z}_{jt}')^{-1},
\end{aligned}
$$

where $\hat{\epsilon}_{jt}^h$ is the residual of the estimation of the cost function (6) and $\hat{z}_{jt}$ is the residual of the linear projection of instrument Z_{jt} on independent variables of the cost function (6). The average electricity intensity for firms other than firm j is an appropriate instrument because a firm's electricity intensity only reflects the technological aspects of the firm and is not expected to correlate with the other firms' cost shocks.[25] The criterion function corresponds to the GMM objective function with the moment condition of $E[\epsilon_{jt}^{h} Z_{jt}] = 0$.

Taking any two models h and h', the null hypothesis that the two models equally satisfy the moment condition can be tested. The Rivers and Vuong (2002)'s test statistic is given by:

$$T = \frac{\sqrt{n}(Q_n^h - Q_n^{h'})}{\hat{\sigma}_n^{hh'}}, \tag{11}$$

where $\hat{\sigma}_n^{hh'2}$ is the estimator of the asymptotic variance of the difference in the criterion functions.[26] Because the specifications of our econometric models are nonnested, the test statistic has a standard normal distribution under the null hypothesis. Therefore, it is possible to select a better model by comparing the value of the statistic with critical values of the standard normal distribution. Because the criterion function (11) is a lack-of-fit criterion, the null is rejected in favor of model h rather than h' if the test statistic T is smaller than -1.96 in the test with $\alpha = 0.05$.

4.2 Data

Most of the data for this study are sourced from the *Yearbook of Aluminum Smelting*[27], which was issued annually from 1948 to 1985, and distributed only to divisions in MITI and organizations associated with the light metal business.

The yearbook provides useful monthly plant-level information on production, shipments, and raw material consumption, including electricity use. Because the yearbook includes industry-level total shipment values and volume information, the average aluminum shipment price data can be calculated by dividing the total shipment values by the total shipment volumes. The import data on bauxite and primary aluminum are drawn from *Trade Statistics of Japan* from the Ministry of

[25]As a robustness check, I use the difference between firm j's electricity intensity and the average electricity intensity for firms other than firm j as the instrumental variable to construct the criterion function. The qualitative results remain unchanged.

[26]There are two ways to estimate the asymptotic variance $\sigma_n^{hh'2}$, namely the bootstrapping and delta methods. See Backus et al. (2021) for the bootstrapping method and Duarte et al. (2022) for the delta method. I obtain similar results from trying both methods, and report the result using the delta method.

[27]In Japanese, the title of the yearbook is "Aluminum Seiren Kogyo Tokei Nenpo." The Japanese Aluminum Association provided me with copies of it.

Finance. The oil price used in the analysis is the West Texas Intermediate crude oil price, which is converted into yen using monthly average yen–dollar rates. The total floor area of buildings on which construction had commenced is sourced from the *Survey of Building Construction Work Started*. All price variables are deflated by an industry deflator (the Corporate Goods Price Index in nonferrous metal products) in constant 1970 Japanese yen.

Month-level data from January 1955 to December 1980 (312 months) were used for the empirical analysis, although the yearbook provides data from 1950 to 1985. I confine the sample period for the empirical analysis to the selected dates for several reasons. First, I use data from 1955 onward because this was the year in which aluminum production in Japan recovered to its prewar level. This also excludes the Korean War (1950–1953) from the analysis, which significantly and unusually affected Japanese aluminum demand. Second, I end the period of analysis in 1980 owing to concerns regarding price data credibility after 1980. The yearbook provides price information other than the shipment price, which is used in the empirical analysis. Prices surveyed by several institutions are listed in the yearbook on a monthly basis. Although the surveyed price data moves in the same way as shipping price data until 1980, the surveyed price data show a downward trend despite the shipment price remaining high after 1980. Therefore, I only used data up to 1980 for the analysis. Table 2 provides descriptive statistics on each variable.

[——Table 2——]

4.3 Results

Demand estimation Table 3 shows the estimation results of the demand function (5). The demand equation is estimated using ordinary least squares (OLS) and 2SLS. The first and second columns in the table show the estimation results for 2SLS and OLS, respectively. The third column presents the results of the first-stage regression of the 2SLS estimation. The estimated price coefficients have the expected signs and statistical significance in the 2SLS estimation. The results of the 2SLS estimation suggest that the price elasticity of aluminum demand is low ($\hat{\alpha} = -0.338$ in column 1). The estimate of the elasticity is similar to that of a previous study; Boyd et al. (1995) estimate that elasticity averaged −0.21 during the period 1965–1988 for the US aluminum industry. The estimate of the coefficient for the demand shifter, the total floor area of buildings on which construction had commenced, also shows the expected sign and statistical significance. The 2SLS estimation results are employed for the following cost function estimation and tests of firm conduct.

[—–Table3—–]

Cost and cost function estimation Using the estimation results of the demand function, each firm's marginal costs under the different assumptions of firm conduct are estimated.[28] Figure 3 shows the estimated marginal costs until 1974. The dashed, solid, and dotted lines represent marginal costs estimated by the models assuming Cournot competition, entry deterrence, and perfect competition, respectively. Under Cournot competition, the more that firms produce, the lower the identified marginal cost becomes. The figure shows that this is also the case under the entry-deterrence model; Nippon Light Metal held a high market share in the 1950s and 1960s, and its marginal costs are estimated to be lower than those of the other firms in the Cournot and entry-deterrence models.

[—– Figure 3—–]

To test the models, the marginal cost functions represented by equation (6) are estimated using two different samples. One sample includes data for the period before the 1973 oil crisis (i.e., from January 1955 to December 1973), whereas the other includes data after the shock (i.e., from January 1974 to December 1980). As seen in Section 3, in the first period, the incumbent firms were likely to be exposed to entry threats and, hence, might have attempted to deter entry. Conversely, after the 1973 oil shock, entry threats disappeared as a result of the reduced profitability of the industry.

[—– Table 4—–]

[28]Although I use month-level data to estimate marginal costs, the values are very similar if I aggregate the month-level data into quarterly-level data.

Table 4 shows the cost function estimation results. Columns (1), (2), and (3) are estimated employing the pre-oil-shock data and using the marginal costs estimated under the assumptions of Cournot, entry deterrence, and perfect competition, respectively. Columns (4) and (5) are estimated employing the post-oil-shock data and using the marginal costs estimated under the assumptions of Cournot and perfect competition, respectively.

To interpret the estimated coefficients, it is useful to introduce engineering and chemical formulas that convert the raw materials, crude oil and bauxite, into the product, aluminum. The estimated cost function includes the bauxite price and the product of the oil price and electricity intensity as explanatory variables. First, β_0, the coefficient of the bauxite price, identifies how much bauxite is used to produce 1 ton of aluminum. Because about 4 tons of bauxite are consumed to produce 1 ton of aluminum, β_0 is expected to be close to 4. Second, β_1, the coefficient on the product term, identifies how much crude oil is needed to produce 1 MWh of electricity. To understand the interpretation of the coefficient, recall that electricity is needed to smelt aluminum and that crude oil is burned to generate electricity. Because $\beta_1 W_{jt}$ is equal to the marginal and unit cost of oil to produce 1 ton of aluminum, the following decomposition reveals why β_1 identifies the oil intensity for the generation of 1 MWh of electricity.

$$
\begin{aligned}
\beta_1 W_{jt} &= \text{unit cost of oil (thousand yen / ton)} \\
&= \text{oil intensity (barrels / ton)} \\
&\qquad\qquad \times \text{oil price (thousand yen / barrel)} \\
&= \text{oil intensity for electricity (barrels / MWh)} \times \text{electricity intensity (MWh / ton)} \\
&\qquad\qquad \times \text{oil price (thousand yen / barrel)},
\end{aligned}
$$

where the oil intensity for electricity represents how much crude oil is used to produce 1 unit of electricity. According to several energy-related statistics, about 1.5 barrels of crude oil enables the generation of 1 MWh of electricity. Therefore, we expect β_1 to be 1.5.[29]

[29]The conversion formula is based on modern technology, and there are two assumptions behind the formula. Burning fuel such as crude oil or gas releases thermal energy. How much energy the burned fuel produces depends on

Both β_0 and β_1 are estimated with the economically correct signs in Table 4, and the estimated values vary depending on the assumption regarding firm conduct and the sample period. If model selection was based on the values of the estimated coefficients, a model with a $\hat{\beta}_0$ close to four and a $\hat{\beta}_1$ close to 1.5 would be selected. Therefore, the Cournot and entry-deterrence models may be selected in the pre-oil-shock period and the Cournot model may be selected in the post-oil-shock period.

Model selection test Employing the residuals of the cost function estimation and the instrumental variable Z_{jt}, the average electricity intensity for firms other than firm j at time t, I perform the model selection test proposed by Rivers and Vuong (2002). I perform not only the test employing the GMM objective function as a criterion but also the test for which the criterion function is the residual sum of squares (RSS). Table 5 reports the results from the tests. The upper half, panel (a), uses the GMM objective function, whereas the bottom half, panel (b), uses the RSS as a criterion. The first and second columns display the results employing the sample before the 1973 oil crisis and the third column reports the test employing the sample after the 1973 oil crisis. Because both are lack-of-fit criterion functions, negative values of the test statistics mean that the model in the row displays a better fit than the model in the column.

[—–Table 5—–]

For the pre-oil-shock period, the table shows that the entry-deterrence model better fits the data than does the Cournot competition model for both criteria, with statistical significance. When

the composition of the imported crude oil. The Agency for Natural Resources and Energy, a division in the Ministry of Economy, Trade, and Industry, has established standard gross calorific values for various energy sources to be used in energy-related statistics. It estimates that 1 liter of crude oil enables the generation of 38.26 MJ of thermal energy (Agency for Natural Resources and Energy, 2020). The standard values are revised every few years; however, the values for crude oil remain almost the same. Furthermore, not all of the thermal energy generated is converted into electricity. The formula assumes that 9,370 joules of thermal energy are required to use 1 Wh of electricity (Agency for Natural Resources and Energy, 2020). This means that 38.4% of the generated thermal energy is consumed as electricity because 1 Wh equals 3,600 joules if the loss is zero. How much thermal energy is transferred as electricity at the point of consumption is affected by several factors, including the efficiency in generating and transmitting electricity. Thermal efficiency, a measure of the performance of a generator, has improved from about 30% in the 1960s to about 40% today in Japan (The Federation of Electric Power Companies of Japan, each year). However, the improvement has not been sufficient to distort the interpretation of the coefficients.

the entry-deterrence and perfect competition models are compared, the result of the test differs depending on which of the two criteria is adopted. Specifically, the GMM criterion slightly favors the entry-deterrence model, whereas the RSS criterion strongly favors the perfect competition model. The results of the two tests employing the pre-oil-crisis sample can be summarized as follows. First, the GMM criterion identifies the entry-deterrence model as the best model, whereas the RSS criterion identifies the perfect competition model as the best model.

For the post-oil-shock period, the result of the test shows that the Cournot competition model better fits the data than the perfect competition model in terms of both criteria, although the results of the RSS criterion are not statistically significant.

Therefore, the testing results suggest that the 1973 oil shock changed the Japanese aluminum smelting industry from an environment in which the threat of entry prevailed and incumbents attempted to deter entry, to an environment where Cournot competition among incumbents prevailed in the absence of entry threats. This conclusion is consistent with the historical fact that several companies ceased their efforts to enter the industry after the 1973 oil shock.

5 Conclusion

In this study, I propose a structural model of noncooperative entry deterrence. I show that the marginal costs of incumbents are interval-identified given the marginal cost of an entrant. Furthermore, using the upper bounds on the interval-identified marginal costs, I conduct a model selection test and show that the entry-deterrence model better explains the data for the Japanese aluminum industry facing entry threat than does the Cournot model with no entry threats. In addition, I point out a caveat of using the upper bound, which is that it assumes that the equilibrium arises where the incumbents are most affected by the entry threat.

Finally, I note two limitations of this study. First, the entry-deterrence model essentially involves a static two-stage game. In the model, the incumbents and a potential entrant only take into account their current profit and, therefore, the incumbents attempt to deter a potential entrant's "hit and run" entry. However, in the real world, both incumbents and the entrant take into account not only their current profit but also their future profit when determining their strategic decisions. Therefore, a dynamic model would be more appropriate to describe the industry. However, the model in this paper is a static one without dynamic aspects.

The effects of introducing dynamics may be imagined. Sweeting et al. (2020) extend a two-stage limit pricing entry-deterrence model to allow for any finite number of periods larger than two. They show that because the incentive to deter entry becomes larger than that in the two-stage game, their extended limit pricing model can explain a larger price decline to deter entry. The result of Sweeting et al. (2020) may suggest a consequence of introducing dynamics into the Gilbert and Vives (1986) model. If, following their results, the introduction of dynamics increased the incentive to deter entry, an entry-deterring equilibrium would occur even at high marginal costs and then higher upper bounds on marginal costs might be identified.

Second, marginal cost is interval-identified. There are two reasons for this: (i) the difficulty of identifying where the limit output Y specifically lies within the interval $[X_C, \overline{Y}]$, and (ii) the existence of multiple equilibria. Because the data do not indicate where the limit output Y is in $[X_C, \overline{Y}]$, the upper bounds on marginal costs correspond to the marginal costs identified under the equilibrium where all firms are barely deterring entry. Furthermore, because there are multiple equilibria in the game, the knowledge of where Y is in between X^C and $\overline{Y}$ is not sufficient for the point-identification. To introduce uncertainty in entry costs and cross sections of markets with observables that affect the uncertainty may assist with the point-identification of marginal costs. Waldman (1987) introduces uncertainty on the limit output Y in the model of Gilbert and Vives (1986). In his model, the first-order condition for the incumbents' profit maximization is used to characterize the entry-deterring equilibrium. Therefore, if the variables that affect the uncertainty associated with the entry cost are observable, the first-order condition may point-identify the marginal cost. Furthermore, introducing cost uncertainty would be appropriate to describe real-world environments. Examination of the empirical validity of these approaches is an important subject that I reserve for future study.

A Appendix

This appendix provides a formal derivation of the best response function represented by equation (2), the proof of Proposition 2, and a method for numerical calculation of the upper bounds of the incumbents' marginal cost. The calculation method reveals why the entrant's marginal cost c_e should be set low to construct a conservative identification region for the incumbents' marginal cost.

A.1 Derivation of the best response function $\phi_i(Z)$

Consider a game as described in Section 2 and an optimization problem for incumbent i. Let Z be the total output of firms excluding firm i, and let $\phi_i(Z)$ be the best response. If there was no threat of entry, firm i would produce according to its Cournot best response $r(Z, c_i)$. Therefore, whenever $Z + r(Z, c_i) \geq Y$, the best response of firm i corresponds to its Cournot best response. Let $\overline{Z}(Y, c_i)$ satisfy the following equation:

$$r(Z, c_i) + Z = Y. \tag{12}$$

Because the Cournot best response function has a slope between -1 and 0, as revealed in the following Lemma 1, the left-hand side of equation (12) is increasing in Z. Therefore, the solution of (12) is unique and the solution $\overline{Z}(Y, c_i)$ represents the minimum output level Z with which firm i can block entry by merely producing the Cournot optimal output. If the solution is negative, it is assumed that $\overline{Z}(Y, c_i) = 0$. In summary, if $Z \geq \overline{Z}(Y, c_i)$, the best response $\phi_i(Z)$ is equal to the Cournot optimal output $r(Z, c_i)$.

When $Z < \overline{Z}(Y, c_i)$, firm i cannot block entry by merely producing $r(Z, c_i)$ because $X_0 = r(Z, c_i) + Z$, which is the total output in the first stage, is less than Y. In this case, incumbent i has two options: deterring entry or allowing it. When firm i attempts to deter entry, it needs to produce more than $Y - Z$. Firm i has no incentive to produce an amount larger than $Y - Z$ for the purpose of entry deterrence because $Y - Z > r(Z, c_i)$ when $Z < \overline{Z}(Y, c_i)$. Hence, when firm i chooses to deter entry, it earns:

$$\overline{\pi}^{NE}(Z, Y, c_i) = (P(Y) - c_i)(Y - Z). \tag{13}$$

Here, $\overline{\pi}^{NE}(Z, Y, c_i)$ represents the value (or maximal profit) of the incumbent arising from deterring entry. Conversely, when entry is allowed, incumbent i plays the role of a Stackelberg leader. Let $s(Z, c_i, c_e)$ be the optimal output of firm i when the potential entrant enters the market and produces optimally given a first-stage total output. When incumbent i chooses to allow entry, it earns:

$$\overline{\pi}^{E}(Z, c_i, c_e) = (P(s(Z, c_i, c_e) + Z + r(s(Z, c_i, c_e) + Z, c_e)) - c_i)s(Z, c_i, c_e). \tag{14}$$

Here, $\overline{\pi}^{E}(Z, c_i, c_e)$ represents the value (or maximal profit) of the incumbent arising from allowing entry.

Firm i deters or allows entry by comparing the two values of (13) and (14). Firm i's optimal strategy involves a threshold value of Z; when Z is larger than the threshold, entry is deterred; otherwise, entry is allowed. First, the value of deterring entry represented by equation (13) is a linear decreasing function in Z. Second, as shown in Lemma 1, the value of allowing entry represented by equation (14) is strictly convex and decreasing in Z. Third, when $Z = \overline{Z}(Y, c_i)$, because $Y - Z$ corresponds to the Cournot best response, the value of deterring entry is larger than that of allowing entry. These three arguments guarantee that a unique solution exists to the equation:

$$\overline{\pi}^{NE}(Z, Y, c_i) = \overline{\pi}^{E}(Z, c_i, c_e). \tag{15}$$

Let the solution to equation (15) be $\underline{Z}(Y, c_i, c_e)$ if it is positive, and zero otherwise. When $\underline{Z}(Y, c_i, c_e) \leq Z < \overline{Z}(Y, c_i)$, the value of deterring entry is larger than that of allowing entry and thus incumbent i produces $Y - Z$. Conversely, when $0 \leq Z < \underline{Z}(Y, c_i, c_e)$, incumbent i allows entry and produces $s(Z, c_i, c_e)$. Therefore, $\underline{Z}(Y, c_i, c_e)$ represents the minimum output level Z at which incumbent i has an incentive to deter entry. In conclusion, the incumbent's best response function is represented by equation (2).

A.2 Proof of Proposition 2

The proposition states that the minimum level of the other firms' outputs required for firm i to deter entry is increasing in its marginal cost. To prove the proposition, several properties related to the two value functions in equations (13) and (14) and the response functions of $r(Z, c_i)$ and $s(Z, c_i, c_e)$ must be established. The following two lemmas summarize these properties.

Lemma 1 (Gilbert and Vives 1986) *The response functions $r(Z, c_i)$ and $s(Z, c_i, c_e)$ are decreasing in Z and have a slope between -1 and 0. The value of allowing entry $\overline{\pi}(Z, c_i, c_e)$ is strictly decreasing and convex in Z.*

Proof. The proof is almost the same as that in Gilbert and Vives (1986).[30] When $r(Z, c_i)$ is positive, it solves the first-order condition for profit optimization. From the implicit function theorem, I have:

$$\frac{\partial r(Z, c_i)}{\partial Z} = -\frac{P' + P''x}{2P' + P''x}.$$

Because the inverse demand function is assumed to be concave, $P'' < 0$, the Cournot best response has a slope between -1 and 0. In the same manner, when $s(Z, c_i, c_e)$ is positive, it solves the first-order condition:

$$P(x + Z + r_e(x + Z)) - c_i + P'(x + Z + r_e(x + Z))(1 + r_e')x = 0, \tag{16}$$

[30]Although Gilbert and Vives (1986) provide a proof under cost homogeneity, it is possible to provide a proof under cost heterogeneity in exactly the same way. Gilbert and Vives (1986) do not show the comparative statics on the incumbents' marginal costs, which would be most relevant for the empirical analysis in this study, because they assume that marginal costs are zero for all firms.

where $r_e(.)$ is the abbreviation of $r(., c_e)$. The implicit function theorem produces:

$$\frac{\partial s(Z, c_i, c_e)}{\partial Z} = -\frac{P'(1+r_e') + P''(1+r_e')(1+r_e')x + P'r_e''x}{P'(1+r_e') + P''(1+r_e')(1+r_e')x + P'(1+r_e' + r_e''x)}$$
$$= -\frac{(1+r_e')(P' + P''(1+r_e')x) + xP'r_e''}{(1+r_e')(P' + P''(1+r_e')x) + xP'r_e'' + (1+r_e')P'}.$$

Therefore, the response function $s(Z, c_i, c_e)$ has a slope between -1 and 0 by the assumption that the Cournot best response function $r(Z, c_i)$ is convex in Z, i.e., $r_e'' > 0$.

Finally, I show that the value of allowing entry represented by equation (14) is decreasing and convex in Z. Let π^E be the profit when entry is realized, i.e., $\pi^E = P(x + Z + r_e(x + Z))x - c_i x$. Because $\overline{\pi}^E(Z, c_i, c_e)$ is the value function of an incumbent as a Stackelberg leader, applying the envelope theorem gives:

$$\frac{\partial \overline{\pi}^E}{\partial Z} = \frac{\partial \pi^E}{\partial Z}|x = s(Z, c_i, c_e)$$
$$= P'(1+r_e')x|x = s(Z, c_i, c_e)$$
$$= sP'(1+r_e')$$
$$= -P(s + Z + r_e(s+Z)) + c_i.$$

The third and fourth lines show that the value function $\overline{\pi}^E$ is decreasing in Z. The fourth equality uses the first-order condition of (16). Therefore, $\frac{\partial^2 \overline{\pi}^E}{\partial Z^2} = -P'(1+s')(1+r_e')$. Because s' and r_e' is between -1 and 0, the second-order derivative is positive and $\overline{\pi}^E$ is convex in Z. ■

Lemma 2 *The two value functions $\overline{\pi}^{NE}(Z, Y, c_i)$ and $\overline{\pi}^E(Z, c_i, c_e)$ have partial derivatives as follows:*

$$\frac{\partial \overline{\pi}^{NE}}{\partial c_i} = -(Y - Z), \qquad \frac{\partial \overline{\pi}^E}{\partial c_i} = -s,$$
$$\frac{\partial \overline{\pi}^{NE}}{\partial Z} = -(P(Y) - c_i), \qquad \frac{\partial \overline{\pi}^E}{\partial Z} = sP'(1+r_e'),$$
$$\frac{\partial \overline{\pi}^{NE}}{\partial Y} = P'(Y)(Y - Z) + P(Y) - c_i, \qquad \frac{\partial \overline{\pi}^E}{\partial Y} = 0,$$

where s and r_e are the abbreviations of $s(Z, c_i, c_e)$ and $r(s + Z, c_e)$, respectively, for notational ease.

Proof. The result for the partial derivatives of the value of deterring entry is straightforwardly calculated from equation (13). Applying the envelope theorem to the value of allowing entry gives:

$$\begin{aligned}
\frac{\partial \overline{\pi}^E}{\partial c_i} &= \frac{\partial \pi^E}{\partial c_i}|_{x=s(Z,c_i,c_e)} \\
&= \frac{\partial}{\partial c_i}(P(Z + x + r_e(x + Z))x - c_i x)|_{x=s(Z,c_i,c_e)} \\
&= -x|_{x=s(Z,c_i,c_e)} \\
&= -s, \\
\frac{\partial \overline{\pi}^E}{\partial Y} &= \frac{\partial \pi^E}{\partial Y}(x)|_{x=s(Z,c_i,c_e)} \\
&= 0.
\end{aligned}$$

The derivation of $\partial \overline{\pi}^E / \partial Z$ is in the proof of Lemma 1. ■

Proposition 2 (Repost) *When $\underline{Z}(Y, c_i, c_e) > 0$, $\underline{Z}(Y, c_i, c_e)$ is increasing in c_i.*

Proof. To guarantee that $\underline{Z}$ solves equation (15), take (Y, c_i, c_e) such that $\underline{Z} > 0$. Because $\underline{Z}$ solves equation (15), from the implicit function theorem, the following equation holds:

$$\begin{aligned}
\frac{\partial \underline{Z}}{\partial c} &= -\frac{\frac{\partial \overline{\pi}^{NE}}{\partial c_i} - \frac{\partial \overline{\pi}^{E}}{\partial c_i}}{\frac{\partial \overline{\pi}^{NE}}{\partial Z} - \frac{\partial \overline{\pi}^{E}}{\partial Z}}|Z = \underline{Z} \\
&= -\frac{-(Y - Z) - (-s)}{-(P(Y) - c_i) - sP'(1 + r_e')}|Z = \underline{Z} \\
&= \frac{Y - (s + Z)}{-(P(Y) - c_i) + P(s + Z + r(s + Z)) - c_i}|Z = \underline{Z} \\
&= \frac{Y - (s + Z)}{P(X^E) - P(Y)}|Z = \underline{Z} \\
&> 0,
\end{aligned}$$

where X^E represents the total output when entry is allowed, i.e., $X^E = s + Z + r_e(s + Z)$. The third equality uses the first-order condition of a Stackelberg leader represented by equation (16). When $Z = \underline{Z}(Y, c_i, c_e)$, $Y > s + Z$ holds.[31] As $\overline{\pi}^{NE} = (P(Y) - c_i) \times (Y - Z) = (P(X^E) - c_i) \times s = \overline{\pi}^E$ at $Z = \underline{Z}$, $P(X^E) > P(Y)$ and the last inequality hold. ■

A.3 A method to calculate numerically the upper bounds of incumbents' marginal costs; right-hand side of equation (4)

To calculate the right-hand side of equation (4), the function $\underline{Z}^{-1}(Y - x_i, Y, c_e)$ is required. However, the function may not be derived explicitly, depending on the shape of the demand function specified and estimated in an empirical analysis. If the function may not be derived explicitly or even when the analytical calculation is difficult, equation (15) suggests an alternative approach for numerically calculating the upper bounds. Because incumbent i, which has the upper bound, is indifferent between deterring or allowing entry given the other firms' total output X_{-i}, the upper bound solves the following equation (17) for c_i:

$$\overline{\pi}^E(X_{-i}, c_i, c_e) = \overline{\pi}^{NE}(X_{-i}, X, c_i), \tag{17}$$

where X is the observable industry total output, which corresponds to Y. The left-hand side $\overline{\pi}^E(X_{-i}, c_i, c_e)$ is the value of a Stackelberg leader as a function of c_i, given the other firms' output X_{-i} and the entrant's marginal cost c_e. This function is represented as:

$$\overline{\pi}^E(X_{-i}, c_i, c_e) = (P(s(X_{-i}, c_i, c_e) + X_{-i} + r_e(s(X_{-i}, c_i, c_e) + X_{-i})) - c_i) \times s(X_{-i}, c_i, c_e).$$

[31] The property that $Y > s(Z, c_i, c_e) + Z$ at $Z = \underline{Z}(Y, c_i, c_e)$ can be proved by contradiction. Assume that $Y \leq s(Z, c_i, c_e) + Z$ at $Z = \underline{Z}(Y, c_i, c_e)$. The assumption induces that $P(Y) > P(X^E) = P(s + Z + r_e(s + Z))$ at $Z = \underline{Z}$ because the values of deterring and allowing entry are equal at $Z = \underline{Z}$. When $Z > \underline{Z}$, the value of deterring entry exceeds that of allowing entry. Therefore, $\partial\overline{\pi}^{NE}/\partial Z > \partial\overline{\pi}^E/\partial Z$ at $Z = \underline{Z}$. This induces $\partial\overline{\pi}^{NE}/\partial Z > \partial\overline{\pi}^E/\partial Z \Leftrightarrow -(P(Y) - c_i) > -(P(X^E) - c_i) \Leftrightarrow P(Y) < P(X^E)$. This contradicts the property above and therefore $s(Z) < Y - Z$ when $Z = \underline{Z}(Y, c_i, c_e)$.

The value function $\overline{\pi}^E$, the response function $s(.)$, and $r_e(.)$ are computable because (X_{-i}, c_e) is observed and $P(.)$ is estimated. Conversely, the right-hand side of equation (17) is the value of deterring entry as a function of c_i. This function is represented as:

$$\begin{aligned}\overline{\pi}^{NE}(X_{-i}, X, c_i) &= (P(X) - c_i) \times (X - X_{-i}) \\ &= -x_i c_i + P x_i.\end{aligned}$$

This is also computable because (P, x_i) is observed. By computing the two value functions and calculating the intersection of the two, the upper bound of the marginal costs can be calculated.

Figure 4 shows an example of how to calculate the upper bound marginal costs. The horizontal axis represents marginal costs, and the vertical axis represents profits (values). The downward-sloping straight line represents the value of deterring entry for different values of c_i, given the other firms' output $Z = X_{-i}$ and the limit output $Y = X$. The curved dotted line represents the value of allowing entry for different c_is given the other firms' output $Z = X_{-i}$ and the entrant's marginal cost c_e. The intersection of the two functions is the upper bound on c_i.

In addition, the figure reveals that the entrant's marginal cost is set to the lowest value of a researcher's prior belief, i.e., $c_e = \underline{c}_e$, to construct the identification region on c_i conservatively. Because the value of allowing entry $\overline{\pi}^E(X_{-i}, c_i, c_e)$ is increasing in c_e, a decrease in c_e shifts the curved dotted line downward and the intersection of the two functions moves to the right: i.e., the upper bound on c_i increases.

[—– Figure 4 —–]

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Tables

Table 1: Shipments by destinations

Year	Total Shipment	Transport	Construction	Metal Product	Packaging	Others
1950–1959	81 (100%)	10 (13%)	2 (3%)	16 (20%)	1 (3%)	51(63%)
1960–1969	497 (100%)	106 (21%)	78 (16%)	83 (17%)	6 (1%)	225 (45%)
1970–1979	1729 (100%)	366 (21%)	571 (33%)	240 (14%)	67(4%)	485 (28%)
1980–1989	2625 (100%)	761 (29%)	747 (28%)	376 (14%)	173 (7%)	568(22%)

Note: Secondary stage annual shipments by shipping destinations in thousands of tons, averaged over 10 years, are listed. The values in the parentheses are the ratios of shipments to the destination over the total shipments. As the raw materials used in the second stage include not only primary aluminum but also secondary aluminum, the total shipment in the table is larger than the value of primary aluminum demand in Figure 1.

Table 2: Summary statistics

variables	unit	n	mean	sd	min	max
production	thousand tons	312	46.42	34.65	3.81	104.24
import	thousand tons	312	16.35	18.99	0.00	89.15
floor	million m^2	312	12.07	6.60	2.13	26.34
eunit	MWh per ton	312	17.46	1.55	14.89	21.50
price	thousand JPY per ton	312	268.75	39.65	186.53	332.50
oil price	thousand JPY per barrel	312	1.87	0.95	0.90	5.62
bauxite price	thousand JPY per ton	312	4.83	1.50	2.11	10.71
prodF	thousand tons	1313	11.03	7.31	0.21	28.31
eunitF	MWh per ton	1313	17.16	2.23	12.63	61.11

Note: The variables “floor” and “eunit” denote the ‘total floor area of buildings on which construction had commenced’ and the “electricity intensity,” respectively. The variables “prodF” and “eunitF” represent the firm-level production quantity and electricity intensity, respectively.

Table 3: Demand estimates

	IV	*OLS*	*F.S.*
	(1)	(2)	(3)
price	-0.338^{**}	-0.079	
	(0.139)	(0.086)	
floor (M.A.)	1.020^{***}	1.138^{***}	0.131
	(0.089)	(0.078)	(0.085)
eunit			0.588^{**}
			(0.243)
oil price (M.A.)			0.364^{***}
			(0.063)
bauxite price			0.235^{***}
			(0.045)
Observations	312	312	312
R^2	0.989	0.990	0.756
Adjusted R^2	0.989	0.989	0.743
Residual S. E.	0.123	0.119	0.077

Note: The dependent variable is demand, which is calculated as the sum of domestic production and imports in columns (1) and (2), whereas the dependent variable is the aluminum price in column (3), as the column shows the first-stage regression of the 2SLS estimation. All three specifications include a linear time trend and month fixed effects; their estimated coefficients are not included in the table. For the floor variable, because there appear to be delays in the effect of floor area under construction on aluminum demand, as seen in Figure 1, the 12-month moving averages are used. Because the effect of oil prices on smelters' production cost is potentially delayed, the oil prices are transformed into 12-month moving averages. All dependent and independent variables except the time trend and the month fixed effects are transformed into logarithmic forms. Heteroskedasticity and serial correlation robust Newey–West standard errors are shown in parentheses. The symbols *, **, and *** denote statistical significance at the 10%, 5%, and 1% levels, respectively.

Table 4: Cost function estimates

	Dependent variable:				
	$\widehat{MC}^C$	$\widehat{MC}^{ED}$	$\widehat{MC}^P$	$\widehat{MC}^C$	$\widehat{MC}^P$
	(1)	(2)	(3)	(4)	(5)
bauxite price	1.961	7.734***	9.426***	11.419***	29.557***
	(1.247)	(1.521)	(1.608)	(3.488)	(1.400)
eunitF ×oil price (M.A.)	1.440	4.452***	5.521***	0.344*	0.267***
	(1.504)	(0.520)	(0.619)	(0.208)	(0.080)
Observations	846	846	846	467	467
R^2	0.714	0.645	0.829	0.805	0.590
Adjusted R^2	0.708	0.637	0.825	0.797	0.573
Residual S.E.	45.458	23.328	16.834	23.542	23.735
Sample		Before		After	

Note: The dependent variables are the marginal costs identified under the different identification assumptions of competition. All specifications include a linear time trend, month fixed effects, and firm fixed effects as explanatory variables, although the estimated coefficients are omitted from the table. Because the effect of the oil price on smelting production cost potentially involves delays, the oil prices are transformed into 12-month moving averages. Columns (1), (2), and (3) are estimated using the sample period before the 1973 oil crisis, whereas columns (4) and (5) use the period after the 1973 oil crisis. Standard errors are clustered by firm and shown in parentheses. The symbols *, **, and *** denote statistical significance at the 10%, 5%, and 1% levels, respectively.

Table 5: Testing results

Panel (a) Criterion : GMM

Sample		Before		After
model h/h'		(ii) Entry Deterrence	(iii) Perfect Competition	(iii) Perfect Competition
(i)	Cournot Competition	2.82 (0.36)	2.38 (0.45)	−1.70 (0.44)
(ii)	Entry Deterrence	–	−1.15 (1.14)	–

Panel (b) Criterion : RSS

Sample		Before		After
model h/h'		(ii) Entry Deterrence	(iii) Perfect Competition	(iii) Perfect Competition
(i)	Cournot Competition	18.52 (3.74)	17.50 (1.57)	−0.25 (3.35)
(ii)	Entry Deterrence	–	9.27 (2.94)	–

Note: Panel (a) lists the values of model selection test statistics with the GMM criterion function based on moment restriction, whereas panel (b) relies on RSS as a criterion function. As the criterion functions used in panels (a) and (b) are both lack-of-fit criterion functions, a negative value suggests that the model in the row displays a better fit than the model in the column. I do not estimate the marginal cost function under the assumption of entry deterrence after the 1973 oil crisis. Therefore, only the test that compares the Cournot and perfect competition models is conducted using the sample after the 1973 oil crisis. To take into account the effect of uncertainty on the demand estimation, I report the standard errors of the test statistics over 100 bootstrap replications in parentheses. For each bootstrap replication, demand and cost functions are reestimated and the test statistics are recomputed.

Figures

Figure 1: Demand and construction activity

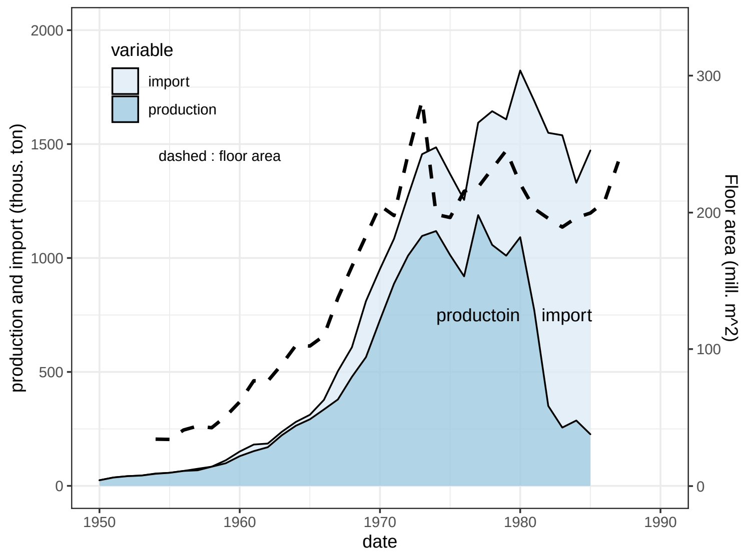


Figure 2: Aluminum, oil, and bauxite prices

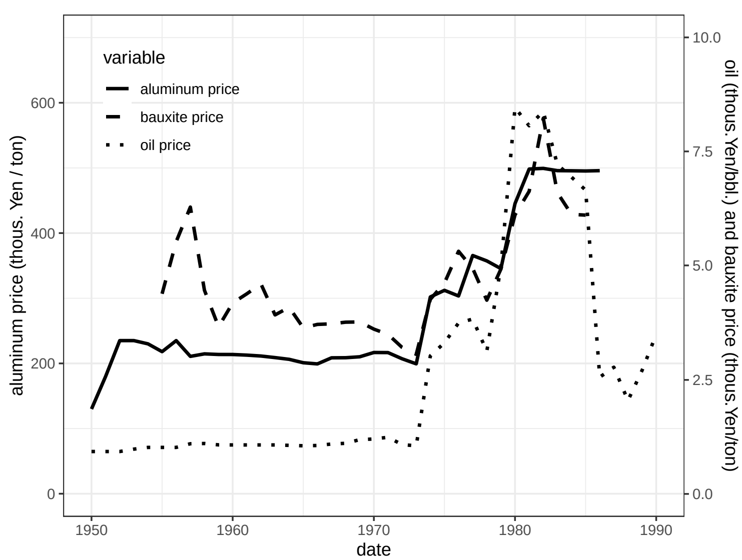


Figure 3: Identified marginal costs under three competing models

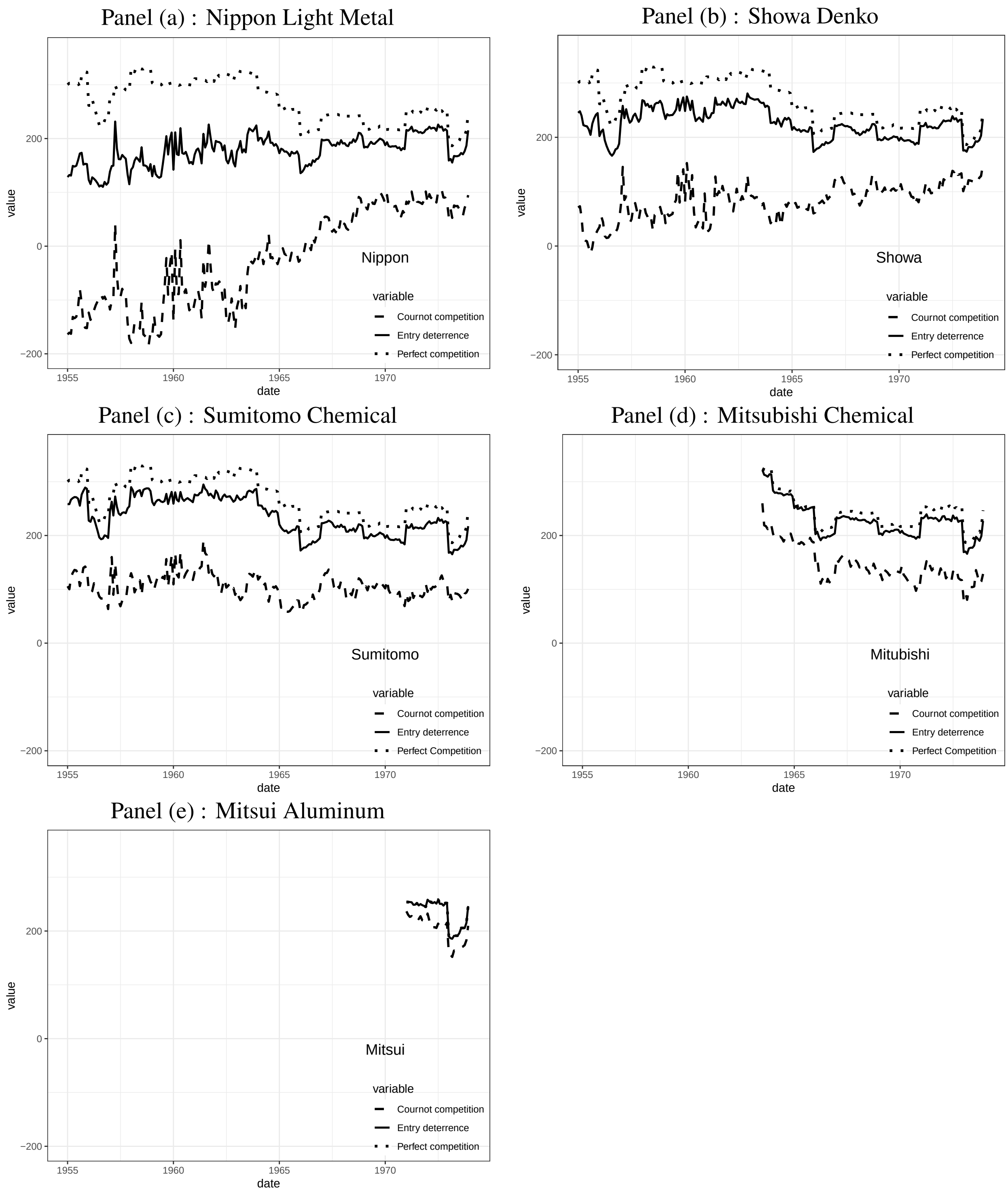
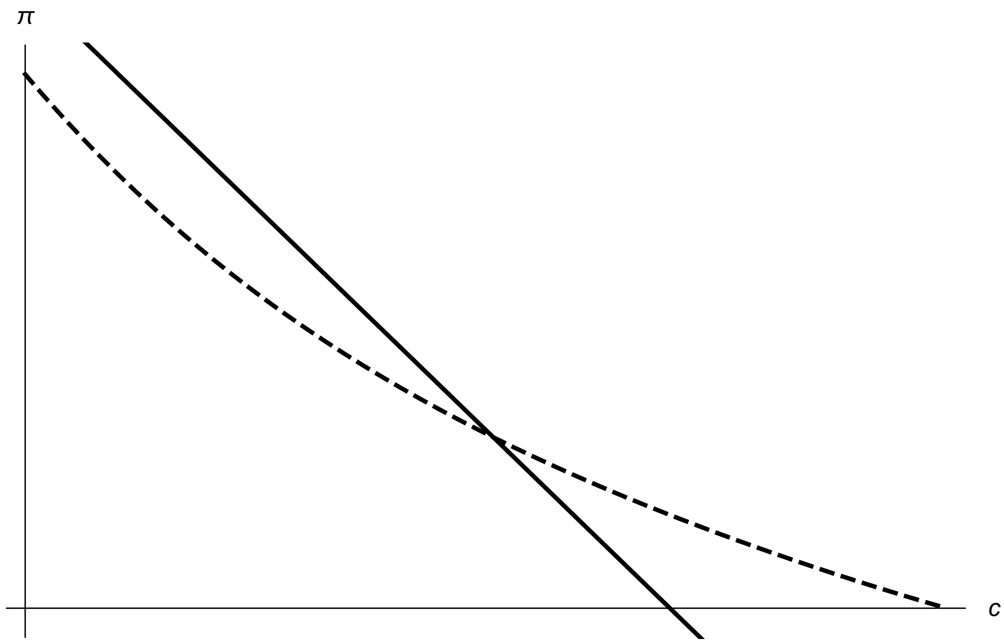


Figure 4: Upper bound on c_i



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