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Article

Breaking Cournot: The Effects of Capacity-Adjusting Technology

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Abstract: The technological improvements modeled for Cournot competition have primarily focused on production cost reductions and scope effects. We consider a case where the technology improves the ability to affect the production capacity constraints instead. We find that although such technological progress entails public benefits in the form of greater consumer surplus and social welfare, it is likely to have limited and even sometimes harmful private effects (e.g., to firm profits). We formally model this technological improvement possibility through the relevant variants of oligopolies and rival technological asymmetries. We describe and discuss the strategic implications for managers and policy-makers considering investing and exploiting such capacity-adjusting technologies. We also flesh out the many core areas for future work to follow up on in our initial unique results.

Keywords: cournot competition; process technology; profits; social welfare; strategic commitment

JEL Classification: D24; D25; D43; L13; L23; M11; O33; C72; C73

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1. Introduction

Dealing with the challenge of *production capacity constraints* has been a strategic issue for management since the beginning of commerce (e.g., Amram and Kulatilaka 1999; Ponte et al. 2017; Trickett 1946). It is the issue that defines the two standard ways of formally modeling strategic competition—with the Bertrand rivalry assuming no such constraint, and the Cournot rivalry assuming a hard (i.e., credibly committed to) production capacity constraint (e.g., Kreps and Scheinkman 1983; Vives 1986). While there exist significant studies on the strategic implications of *technological advances* that alter that capacity constraint, such studies have primarily focused on flexible manufacturing systems that allow firms to switch between the manufacture of two (or more) different products, so as to afford such firms the ability to shift their available capacity *between* products in a period (e.g., Fine 1993). Other relevant work has considered the technology-enabled production capacity flexibility under conditions of uncertain demand across multiple periods (e.g., Ardjmand et al. 2016; Chen et al. 2016; Freitag et al. 2020; Mills 1984). Surprisingly, it appears that *no* work (at least from our understanding) has considered the strategic effects of technology on simply *making the capacity alterable within one period of play*. Our contribution to the literature, then, lies in addressing this important gap and describing the resulting unique strategic effects.

We focus on the research question of, "*What are the main strategic effects of such intra-period capacity-adjusting technology?*" (denoted as CAT henceforth). We explore this question through an analysis based on a standard economic game theory strategy model, i.e., we assume Cournot competition over a discrete time period among various kinds of rivals. Exploring this question in this way fills a current gap in the strategic and economic literature, i.e., about how technology can affect the production constraints of products and services. However, it also provides interesting implications for practice. For example, our theoretical answers to the research question provide one clear basis for managers and policy-makers to build better-informed decisions about investing in and exploiting such technologies. Those decisions are important because the factors that affect the production capacity, supply, availability, and utilization are strategic to almost all industries. They are strategic because of the many critical interdependencies with rivals, suppliers, distributors, complementors, and consumers entailed (e.g., suppliers must be available to provide extra inputs if the manufacturing capacity increases or the production will not actually increase). They are also strategic because the capacity (that is utilized) directly affects the price (i.e., in terms of where market supply and demand meet); thus, it also directly affects the firm's profits, the consumer surplus, and social welfare (e.g., Banker et al. 1996).

Our analysis of the research question reveals that this strategic issue has some unique outcomes. It also entails several comforting expected relationships (e.g., even this kind of technological improvement translates into benefits to consumers and for social welfare). Of the results that are less expected, our analysis reveals that a lone firm with CAT in an industry will choose *not* to use the technology's full potential in most cases. We also show that when there are at least two firms with CAT in an industry, each will be *worse off* the better the technology is in providing production capacity flexibility. These novel results have important strategic implications (and point to areas for future research) that we discuss later in the paper. Prior to this discussion, we provide the appropriate context and analysis. We begin by considering the related literature. We then describe the formal model and work through one representative example of interest. We finish the pre-discussion by summarizing the fuller set of analyses, in terms of the results over the basic variant cases and in terms of what patterns they indicate.

2. Related Literature

The literature on the underlying problem of capacity constraints covers many types of industries, as well as many types of technologies that affect those constraints. The capacity constraints not only affect the heavy manufacturing industry, where the production plant is a large investment that cannot be easily adjusted, but also affects other industries, including the services sector, where the supply is often not only constrained but also perishable within a cycle (e.g., the limited number of seats on a flight leaving an airport that hosts a limited number of open terminal gates at a time). Consider the airline industry as one highly visible service sector example. Airlines use yield management to optimize performance given their seat constraints: "*The airline industry has been on the forefront of using yield management, but yield management has potential application to any firm constrained by capacity. Other services which have adopted yield management include the lodging, rental car, delivery service, rail, and cruise line industries* ... " (Kimes 1989, p. 348). The situation is well characterized by the following description: "*For capacity-constrained firms, providing additional capacity is a very expensive proposition, but selling another unit of available capacity is relatively inexpensive*" (Kimes 1989, p. 350). In other words, the challenge of addressing capacity constraints, whether through optimization-related technologies such as computerized yield management or otherwise, is ubiquitous in the economy, cutting across most of the economy.

The practical challenge of addressing capacity constraints exists in most competitive industries; as such, business researchers respond to the demand for relevant answers and insights with a variety of approaches and studies. Such research includes the use of formal economic modeling. Much of the economics- and strategy-related modeling uses Cournot competition, including many papers that have considered the various effects of technological advances on such rivalries. For example, there is a rich body of literature on flexible manufacturing systems, where the focus is on technological flexibility that allows multiple (differing) products to be made using the same machines. Such flexibility creates a challenge in optimizing *how to distribute a given capacity* (versus how to expand it overall). Fine and Freund (1990) analyzed such a rivalry in product-flexible manufacturing systems (PFMS) technology using a Cournot model, where the capacity choice is made prior to knowing the demand(s). In fact, the topic of production flexibility to address various capacity-related concerns has been a subject of economic inquiry for at least 80 years (e.g., Stigler 1939[1]). However, that research experienced a spike in the 1980s and 1990s, when PFMS became more feasible with significant cost reductions via increased computing power and the use of robotics and numerically controlled machines (e.g., Fine 1993; Jones and Ostroy 1984; Nemetz and Fry 1988).

While most of the literature has focused on technology that affects capacity-related flexibility in terms of *scope* (e.g., Roller and Tombak 1989), there are papers that do focus on *scale* considerations (as we do here). For example, Vives (1986) analyzed what happens when extra capacity comes at a finite cost, although that analysis was over two periods only, and was mostly utilized to describe the transition from Cournot to Bertrand rivalry methods as the extra capacity cost decreased from very high levels to very low levels[2]. As described in that paper: "*We take as a starting point the following interpretation of Cournot competition: a firm's purchasing capacity at a constant marginal cost c, and once the capacity is set production costs are zero up to the capacity limit and infinite afterwards* ... *The more flexible the technology, the more the capacity loses its precommitment power and the closer we are to the Bertrand world*" (Vives 1986, pp. 218–19). That approach has been recently updated and expanded by Lamantia (2011), who introduced different cost functions into the analysis. The core relational ideas of that approach have also been tested empirically by Haskel and Martin (1994), who tried to determine whether a firm's profit levels (ranging from the highs of Cournot-like profits to the lows of Bertrand-like profits) relate directly to their industry's capacity constraint flexibilities. They found that in their sample of UK manufacturing industries, there indeed exists a supporting (statistically) significantly negative relationship (i.e., where more flexibility lowers profit levels).

Other work involving capacity flexibility also exists (e.g., Henkel 2002). Such work has found similar results to ours; for example, when given a choice, *partial* commitment (to capacity) gives a firm an advantage over others that do not have the technological capability to adjust. With that said, *no* other previous paper (to our knowledge) approaches the research question in the straightforward and strategically oriented manner that we do here. Indeed, while the related literature indicates that the challenge of addressing capacity constraints is ubiquitous, and that (P)FMS has relieved some of the issues involved (although only those pertaining to the *scope*), the simple scale-driven problem faced by a manager in a firm with CAT, competing against one rival within one period—a rival that may also have CAT—has yet to be tackled. We do so below in a formal model.

Prior to describing our model, it is worth mentioning an important implication of CAT. In this case, we do think that better technology does alter a firm's ability to "do more stuff" within a given time. That implies that the firm is likely to have a timing advantage (or, at a minimum, no disadvantage) relative to a non-CAT firm. This is because the ability to do more stuff in a given period of time usually involves doing at least some of that stuff before a less-flexible firm. (In reality, that may be due to factors such as having better trained staff, a better supply-chain network, machines with a faster setup, and so on.) That possible timing advantage in a competitive situation, especially one involving capacity commitments, often translates into a profit advantage, as the Stackelberg model indicates (von Stackelberg 1934). Therefore, for the cases in our model that consider timing advantages arising from CAT, there is a related study on Stackelberg variants to consider (e.g., Annen 2019; Chang et al. 2021).

3. Model

We take the standard approach of analyzing the simplest model of our focal phenomenon. This formalized analysis provides robust yet generalizable outcomes from which strategic insights can emerge (e.g., Casadesus-Masanell and Zhu 2013). We use the Cournot competition model and we optimize the rational choices through backward induction in cases where multiple sequential stages are involved in a period. We assume rational, risk-neutral, profit-maximizing managers who focus on capacity choices. When both managers take an action (e.g., set a capacity) at the same time (i.e., in the same stage), they do so simultaneously. For simplicity, we assume that no discounting occurs within a period of competition.

In the full analyses described later in this section, we consider all relevant monopoly and duopoly variants of the general base model, and summarize the results in a table. Instead of working through the algebra for every such variant, we provide a full analysis of *one* interesting representative case. We do so in order to save space and minimize redundancy. Once that is completed, we then refer to the full set of results, and describe the main patterns found across them.

Therefore, we now consider the following example as illustrative of how the full range of results were generated. In this example, we analyze the case of a duopoly with asymmetric firms, which are asymmetric in the sense that one firm has CAT and the other does not. Each firm produces the same single product (or service), and its manager chooses its production capacity(ies) within the period of operation in order to optimize its profits, assuming that the other firm's manager is doing so as well (and that each manager knows that, and so on). The marginal production costs are normalized to zero, and the fixed costs are also normalized to zero, without a loss of generality. Thus, the competition can be modeled as being of the Cournot type.

We consider now the single period of competition. For the firm without CAT, its manager has only one choice regarding their production capacity in the period. For the firm with CAT, we assume that its manager can have more flexibility in choosing capacities within the period; specifically, in this example, we assume its manager has technology that can alter its production capacity up to three times (m = 3) in this single period of competition. We assume that there is no discounting within the period by any party, and that the consumers effectively see one price, being indifferent between purchasing earlier or later in the period.

We assume full knowledge by all relevant parties. Consumers will see one price, based on the full production capacity chosen by each firm for the period. Neither the consumers nor the managers will engage in any discounting (of money or utility) within that period. Each manager knows what the rival manager faces and the capabilities of each firm; there is no asymmetric information. If both firms take an action in any one stage within the period (because there can be multiple stages of action within the period) then that action occurs simultaneously.

We denote the three capacities of the with-CAT firm as x, y, and z (with x used in the first stage, y in the second, and z in the third in that period). We denote the total capacity of the without-CAT firm as d. We denote the equilibrium market price as p. We denote the maximum demand as a, and assume the inverse demand function of $p = a - Q$, where Q is the sum of all firms' quantities available to the market in the period.

We use backward induction to solve the maximization-of-profits decisions over the production capacities. Now, we have several options over when we can assume the non-CAT firm actually sets its capacity; specifically, it could set its capacity when the CAT firm sets x, y, or z. Because we are focusing on a firm with greater flexibility (i.e., the CAT firm), we assume the non-CAT firm never has a timing advantage over the CAT firm, but can have either a non-existent, short, or long timing *dis*advantage relative to the CAT firm. Therefore, there are three cases to consider for this example of an asymmetric duopoly (i.e., with one CAT and one non-CAT firm) where there are three stages assumed (i.e., m = 3): the case where the non-CAT firm sets its capacity in the first stage, the case where that occurs in the second stage, and the case where that occurs in the third stage. For illustrative purposes, in terms of depicting the algebra involved, we assume the long disadvantage case—where the non-CAT firm must wait until the third stage to set its capacity (whereas the CAT firm can set different capacities in each of the three stages).

Starting at the end, the with-CAT firm maximizes profits over its choice of the third-stage capacity z:

$$\max_{z} \{z \cdot (a - x - y - z - d)\} \rightarrow z^* = \frac{a - x - y - d}{2}$$

Similarly, we can determine the optimum capacity for the without-CAT firm at this point:

$$\max_{d} \{d \cdot (a - x - y - z - d)\} \rightarrow d^* = \frac{a - x - y - z}{2}$$

These two equations can be used to simplify each identity through substitution as:

$$z^* = \frac{a - x - y}{3},\ d^* = \frac{a - x - y}{3}$$

With the third and final stage's production limits determined, we can then move back and optimize the choice in the penultimate stage as:

$$\max_{y} \{(y + z) \cdot (a - x - y - z - d)\}$$

We then substitute in the values for z and d and solve it as:

$$\max_{y} \{\frac{(a + 2y - x)}{3} \cdot \frac{(a - x - y)}{3}\} \rightarrow y^* = \frac{a - x}{4}$$

This value can be substituted into the equations for z^* and d^* to simplify it as:

$$z^* = \frac{a - x}{4},\ d^* = \frac{a - x}{4}$$

With the penultimate stage's production limits determined, we can then move back and optimize the choice in the first stage as:

$$\max_{x} \{(x + y + z) \cdot (a - x - y - z - d)\}$$

We can then substitute in the values for y, z, and d and solve them as:

$$\max_{x} \left\{ \frac{(a + x)}{2} \cdot \frac{(a - x)}{4} \right\} \rightarrow x^* = 0$$

This value can be substituted into the equations for y^*, z^*, and d^* to simplify it as:

$$y^* = \frac{a}{4},\ z^* = \frac{a}{4},\ \ d^* = \frac{a}{4}$$

Thus, the with-CAT firm produces its $x + y + z = \frac{a}{2}$ total, the without-CAT firm produces its $d = \frac{a}{4}$ total, and the price that consumers see in the period is then $p = \frac{a}{4}$. The profits are $\frac{a^2}{8}$, $\frac{a^2}{16}$ for the with-CAT and without-CAT firms, respectively, and the consumer surplus and social welfare can be computed as $\frac{9a^2}{32}$ and $\frac{15a^2}{32}$, respectively. These outcomes (for this one of three possible cases for this example) may look familiar, because it has the Stackelberg profits and social benefits. Perhaps that is not surprising because the CAT firm uses its timing advantage (i.e., producing in the second stage before both firms can set capacities in stage three). However, this is not a Stackelberg model[3].

The results for the full analysis of this example (i.e., asymmetric duopoly with $m = 3$) are summarized in Table 1 (in the 4th, 5th, and 6th data rows). For example, when there is no timing advantage—when both firms can set the capacity at the start of the period—in stage one the CAT firm experiences the worse profits of the two (because it cannot commit to not changing its capacity in the other two stages when the non-CAT firm can). Further results for other relevant possibilities in this competition involving at least one CAT firm are also provided in the table. In the table, we detail the main economic outputs for all of the relevant monopoly and duopoly models.

Table 1. Summary of main analysis results.

Type of Rivalry	Firm Profits (CAT Firm Shown First)	Consumer Surplus	Social Welfare	Notes
Monopoly, w or w/o capacity-altering technology (CAT)	$\frac{a^2}{4}$	$\frac{a^2}{8}$	$\frac{3a^2}{8}$	$p = \frac{a}{2}$, $q = \frac{a}{2}$; a CAT monopolist does NOT add capacity when given the option to do so
Duopoly w/o CAT (reference case)	$\frac{a^2}{9}$ for each firm	$\frac{2a^2}{9}$	$\frac{4a^2}{9}$	$p = \frac{a}{3}$, $q = \frac{a}{3}$; this is the standard outcome w/o CAT
Duopoly w/CAT, symmetrical firms, m stages available to adjust capacity, simultaneous actions when taken in the same stage	$\frac{m \cdot a^2}{(2m+1)^2}$ for each firm	$\frac{2m^2 \cdot a^2}{(2m+1)^2}$	$\frac{2m \cdot (m+1) \cdot a^2}{(2m+1)^2}$	$p = \frac{a}{2m+1}$, $q = \frac{m \cdot a}{2m+1}$; note that as m increases, the results move towards Bertrand outcomes
Duopoly w/CAT, asymmetrical, m = 3 stages, assuming that the CAT firm has 2 stages timing advantage	$\frac{a^2}{8}$, $\frac{a^2}{16}$	$\frac{9a^2}{32}$	$\frac{15a^2}{32}$	$p = \frac{a}{4}$, $q = \frac{a}{2}, \frac{a}{4}$; the CAT firm does not add capacity when given option to do so in the first stage
Duopoly w/CAT, asymmetrical, m = 3 stages, assuming that the CAT firm has 1 stage timing advantage	$\frac{a^2}{12}$, $\frac{a^2}{18}$	$\frac{25a^2}{72}$	$\frac{35a^2}{72}$	$p = \frac{a}{6}$, $q = \frac{a}{2}, \frac{a}{3}$; the CAT firm only produces in the first and last stages, and consumers do well here
Duopoly w/CAT, asymmetrical, m = 3 stages, assuming that the CAT firm has no timing advantage	$\frac{a^2}{16}$, $\frac{a^2}{8}$	$\frac{9a^2}{32}$	$\frac{15a^2}{32}$	$p = \frac{a}{4}$, $q = \frac{a}{4}, \frac{a}{2}$; the non-CAT firm enjoys a commitment advantage; the CAT firm only produces in the final stage
Duopoly w/CAT, asymmetrical, m = 3 stages, assuming that the CAT firm has no timing advantage and that the non-CAT firm can only decrease its initial capacity after the first stage	$0.06a^2$, $0.04a^2$	$0.39a^2$	$0.49a^2$	$p \approx 0.11$, $q \approx 0.56, 0.33$; both firms lose profits as neither can commit to holding a capacity flow; the less-flexible firm does worse because its final-stage commitment must be lower than its first.

When we consider the *symmetrical* Cournot case over multiple stages—with the most basic case of interest being the CAT firm *duopoly*—we can conduct a similar analysis to the one above. We can recognize a pattern in the outcomes based on the main variables, as related to the number of capacity adjustment stages within a period, m. In this analysis, both firms are equally capable of making adjustments in any stage, and when they do, they occur simultaneously. Backward induction is used to identify optimal choices. We provide the outcome patterns in the table in the third data row.

A final possibility that we model here involves having the non-CAT firm set its maximum capacity when the CAT firm sets x, but then allowing that non-CAT firm to alter its output—but only downwards and only when the CAT firm sets y and then z. Given that the fractions involved in that analysis become unwieldly, we simply report the approximate numerical values in the table instead (in the last row). (Note that q in the table denotes a firm's quantity produced in a period.)

The results of the full analysis of possible relevant cases provide the following insights:

- CAT unequivocally increases consumer surplus and social welfare. This is because the flexibility reduces the private benefits possible from capacity constraint commitments;
- CAT increases the profits for the firm holding it relative to any firm not holding it *only* when it provides a timing advantage, with profits increasing with that advantage; however, CAT actually decreases the profits when it provides no timing advantage. The relationship between CAT and the overall performance advantage is complicated because it involves a trade-off regarding flexibility—such flexibility can provide advantages regarding timing as well as disadvantages in an inability to commit to a capacity (prior to the last stage). Therefore, when the timing advantage exists, it outweighs the commitment inability disadvantage. However, when there is no timing advantage, the flexibility is disadvantageous. To be clear, CAT is not simply a timing story (like Stackelberg), but a trade-off story instead;
- Having at least two rivals with CAT means *the profits are driven to zero* (at a decreasing rate as the number of possible intra-period adjustments, m, increases), while the consumer surplus is driven to its maximum (i.e., of $a^2/2$) (at a decreasing rate with m), while the social welfare is driven to a maximum level (i.e., with maximum consumer surplus, also at a decreasing rate with m). The effect of each firm not being able to commit in every stage but the last meant the firms move further and further towards being Bertrand rivals, i.e., towards being firms with complete flexibility as m increases. This is because as the time divisions are compressed (i.e., the number of stages grows larger), the discrete time becomes near-continuous in nature. Because neither firm can limit its capacity in the period, then the competition is of the Bertrand type. The reason they cannot limit their capacity is that as the number of stages grows larger, any advantage to capping capacity in any one stage declines, meaning any tacit coordination in restricting supply to keep prices above costs gets lost;
- Having only one firm with CAT means that *at most, only two stages will ever be used for capacity changes,* regardless of whether the number of possible intra-period adjustments CAT could provide is greater than one (i.e., for any $m > 2$). This is because with no discounting, *only* two stages are ever needed—one to exploit any timing advantage (by producing early) and the other to commit (in the last stage) to the remainder of the capacity use. Therefore, in the case illustrated here, the first stage is not needed to exploit the timing advantage (because the second stage is used for that);
- An asymmetric firm will have higher profits than if neither has CAT *only* when the timing advantage is non-existent or long; in fact, it appears that the *lucky* firm (i.e., being the non-CAT firm when there is no timing advantage and the CAT firm when there is a long timing advantage) will experience, at most, the same gains as it would with a Stackelberg advantage.

These results indicate that the technological progress—here in technology that reduces the immediate (inter-period) constraints on the production capacity (i.e., CAT)—has *very conditional* benefits for the firm that possesses that technology, while having unconditional benefits for consumers. That is both good news and bad news. It is good news for consumers. It is mostly bad news for the technologically enhanced (CAT) firm(s). Unless the new technology provides a (sizeable) timing advantage against a rival, it is bad for profitability. In all other cases, such new technology undermines a firm's ability to hold its commitments to Cournot-like tacit collusion to restrict supply. Further, even when the firm with CAT has the long timing advantage, it will only apply its capacity adjustment ability in a limited way (i.e., to alter production capacity one more stage than its rival(s), unless it is a monopolist, in which case it will not deploy it at all). In other words, this type of technology is good for society but has limited benefits when only one firm in an industry possesses it.

Before we discuss the many implications of these new results, it is worthwhile to consider one further obvious advantage that CAT brings. An adjustment capability is obviously beneficial in *uncertain* contexts, specifically when the demand fluctuates within a period of play. As long as that uncertainty is resolved within the period—so the CAT firm can then adjust its capacity with certainty—then it will reap an advantage. In such a case, CAT is a valuable option—one that allows the firm to delay its commitment to a costly action (i.e., of production). This value works whether the uncertainty is risky or ambiguous (i.e., whether the demand's distribution is knowable prior to the period beginning or not).

To illustrate the value, we consider the simplest case, whereby the demand is risky *ex ante*—it could either be very low (i.e., 0) or very high (i.e., $2 \cdot a$), with an expected value in the middle (i.e., a). For simplicity, we assume that each the demand has an equal *ex ante* probability of occurring, and each firm knows that. We assume a non-trivial cost rate (f; $a > f' > 0$) to the unused capacity (or unsold product) in order to make bad choices economically unattractive (i.e., as this is both realistic and a reason for not wasting resources). We assume that the period has two stages, and that the final demand level is only revealed between the two. The non-CAT firm can only commit to a capacity prior to knowing the actual level of demand, whereas the CAT firm can wait for the level to be revealed.

By applying backward induction as before, the equilibrium finds the non-CAT firm committing to a total capacity of '$a - f'$', and the CAT firm committing to a non-zero capacity *only* when demand is high, with '$(a + f)/2$'. The CAT firm's *expected* profit is higher under the condition '$f > a \cdot (3 - 2\sqrt{2})$'. The CAT firm's actual profit is higher whenever the low demand condition holds. When the high demand condition occurs, however, the CAT firm's actual profit is higher only when '$f > a/3$'. Therefore, we note that even the advantage that a CAT firm would be expected to gain under uncertain (or fluctuating) demand actually *is conditional*; in this case, it is conditional on there being a significant penalty for making a mistake (e.g., for creating unused capacity or disposing of unsold product). In other words, this is an unusual case of an option having only conditional value even though it does delay the commitment. This conditionality arises because early commitment is also valuable in these capacity-setting games; the positive and negative effects of early commitment are a trade-off in this case.

4. Discussion

Our analysis has focused on the question of "*What are the main strategic effects of intra-period capacity-adjusting technology?*" Our formal model has answered that question. It also began to address the gap in the literature on the effects of the inter-period capacity-constraint-related production-scaling flexibility in a competitive environment. We found that such flexibility—assumed to be brought on by technological improvements—does unequivocally increase the consumer surplus and social welfare. However, its effects on the firms holding such flexibility (and the extent of its exploitation by them) are highly sensitive to whether their rivals also hold it, and to just how much of a timing advantage it provides. The latter results are *novel*, and are based on the recognizable patterns of rationally, with strategic optimal uses of CAT over multiple game theory cases.

These results have significant implications for policy-makers, for managers, and for strategy researchers. Given the unconditional public benefits from CAT, policy-makers should support its creation and its use in order to increase consumer surplus and social welfare in their economies. This may entail government funding of R&D into CAT, and its free licensing to industry. (The rational cap on such R&D funding is estimable based on the increase in expected benefits, across the affected industries and across time.) Policy-makers may also wish to legislate some form of forced licensing of any patented CAT in order to increase its social benefits (given the private incentives of the patent holder to restrict its own CAT usage otherwise).

There are also strategic implications for managers given the effects of CAT on a firm's profits. Acting at the firm level, a manager should invest in R&D to gain an asymmetric advantage through CAT when feasible. (The model provides a way to estimate the rational maximum spending on CAT-related R&D that should be done once the demand, cost, and timing functions are specified for the industry, where the R&D is capped by the benefits of having an advantage from a proprietary CAT relative to the costs of being at a disadvantage when a rival has CAT.) Further, that R&D investment should *only* be targeted at gaining *one* extra capacity adjustment in a period when CAT is expected to be unique to the firm, as it is not valuable to invest in further flexibility in this scenario, *as long as the non-CAT rival is at a timing disadvantage*. When this is not the scenario, then there is an incentive to limit the industry's R&D expenditure in order to control the industry's capacity to the benefit of the incumbents (e.g., Wood 2009). One way is to collude to restrict CAT-related R&D (which should be made illegal by any savvy policy-makers based on our analysis). Another way is to choose R&D levels in what amounts to a *meta-game* of the Cournot variety—where firms choose R&D spending on CAT-related capacity adjustments first and then decide how to apply those adjustments after. The rational choices of R&D spending on CAT should be akin to optimizing returns from committing to restricting the overall capacity (including any intra-period adjustments), and so should address the death spiral to zero profits when m increases in the model in the case where there at least two rivals with CAT. We leave this new variant, as well as many others that are described below, for future work.

Besides the implications for policy-makers and managers, there are a host of areas for future work based on our model and analysis here. In other words, the results hold implications for strategy researchers as well. We flesh out several such areas now.

When the fixed costs are modeled as non-zero, then there emerges the possibility for a CAT-advantaged firm to *force out* its rival without CAT (e.g., if the per-period fixed costs exceed $\frac{a^2}{16}$ in a duopoly). If that occurs, then the CAT is even more privately beneficial than under our original model, although it is also less publicly beneficial (and likely even somewhat harmful to the consumer surplus and possibly also social welfare).

When the demand levels are uncertain there may be further private and public benefits to CAT. CAT may have an *option value* when the costs of the capacity overinvestment are sufficiently high. With the ability but not the obligation to adjust the capacity to the demand levels, the option value of CAT could be calculable in risky cases, once the usual variance, exercise cost, timing, and other factor values are provided. Additionally, that option value is likely to increase the optimal level of R&D investment in CAT.

The future work should also be directed at understanding the *drivers* of CAT—their origins, forms, and limits. For example, it may be the case that CAT's abilities arise as dynamic capabilities—as organizational skills in reconfiguring manufacturing routines (e.g., Teece 2007). Given it is likely that different technologies underlying CAT exist, some of which may involve both external partners and internal labor sources, further exploration of the characteristics (e.g., the costs, response times and limits) of these alternatives is worthwhile to pursue in order to find the best fit for an industry.

Besides modeling the technologies and the demand risk variants, it may also be insightful to consider the fuller modeling of the supply chain itself. For example, when the capacity can vary within a competitive period, the investments and decisions of the suppliers, distributors, and complementors are likely to be affected as well. In turn, this will alter the value of vertical integration initiatives, of vertical alliances, and of other business partnerships. Such vertical effects have relevance to shared-economy businesses, especially when they compete against more traditional capacity-constrained rivals.

Further possibilities for additional future work lie in the realm of expanding the model by relaxing its various assumptions. For example, alternative bases of decision-making to the game theory super rationality assumed here could be explored[4]. Other possible changes to assumptions to explore include adding non-zero marginal costs, adding the threat of limited entry, and adding low-level intra-period discounting.

More practical future study possibilities involve testing the hypotheses implied by the results of our analysis (perhaps leveraging related empirical work by others, e.g., Daniel 1995; Lindberg et al. 1988; Pinheiro et al. 2022). As has been done when testing the previous scale-related relationships shown by Vives (1986), researchers could analyze industries exhibiting different CAT-related abilities and test whether the R&D investments into CAT are capped (e.g., to give an advantage for only one extra intra-period adjustment), whether the CAT-related advantages are on the order of the profit levels that the model predicts (e.g., double the profits of the disadvantaged firm when timing is optimal), whether the profits do drop in the diminishing marginal manner described when CAT is *not* capped among at least two rivals, and whether the CAT-advantaged firm increases production as the stages pass.

Overall, our analysis of the research question exploring the strategic effects of CAT has produced some *unique* results, with several implications for policy, management, and future research decisions. Work like this is important to do in order to fill existing gaps in our understanding of technology's possible effects on rivalry, so as to help managers and policy-writers make better strategic decisions. Indeed, when the results of the research are new, it is valuable to make decision-makers aware so that they can better prepare or exploit the factors in those phenomena. Therefore, such new results are likely to continue because the interaction between *engineering* (in terms of the commercialization of scientific technological advances) and *strategy* (in terms of the exploitation of economic forces aimed at maximizing organizational performance) will continue to generate new combinations of outputs—outputs that we as researchers and teachers are responsible for helping make sense of and directing towards uses that increase productivity and social welfare.

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Notes

[1] For clarity, Stigler (1939) does *not* consider Cournot rivalry, but instead focuses on what production flexibility means and where it may come from in more general terms.

[2] Kreps and Scheinkman (1983) also connect Cournot and Bertrand competition types, using a two-period, symmetric-player model, where capacities are set first and prices second. They do not consider intra-period production-flexibility-based competition, nor asymmetric players in that competition, as we do here.

[3] Note that although the profits and production are the same as in the Stackelberg model, the timing of the actions is *not*. When the timing advantage is long, the CAT firm commits to matching the capacity of the non-CAT firm when the latter commits (i.e., in stage three). In the case when there is no timing advantage, the non-CAT firm can credibly commit to a capacity level that the CAT firm cannot. Those cases differ from the Stackelberg structure where the two firms commit at different times only, and only do so once in the game.

[4] When considering any non-fully rational decision-making, it is important to note that reasonable mistakes are possible in the calculations made. For example, if a manager were to use the seemingly reasonable heuristic model to divide up a period into stages and then to apply that to dividing up a period's demand into similar sub-demand units, this would be sub-optimal. Simply dividing the period's maximum demand by the number of periods (i.e., as $\frac{a}{m}$) would carve out large squares of consumer surplus under the demand curve (i.e., the p by Q line). That would then result in much less quantity being supplied in the period, which may actually be good for those non-fully rational firms, especially in symmetric CAT-endowed cases, until they see the higher-than-expected profits and adjust the next period, when there is a next period to the model.

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