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Time-To-Build Investment and Uncertainty in Oligopoly

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TIME-TO-BUILD INVESTMENT AND UNCERTAINTY IN OLIGOPOLY

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Abstract: This paper examines how time to build alters strategic investment behaviour under oligopoly. Facing demand uncertainty, firms decide whether to invest early or wait until uncertainty has been resolved. A game that captures time-to-build investment is contrasted with another one in which investment is quick in place. We show that a time lag between *when* and *how much* to invest reduces the incentive to delay. When investment requires time to complete, early investment occurs more to avoid becoming a follower than to become a strategic investment leader. The opposite is true with quick-in-place investment. A brief welfare analysis is provided.

Key Words: Time-to-build Investment, Uncertainty, Strategic Commitment, Flexibility, Oligopoly.

JEL Codes: D80, L13.

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1. Introduction

Almost all forms of investment have three crucial features in common: investment plans are made under uncertainty, are at least partially irreversible and take some time to be completed. The implications of the irreversibility of investment have been widely discussed, not least in the industrial organisation literature in the context of strategic commitment. The argument relies on the now well-understood idea that firms may have an incentive to commit in advance to investment in order to affect the strategic environment in which future competition takes place¹. By contrast, the option value approach to investment decisions stresses the importance of delaying investment because the future is uncertain. Delaying investment then has the advantage of retaining flexibility². These two strands of the literature on investment suggest that investment decisions in an oligopoly setting result from a trade-off between the strategic importance of investment commitment and the flexibility advantage of investment delay. This trade-off forms the starting point of our analysis, which, unlike previous work on this theme³, endogenises the decision when to invest for both firms in a duopoly.

While uncertainty and irreversibility, and hence the flexibility-commitment trade-off, feature in this paper, prominence is given to the simple real-world fact that investment projects take time. In the literature investment is most commonly modelled as being fully in place immediately after the investment decision is made. Certain types of investment indeed exhibit this feature. Adopting a newly available technology, for instance, is an investment that arguably is “quick-in-place”⁴. By contrast, investing in R&D to *develop* a new

¹ Tirole (1988) provides a textbook treatment of this issue.

² See Dixit and Pindyck (1994) for a comprehensive discussion.

³ Our paper is the first to examine endogenous investment timing by both of the firms in a duopoly. However, the theme of commitment versus flexibility in a strategic environment has been studied in different models. Some authors endogenised the investment timing of one firm only, while others explored endogenous timing in output or price games with uncertainty. Examples are Appelbaum and Lim (1985), Spencer and Brander (1992) and Sadanand and Sadanand (1996). Note that the flexibility in timing discussed in these papers is quite different from the technological flexibility discussed in, for instance, Vives (1989) and Boyer and Moreaux (1997). In those models there need not be a trade-off between flexibility and strategic commitment.

⁴ A quick-in-place timing assumption is more likely to fit a model in which early price- or production-setting rather than early investment is the key issue. Canoy and Van Cayseele (1996) study the trade-off between price commitment and price flexibility. In their model, early price-setting implies that the committed firm has its price level immediately in place. Sadanand and Sadanand (1996) look at a similar trade-off with production-setting.

technology requires time. In fact, most investment requires a significant period of time to be completed, often referred to as “time to build”, a “construction lag” or a “gestation period” (Bar-Ilan and Strange, 1996). Clearly, a new factory is not built overnight but typically takes several months if not years before completion. Industries in which investment typically takes time to build are, for instance, Aerospace and Pharmaceuticals (Pindyck, 1991). Ghemawat (1984) reports that, for a typical plant in the titanium dioxide industry, there is a lag of at least four years between the decision to construct and the actual start-up date.

Implications of time to build have been widely explored in option value theory of investment (Majd and Pindyck, 1987; Bar-Ilan and Strange, 1996) and studied in the context of growth and business cycle theory (Kydland and Prescott, 1982). However, oligopoly theory, which places strategic behaviour at its core, remains silent about the implications of time-to-build. In an attempt to fill this gap in the literature, our paper demonstrates that this innate characteristic of investment affects the *strategic* incentives to invest early. More specifically, the paper has two main contributions. First, “time-to-build” investment is shown to generate a different type of strategic investment behaviour between rival firms than “quick-in-place” investment. Second, because these two forms of investment have different strategic implications, they also have different welfare implications, which need to be taken into account for investment policies affecting oligopolistic industries.

The most straightforward and simple way to demonstrate how time-to-build investment influences strategic investment behaviour is by considering two different investment-timing games. In the first game, investment is immediately in place; investing early implies that firms select the investment *level* to which they are then committed. In the second game, investment takes time to build; firms first commit to the timing of their investment but do not yet fix the actual capital level. After having chosen *when* to invest, firms observe the timing decision made by their rival before finalising their investment levels.

We show that with “quick-in-place” investment the strategic incentive for investing early is primarily *aggressive*: firms want to acquire investment leadership. At moderate levels of uncertainty, one firm typically emerges as the industry’s leader in investment, while the rival

retains investment flexibility. By contrast, with “time-to-build” investment, the main strategic reason to invest early is *defensive*: firms want to invest early to avoid the loss of market share associated with being a follower. So, early investment by all firms or by none at all emerges as the typical investment-timing pattern.

In section two of the paper we set up the basic model in which two rival firms choose capital and output for a market characterised by demand uncertainty. In section three, the investment-timing pattern that emerges when investment is quick in place is discussed. In section four we examine the investment timing when investment takes time to build and compare the pattern obtained with the one in the benchmark case with quick-in-place investment. Section five completes the comparison by discussing investment timing when one firm has a cost advantage. In section six some welfare issues are addressed. Section seven concludes.

2. The model: Investment with demand uncertainty

This section outlines the basic model, which will be used to study strategic behaviour both with time-to-build and quick-in-place investment. Two firms produce an identical product and choose capital and output, denoted respectively by k_i and q_i ($i = 1, 2$). Firms face uncertainty about market demand. This is captured by an inverse demand function with a stochastic component:

$$p = a - Q + u \tag{1}$$

with $Q = q_1 + q_2$ and $u \in [u, \bar{u}]$ the stochastic demand component with zero mean and variance σ^2 . Firm i 's total cost, TC^i , is given by⁵:

$$TC^i = (c_i - k_i)q_i + \frac{k_i^2}{2h} \text{ with } TC_{k_i}^i = -q_i + \frac{k_i}{h} \text{ and } TC_{q_i}^i = c_i - k_i \tag{2}$$

The parameter h is inversely related to the cost of capital and c_i is a positive constant.

$TC_{k_i}^i$ and $TC_{q_i}^i$ are defined respectively as the marginal cost of capital and the marginal

⁵ Because it is easy to work with, this cost function is commonly used in oligopoly models with strategic investment (for a recent example, see Grossman and Maggi (1998)).

production cost. Investing in capital reduces the marginal cost of production for firm i .

Profits of firm i are given by:

$$p_i = pq_i - TC^i \quad i = 1,2 \quad (3)$$

The model consists of two periods. There is uncertainty about demand in the first period, which is resolved at the start of period two. Firms decide whether to commit to their capital in the first period or postpone investment to the second period. For simplicity, we assume throughout that firms are risk neutral. Hence, their investment timing decisions follow from maximising expected profits.

Outputs are always chosen simultaneously in period two, that is, after uncertainty has been resolved. The equilibrium output for firm i is⁶:

$$q_i = \frac{1}{3}(2A_i - A_j + 2k_i - k_j + u) \quad (4)$$

with $A_i \equiv a - c_i$ and $i, j = 1,2 \quad i \neq j$

When capital is chosen in period one, it is set before output. But, if it is chosen in period two, it is determined simultaneously with output. If a firm chooses to invest early, it determines its capital in period one by maximising expected profits ($\max_{k_i} E p_i$).

Commitment to capital in the first period⁷ gives firms a strategic advantage because it allows them to influence future outputs to their advantage. However, by doing so, the firm reduces its output flexibility compared to when it delays investment until period two. In the latter case, period-two profits are maximised with respect to capital ($\max_{k_i} p_i$) and the investment level will be chosen in accordance with any unexpected shocks in demand (i.e., $k_i = k_i(u)$

with $\frac{\partial k_i}{\partial u} > 0$). This will enhance the firm's output flexibility.

⁶ We restrict attention to interior solutions.

⁷ There exists a literature concerned with the issue of partial commitment in multi-period output settings (see, for instance, Pal (1996)). However, partial commitment is probably less realistic with capital commitment, since the costs of adding capital to an existing level may be prohibitively high in the short run, due to the existence of indivisibilities and incompatibility in technologies.

Despite the fact that firms are risk neutral, they value flexibility. This follows from the fact that expected profit is increasing in the variance of demand⁸. Due to the indirect effect of capital on output, the positive effect of the variance on expected profits is larger under investment flexibility than under commitment. Hence, our model captures the fact that, in practice, investors who value flexibility have an incentive to delay investment when they face significant uncertainty. This feature is consistent with option value theory in finance, implying that a rise in uncertainty increases the option value of investment delay.

Firms face this trade-off between flexibility and commitment both with quick-in-place and time-to-build investment. We model quick-in-place investment as an “Action Commitment Game” (*ACG*). Action Commitment means that, if a firm decides to invest early, it commits not only to invest in period one, but also to a particular *level* of capital (see figure 1a). In other words, commitment in *ACG* implies compressing the timing and level of investment into a single action. The nature of commitment with time-to-build investment is different and is more appropriately captured by a different game, referred to as an “Observable Delay Game” (*ODG*)⁹. In that game, firms first decide when to invest, but because investment takes time, the actual level of capital is not immediately fixed. Only in a later stage, after the timing decisions have been made and observed by both parties, do firms select their investment levels, knowing in which period the rival will invest (see figure 1b)¹⁰. So, a firm that chooses to commit and thus invests early, determines its capital level after the investment timing choices are made, but before uncertainty has been resolved.

[Figures 1a and 1b about here]

In the remainder of this section we will discuss features that are common to the investment timing games with quick-in-place (*ACG*) and with time-to-build investment (*ODG*). In

⁸ The positive effect of the variance on *ex ante* expected profits is due to the fact that the actual *ex post* realisation of profits is convex in u . Note that risk aversion would simply strengthen the gains from remaining flexible.

⁹ Hamilton and Slutsky (1990) introduced the “Action Commitment” and “Observable Delay” terminology in endogenous timing games. They restrict attention to price and output games and do not look at investment decisions; since they assume certainty, they are not concerned with the trade-off between commitment and flexibility.

¹⁰ Firms’ timing decisions are assumed too costly to be reversed.

either game, there are four possible timing combinations: (C_1, C_2) , (C_1, D_2) , (D_1, C_2) and (D_1, D_2) , where C_i and D_i refer to commitment and delay, respectively. It follows directly that these combinations are the *candidate* timing equilibria in *ODG*. It is also straightforward to show that these combinations are the four candidate timing equilibria in *ACG*¹¹. Moreover, the capital levels for each of the four candidate equilibria in *ACG* are the same as those in the corresponding equilibria in *ODG*; they are given by the expressions in table 1¹².

Table 1: Capital levels for the different candidate equilibria in *ACG* (quick-in-place investment) and in *ODG* (time-to-build investment)^a

	C_1, C_2	C_1, D_2	D_1, C_2	D_1, D_2
k_1	$k_1^{cc} = \frac{4}{3}hEq_1^{cc}$	$k_1^{cd} = \frac{2(2-h)}{3-2h}hEq_1^{cd}$	$k_1^{dc}(u) = hq_1^{dc}(u)$	$k_1^{dd}(u) = hq_1^{dd}(u)$
k_2	$k_2^{cc} = \frac{4}{3}hEq_2^{cc}$	$k_1^{cd}(u) = hq_2^{cd}(u)$	$k_2^{dc} = \frac{2(2-h)}{3-2h}hEq_2^{dc}$	$k_2^{dd}(u) = hq_2^{dd}(u)$

^a The first [second] superscript on the k_i and the q_i variables refers to the commitment (*c*) or delay (*d*) decision by firm one [two].

In two of these candidate equilibria, firms choose their capital simultaneously: they both invest early (C_1, C_2) , or alternatively, choose to delay (D_1, D_2) . In those cases, firms' choices of capital per unit output are symmetric, but larger for investment commitment than for delay (i.e., $\frac{k_i^{cc}}{Eq_i^{cc}} > \frac{k_i^{dd}(u)}{q_i^{dd}(u)}$). In the other two candidate equilibria ((C_1, D_2) and (D_1, C_2)), one firm is a Stackelberg leader in investment, while the other is a follower. The

¹¹ To see this in *ACG*, define $r_i(k_j)$ as firm i 's *first*-period capital reaction function. If firm two delays, then (depending on \mathbf{s}^2 and other parameters) firm one's best response is either delay or play k_1^{dd} . If k_1^{dd} is played, firm two's best response is either delay or $r_2(k_1^{dd})$. But, k_1^{dd} is not the best reply to $r_2(k_1^{dd})$ (hence, $(k_1^{dd}, r_2(k_1^{dd}))$ is not an equilibrium). So, if firm two delays, the only possible equilibria are (k_1^{cd}, D_2) and (D_1, D_2) . If firm two commits to a particular capital level \hat{k}_2 , firm one's best response is either delay or $r_1(\hat{k}_2)$. But $(r_1(\hat{k}_2), \hat{k}_2)$ is only an equilibrium if $\hat{k}_2 = k_2^{cc}$ (and $r_1(k_2^{cc}) = k_1^{cc}$). If firm one delays, firm two leads and plays k_2^{dc} . So, if firm two commits, the only possible equilibria are (k_1^{cc}, k_2^{dc}) and (D_1, k_2^{dc}) . Thus, there are the four candidate equilibria in *ACG*, one for each of the four possible timing combinations.

¹² Expected profits in each candidate equilibrium are given in table A of the Appendix.

committed capital level per unit output chosen by the leader is larger than that chosen by

either firm when both firms commit ($\frac{k_1^{cd}}{Eq_1^{cd}} = \frac{k_2^{dc}}{Eq_2^{dc}} > \frac{k_i^{cc}}{Eq_i^{cc}}$).

In the next two sections, we derive and discuss the investment-timing pattern that emerges with quick-in-place and time-to-build investment respectively, when firms have symmetric costs ($c_1 = c_2$ and $A_1 = A_2$). To prevent the discussion from becoming too taxonomical, only pure strategies are considered. Since the analysis involves many unwieldy algebraic expressions, graphical simulations are extensively used to ease the exposition. This approach allows us to minimise the number of equations we give in the text, but does not reduce the generality of our analysis in any way.

3. Quick-in-place investment

In this section we look at the benchmark game, *ACG*, which captures quick-in-place investment in a simple and straightforward manner: if a firm decides to commit, it will do so by choosing an investment *level* in stage one; however, if investment delay is preferred, the firm chooses its capital investment flexibly in the second period (see figure 1a). Which of the candidate equilibria represented in table 1, if any, eventually prevail, depends crucially on the level of uncertainty (\mathbf{s}^2) and the \mathbf{h} -parameter (which is inversely related to the marginal cost of capital)¹³. This benchmark allows us to assess how strategic incentives change when investment takes time to build.

The investment timing that emerges is shown in $(\bar{\mathbf{s}}^2, \mathbf{h})$ -space (where $\bar{\mathbf{s}}^2 \equiv \mathbf{s}^2 / A_1^2$ is the normalised variance) in figure 2. This figure gives loci along which a firm is indifferent between commitment and delay, given a particular investment timing choice of its rival. At levels of uncertainty ($\bar{\mathbf{s}}^2$) above the relevant locus, the firm prefers to delay, given the choice made by its rival. At levels of uncertainty below the locus, it will commit. Along the top locus ($E\mathbf{p}_1(C_1, D_2) = E\mathbf{p}_1(D_1, D_2)$), firm one is indifferent between commitment and

¹³ Throughout the paper the \mathbf{h} -values are limited to guarantee interior solutions and by stability considerations.

delay, given that its rival delays its investment. Above this locus, the expected profit from delay exceeds that from commitment (given rival delay). The lower two loci represent commitment-delay indifference curves given rival commitment. When the rival commits in *ACG*, it is committed to a *particular* investment level. Hence, to find the relevant investment timing indifference curves we must take the *actual* investment level into account. As mentioned earlier, there are two candidate equilibrium capital levels for firm two if it commits, k_2^{dc} and k_2^{cc} . There are therefore two relevant indifference curves given rival commitment: one given that firm two commits to the leadership capital level, k_2^{dc} ($Ep_1(C_1, k_2^{dc}) = Ep_1(D_1, k_2^{dc})$) and another one given that firm two chooses the capital level prevailing under simultaneous commitment, k_2^{cc} ($Ep_1(C_1, k_2^{cc}) = Ep_1(D_1, k_2^{cc})$). Thus, figure 3 depicts a total of three indifference curves for each firm. Given cost symmetry, the loci of firm one naturally coincide with those of firm two. The difference between these indifference curves as well as their implications for the equilibrium outcomes are discussed in Appendix B.

[Figure 2 about here]

In figure 2, the (\bar{s}^2, \mathbf{h}) -space is divided into four areas by the firms' indifference loci. In area IV, both firms delay investment. In this region the level of uncertainty is too high for firms to forego flexibility. Delaying investment is preferred by each firm, independently of the rival's timing choice, hence delay by both is the unique equilibrium. In area III, there are two leader-follower equilibria. Here, each firm prefers to delay *if* its rival commits. On the other hand, if a firm's rival delays, commitment will be chosen. Only in region I is uncertainty so low that commitment by both firms, the outcome that would prevail under certainty, is the unique equilibrium. Finally, in region II, the two leadership equilibria and commitment by both firms are sustained as equilibria. Note, however, that this region is very narrow, especially at low values of \mathbf{h} ¹⁴. One could argue that region II is merely a fuzzy boundary between areas I and III, caused by the inherent stickiness of early investment in *ACG*.

¹⁴ For instance, at $\mathbf{h} = 0.15$, region II is only 0.00060 wide in terms of \bar{s}^2 , while this distance narrows down even further to a \bar{s}^2 -range of 0.00005 at $\mathbf{h} = 0.05$.

In figure 2, a firm's indifference locus given rival delay is above, and rises much faster in h than the loci given rival commitment. Intuitively, the relative value of investment commitment is much higher if the rival firm remains flexible than if the latter invests strategically. This suggests that “*defensive commitment*”, that is, strategic investment to avoid becoming the follower, tends to have a relatively low value in this game compared to “*aggressive commitment*” to become a leader. It is for this reason that for intermediate levels of uncertainty we get investment leadership despite the fact that firms are *ex ante* identical. Note that a leadership equilibrium implies a real *ex post* difference between the firms, with the leader having a higher capital investment and lower marginal production costs than the follower in equilibrium.

4. Time-to-build investment

With time-to-build investment, firms observe each other's investment timing before they complete the investment project. This then allows them to alter the actual level of investment in a later stage. The structure of the game that captures this feature, i.e., the “Observable Delay Game” (*ODG*) is shown in figure 1b. Note that period one now consists of two stages. In the first stage firms decide when to invest and only later irrevocably fix the level of investment (i.e., in stage two if they opt for commitment, and in stage three if they prefer delaying investment)¹⁵. Because firms observe the outcome of the investment timing stage, the nature of commitment is less “sticky” than with the quick-in-place investment in *ACG*. This feature changes the nature of commitment compared to the previous game and has several important implications.

First, as a result of the two-step commitment in *ODG*, the two indifference loci for rival commitment that prevailed in *ACG*, here collapse into a single indifference locus (see figure 3). Consider, for instance, firm one's investment timing decision in stage one, given that firm two chooses to commit but can only fix its capital level in stage two. Firm one will compare its expected profits from also committing, $Ep_1(C_1, C_2)$, to those from delaying investment,

¹⁵ So, in this model delaying implies that the investment project can only be completed in period two.

$E p_1(D_1, C_2)$, knowing that its investment timing choice will affect the optimal level of firm two's capital in stage two (k_2^{cc} if C_1 and k_2^{dc} if D_1). Because firms now have to take into account the effect of their own investment timing decision on the rival's capital level, there is only one indifference locus given rival commitment, implying that each firm now only has two indifference loci in total.

Second, by contrast to the game with quick-in-place investment, the indifference locus for a particular firm given rival commitment is above and steeper than its corresponding locus given rival delay. This suggests that in *ODG* firms tend to invest early more for defensive than for aggressive reasons, that is, more out of fear of ending up as the follower than to gain a first-mover advantage. In *ACG*, the opposite was true; there, “*aggressive commitment*” was more valuable than “*defensive commitment*”.

The investment timing that emerges now is graphically represented in figure 3. In the discussion we mainly point out the differences with the previous game. Unlike in *ACG*, investment leadership does not arise as an equilibrium in any region of the graph. Instead, the two equilibria that can prevail at intermediate levels of uncertainty are commitment by both firms, or investment delay by both (see region II in figure 3). In area II, a firm only invests early if its rival does so as well. Its own commitment guarantees that the rival's strategic investment is smaller, thereby avoiding severe reductions in future outputs. This confirms the intuition that strategic investment here occurs out of a predominantly defensive motivation. Also, the area where both firms choose to commit is larger than in *ACG*, illustrating that commitment is relatively more attractive to firms in *ODG*. Moreover, the “fuzziness” of the boundary between the lower regions, observed in *ACG* (see region II in figure 2), has disappeared completely.

[Figure 3 about here]

5. Cost asymmetry

Here, we briefly discuss the effect of cost asymmetries ($c_2 > c_1$ implying $A_2 < A_1$) on firms' investment timing. Cost asymmetry raises the relative value of commitment to the low-

cost firm. Hence, each indifference locus of the latter will lie above the corresponding indifference locus of its high-cost rival.

Consider cases with a “large” cost asymmetry. We use this term to refer to relative cost differences for which *all* the low-cost firm’s indifference loci lie above *all* those of its higher-cost rival¹⁶. Figures 4a and 4b illustrate this respectively for the games with quick-in-place (*ACG*) and time-to-build investment (*ODG*) (with $A_2 = 0.8A_1$). At intermediate levels of uncertainty investment leadership by the low-cost firm prevails both in *ACG* (region III in figure 4a) and in *ODG* (region II in figure 4b). Hence, both with quick-in-place and with time-to-build investment, the relative value of commitment is higher for the low-cost firm than for its high-cost counterpart. However, given the same cost asymmetry, the area where investment leadership occurs is smaller in *ODG* than in *ACG*, since the high-cost firm has an increased incentive to invest defensively. Consequently, here, as in the case with symmetric costs, the region of commitment by both firms is larger than in *ACG*¹⁷.

[Insert Figures 4a and 4b about here]

Superimposing the corresponding (\bar{s}^2, h) -diagrams of the two games allows us to compare them, given the same ranges of uncertainty and other parameter values. Without showing this combined graph explicitly¹⁸, the outcomes are shown in Table 2 for the symmetric-cost case as well as for the case with “large” cost asymmetries.

¹⁶ In addition to the symmetric-cost case and cases with large cost asymmetries, a third and final possible scenario prevails when the cost asymmetry is sufficiently “small”, implying that the relative cost disadvantage of the high-cost firm is not large enough for *all* its indifference loci to lie below its rival’s. The diagrams for “small” cost asymmetries (available from the authors on request) now take a hybrid form, combining features of the symmetric-cost case and the large cost asymmetry case.

¹⁷ Note that, again, the fuzzy boundary in *ACG* demarcating the region between investment leadership and commitment by both collapses into a one-dimensional curve in *ODG*.

¹⁸ The combined diagram can be easily obtained from superimposing figures 2 and 3 for the symmetric-cost case, and figures 4a and 4b for the case with a “large” cost asymmetry.

Table 2: Investment timing with quick-in-place versus time-to-build investment

	\bar{S}^2	<i>Quick-in-place Investment (ACG)</i>	<i>Time-to-build Investment (ODG)</i>
COST SYMMETRY	Very High	(D_1, D_2)	(D_1, D_2)
	High	(D_1, D_2)	$(D_1, D_2); (C_1, C_2)$
	Intermediate	$(C_1, D_2); (D_1, C_2)$	(C_1, C_2)
	Low	$(C_1, D_2); (D_1, C_2)$ (C_1, C_2)	(C_1, C_2)
	Very Low	(C_1, C_2)	(C_1, C_2)
"LARGE" COST ASYMMETRY	Very High	(D_1, D_2)	(D_1, D_2)
	High	(C_1, D_2)	(C_1, D_2)
	Intermediate	(C_1, D_2)	(C_1, C_2)
	Low	$(C_1, D_2); (C_1, C_2)$	(C_1, C_2)
	Very Low	(C_1, C_2)	(C_1, C_2)

The bands of uncertainty levels range from the upper zone (labelled as “very high”) to the lowest one (labelled as “very low”). Shaded cells indicate that different outcomes occur for the two games in the specified range of uncertainty. The comparison clearly indicates the greater importance of defensive commitment in *ODG* relative to *ACG*, which is reflected in the emergence of (C_1, C_2) as an equilibrium, even at “high” levels of uncertainty. Unlike in *ODG*, (C_1, C_2) never co-exists with (D_1, D_2) in *ACG*. In *ACG*, the leader-follower equilibria occur at “intermediate” and “low” levels of uncertainty, whereas they can never occur under cost symmetry in *ODG*. With “large” cost asymmetries, the investment timing outcomes of the two games are more similar to each other than under cost symmetry. The main difference between the two cases is that, at “intermediate” levels of uncertainty, the high-cost firm is willing to follow in *ACG* but reacts with defensive commitment in *ODG*. Still, it remains true that overall there is less commitment in *ACG* than in *ODG*.

6. Welfare issues

Given the four candidate investment timing equilibria, we now ask what the best timing outcomes are from a social perspective. We then examine whether these outcomes differ

from those generated by the market with time-to-build and with quick-in-place investment. In our partial equilibrium set-up, welfare is naturally defined as the sum of expected consumer surplus and expected industry profits¹⁹. Capital commitment implies strategic behaviour with investment above the cost minimising level. From a social perspective, more capital commitment therefore raises the social cost of investment and, in addition, foregoes the social benefits from flexibility. However, it will also lead to higher production and therefore lower prices for consumers.

In figures 5a and 5b, the actual investment-timing outcomes (with cost symmetry) are indicated by superscript m , while the socially preferred outcomes are superscripted by s . A shaded label highlights the areas in which the market outcome differs from the socially preferred investment timing. For both games the socially preferred timing outcomes coincide with the market outcomes at fairly *high* (area IV in figures 5a and 5b) and at fairly *low* (area D) uncertainty. In the former case, both firms delay, whereas they both commit in the latter case. At *moderate* levels of uncertainty (areas II and III), however, comparing the socially preferred outcomes to the ones generated by the market leads to different implications in *ACG* than in *ODG*. In *ACG* (figure 5a), the market produces too much commitment in area III, but too little commitment in area IIb (and possibly in area IIa). In *ODG* (figure 5b), the market will never produce too little but may involve too much strategic commitment (i.e., the market generates (C_1, C_2) where (D_1, D_2) is socially preferred)²⁰.

[Insert Figures 5a and 5b about here]

This brief positive welfare analysis indicated which of the four candidate investment timing equilibria yield the highest welfare for different ranges of uncertainty and allowed us to compare these with those generated by the market. However, it is clear that policy intervention could improve welfare since the oligopoly distortion implies that firms are producing too little. In addition, when firms are investing strategically they choose more than

¹⁹ Like profits, consumer surplus is convex in u , implying that consumers also like firms to be flexible.

²⁰ When there is a substantial cost asymmetry between firms, we find that comparisons between the market and the socially preferred outcomes are qualitatively the same for both games. Having the low-cost firm as the leader is socially preferred unless uncertainty is very high.

the socially cost-minimising capital level²¹. The standard instruments to deal with these distortions are production subsidies and capital taxes. Moreover, besides affecting the levels of output and investment, the government may also wish to change firms' investment timing. Compared to quick-in-place investment, more firms tend to invest too early with time-to-build investment. As a result they lose their flexibility, implying that the government may want to engage in commitment deterrence²². Hence, a first-best package of policies will simultaneously and directly address these three possible inefficiencies of underproduction, overinvestment and inflexibility.

7. Conclusion

The implications of the simple real-world fact that investment projects take time to complete were considered in an oligopoly setting. Standard investment theory finds that an increase in uncertainty causes delay. However, under oligopoly with quantity-setting firms, there is an incentive to invest early. There are two closely related reasons for this. First, there is an aggressive motive to win a first-mover advantage and second, there is a defensive motive to avoid being saddled with a second-mover disadvantage. We have shown that a time lag between *when* and *how much* to invest reduces the incentive to delay induced by uncertainty. In particular, the defensive motive for early investment is greater when investment requires time to put in place. We have shown that with such investment projects, firms within the industry *all* tend to invest early at levels of uncertainty for which some firms would have delayed if the investment were of the quick-in-place type. This is consistent with Bar-Ilan and Strange (1996), who find –in a totally different model *without* strategic behaviour- that time-to-build induces firms to invest earlier rather than later.

A case study of the bulk chemical industry by Ghemawat (1984) provides empirical confirmation of our model's predictions. Two of his observations are particularly relevant here. First, he concluded that the lowest-cost producer in the titanium dioxide industry, Du Pont, chose for investment leadership as a deliberate growth strategy. This corroborates

²¹ This distortion is absent in models that are concerned with endogenous production -as distinct from investment- timing. Hence, a welfare analysis (of which, to our knowledge, there are as yet no examples) in such models would differ from ours.

²² Dewit and Leahy (2001) consider policies to deter commitment in an open economy setting.

our finding that, in the presence of cost asymmetries, the low-cost firm has the greater incentive to invest early. Second, he points out how the presence of significant construction lags in the industry effectively allowed “defensive” commitment. He cites (p. 157) how one firm, Kerr-McGee, prevented its rival, Du Pont, from obtaining a first-mover advantage: by introducing its own investment plans before Du Pont’s expansion had fully materialised, Kerr-McGee forced Du Pont to revise its initial capacity plans. This illustrates the difficulty of effectively obtaining leadership with time-to-build investment, as was emphasised in our paper.

Finally, our paper explored the welfare implications of time-to-build investment. Our analysis suggests that in industries in which investment takes time to be completed firms tend to invest too early from a social perspective. Too much investment delay, however, never occurs. This is not true with quick-in-place investment; then, even at moderate levels of uncertainty, it is possible that not enough firms invest early. These findings suggest that investment policies may require a lot more thought and may possibly need to take into account the duration of investment projects until completion.

Appendix A

Table A: Expected profits in the different candidate equilibria under Action Commitment and Observable Delay

	C_1, C_2	C_1, D_2	D_1, C_2	D_1, D_2
EP_1	$g(Eq_1^{cc})^2 + \frac{1}{9}s^2$	$z(Eq_1^{cd})^2 + \left(\frac{1-h}{3-2h}\right)^2 s^2$	$j(Eq_1^{dc})^2 + \frac{1-h/2}{(3-2h)^2} s^2$	$j(Eq_1^{dd})^2 + \frac{(1-h/2)}{(3-h)^2} s^2$
EP_2	$g(Eq_2^{cc})^2 + \frac{1}{9}s^2$	$j(Eq_2^{cd})^2 + \frac{1-h/2}{(3-2h)^2} s^2$	$z(Eq_2^{dc})^2 + \left(\frac{1-h}{3-2h}\right)^2 s^2$	$j(Eq_2^{dd})^2 + \frac{(1-h/2)}{(3-h)^2} s^2$

with $g \equiv 1 - (8/9)h$, $z \equiv 1 - 2h\left(\frac{2-h}{3-2h}\right)^2$ and $j \equiv 1 - h/2$.

Appendix B: Determination of the investment timing equilibria

(i) The investment timing equilibria with quick-in-place investment (ACG)

To find the equilibria in different regions of the (\bar{s}^2, h) -space we proceed by asking when each of the *candidate* equilibria will *not* be an equilibrium. For concreteness and without loss of generality, we consider possible deviations by firm one from each candidate equilibrium.

(a) The candidate equilibrium (D_1, D_2)

On the highest locus in figure 2, each firm is indifferent between commitment and delay given investment delay by its rival. Given rival delay, firm one, in deciding when to invest, compares the profits $EP_1(D_1, D_2)$ and $EP_1(C_1, D_2)$, taking into account that its rival reacts to its investment timing decision. For instance, on the locus $(EP_1(C_1, D_2) = EP_1(D_1, D_2))$ firm one is indifferent between choosing k_1^{cd} in period one and delaying its capital choice until period two (when it will choose $k_1^{dd}(u)$). Below this locus (areas I-III), (D_1, D_2) cannot be an equilibrium.

(b) The candidate equilibria (C_1, D_2) and (D_1, C_2)

The highest locus in figure 2 also demarcates the maximum uncertainty upper limit for the leader-follower equilibria, $(C_1, D_2) = (k_1^{cd}, D_2)$ and $(D_1, C_2) = (D_1, k_2^{dc})$. In other words, (C_1, D_2) (and by symmetry (D_1, C_2)) cannot be an equilibrium above this locus (area IV), since in that region $EP_1(k_1^{cd}, D_2) < EP_1(D_1, D_2)$. The lowest of the three loci in the figure provides the lower bound for leader-follower equilibria. Below this locus (area I) we have

$EP_1(C_1, k_2^{dc}) > EP_1(D_1, k_2^{dc})$, and hence firm one will wish to deviate from delay given that firm two chooses the investment leadership capital level, k_2^{dc} .

(c) The candidate equilibrium (C_1, C_2)

This is an equilibrium at $\bar{S}^2 = 0$, when there are no flexibility advantages of delaying and both firms commit, regardless of the timing strategy of their rival. Next, consider the range of \bar{S}^2 and h over which $(C_1, C_2) = (k_1^{cc}, k_2^{cc})$ cannot be an equilibrium. Given k_2^{cc} , there is a locus (the second highest in figure 2) along which firm one is indifferent between commitment and delay. Above this locus (areas III and IV), we have $EP_1(C_1, k_2^{cc}) < EP_1(D_1, k_2^{cc})$, hence, firm one wants to delay and therefore (C_1, C_2) cannot be an equilibrium. On or below the locus, firm one will not wish to deviate from k_1^{cc} (by symmetry, firm two will not want to deviate from k_2^{cc} in that region). Thus, commitment by both firms will be an equilibrium at all uncertainty levels that are not above this locus.

(ii) The investment timing equilibria with time-to-build investment (ODG)

The investment timing equilibria are determined by a method similar to the one described in (i), but now using the loci represented in figure 3.

(a) The candidate equilibria (D_1, D_2) and (C_1, C_2)

Above both indifference loci in figure 3 (area III) delay will be played by each firm, regardless of its rival's timing choice. Hence, (D_1, D_2) is the unique equilibrium in area III. Below both indifference loci (area I), commitment will be played by each firm, regardless of its rival's timing choice. Hence, (C_1, C_2) is the unique equilibrium in area I. In the intermediate region (area II), commitment is the best response to rival commitment, while delay is the best response to rival delay. Therefore, both (D_1, D_2) and (C_1, C_2) are equilibria in area II.

(b) The candidate equilibria (C_1, D_2) and (D_1, C_2)

When commitment is the best response to delay (area I), delay *is not* the best response to commitment, but, when delay *is* the best response to commitment (area III), commitment is not the best response to delay. Hence, (C_1, D_2) and (D_1, C_2) are never equilibria.

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Figure 1a: The game with quick-in-place investment (ACG)

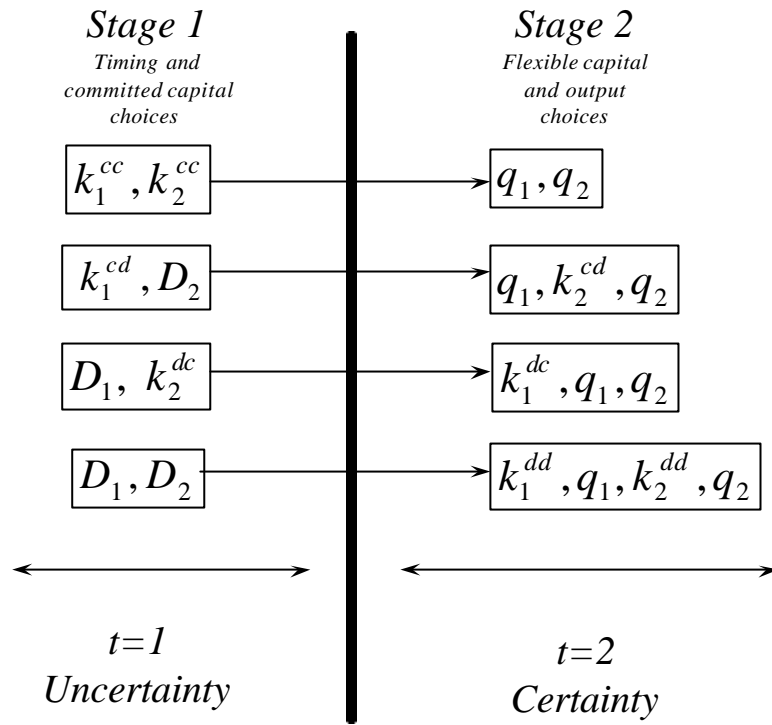


Figure 1b: The game with time-to-build investment (ODG)

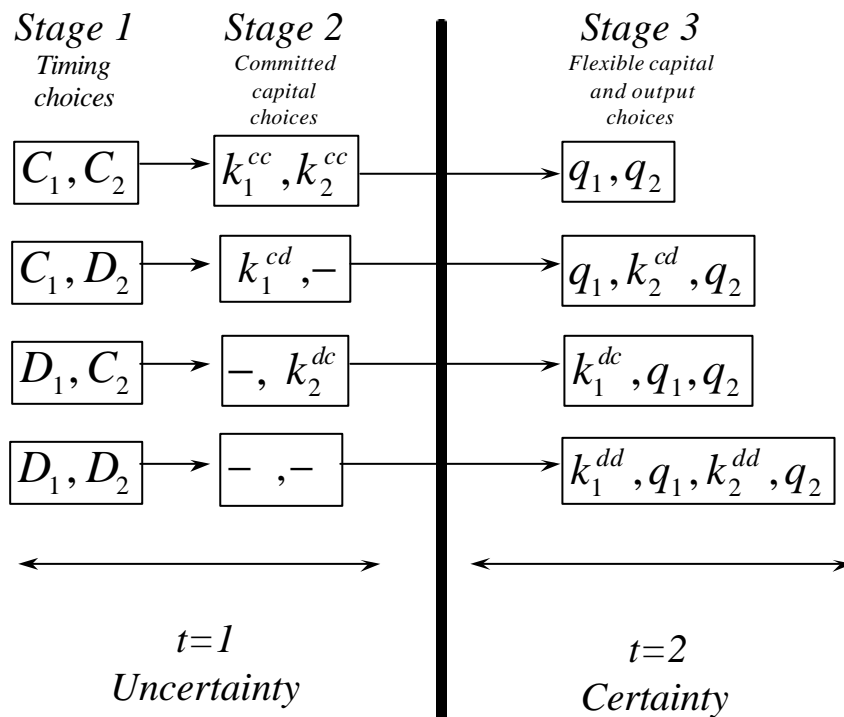


Figure 2: Investment timing with quick-in-place investment (ACG) for cost symmetry ($A_1=A_2$)

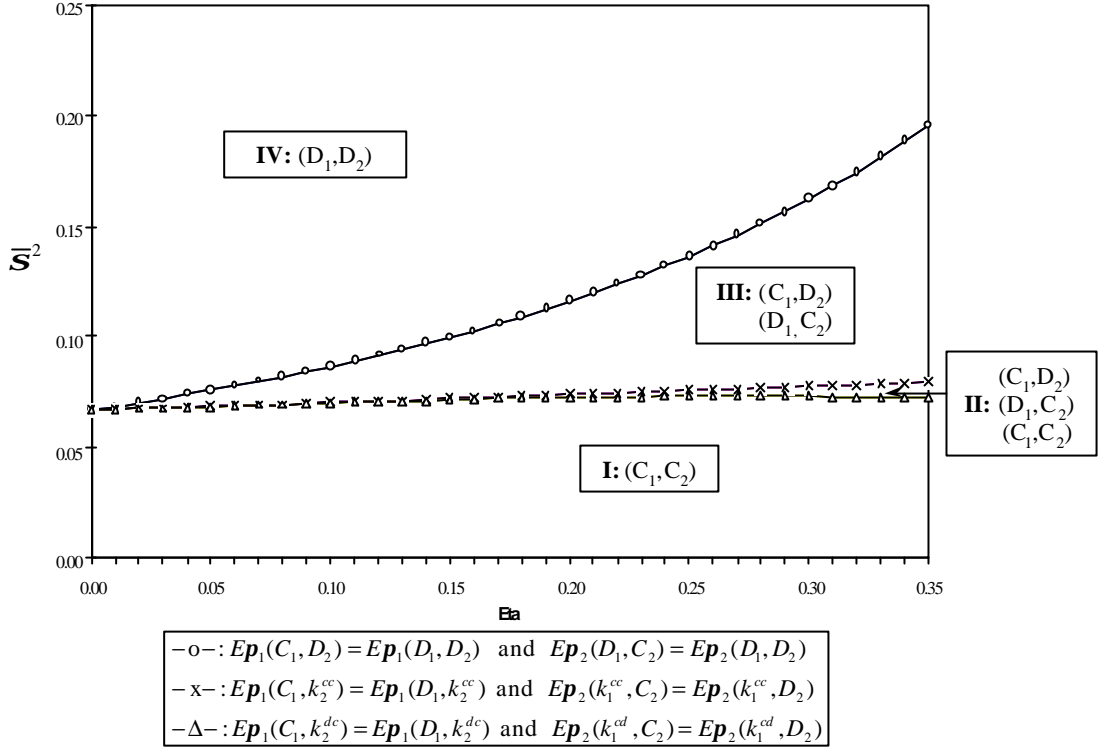


Figure 3: Investment timing with time-to-build investment (ODG) for cost symmetry ($A_1=A_2$)

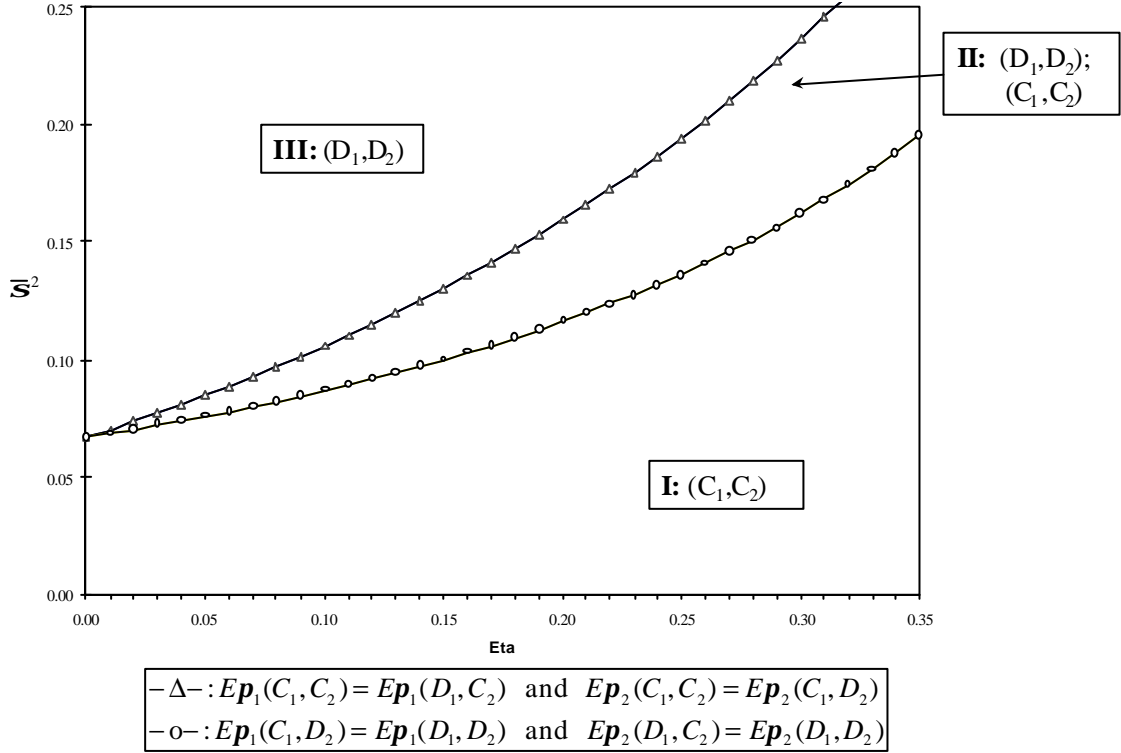


Figure 4a: Investment timing with quick-in-place investment (ACG) for "large" cost asymmetries ($A_2=0.8A_1$)

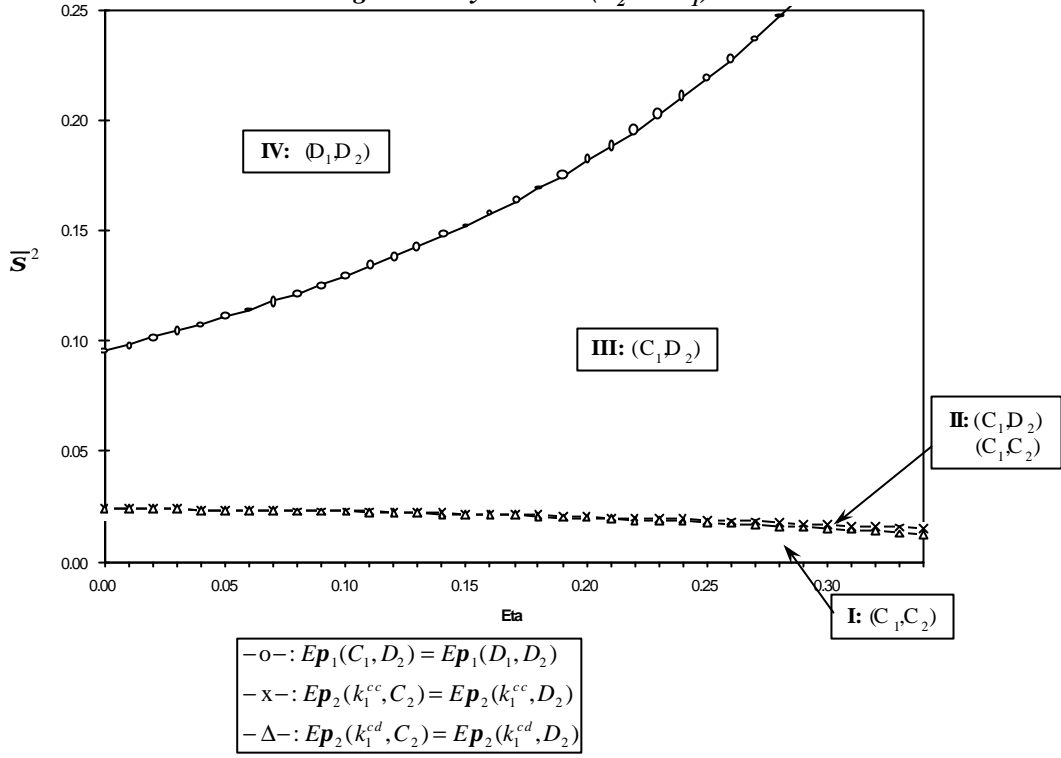


Figure 4b: Investment timing with time-to-build investment (ODG) for a "large" cost asymmetry ($A_2=0.8A_1$)

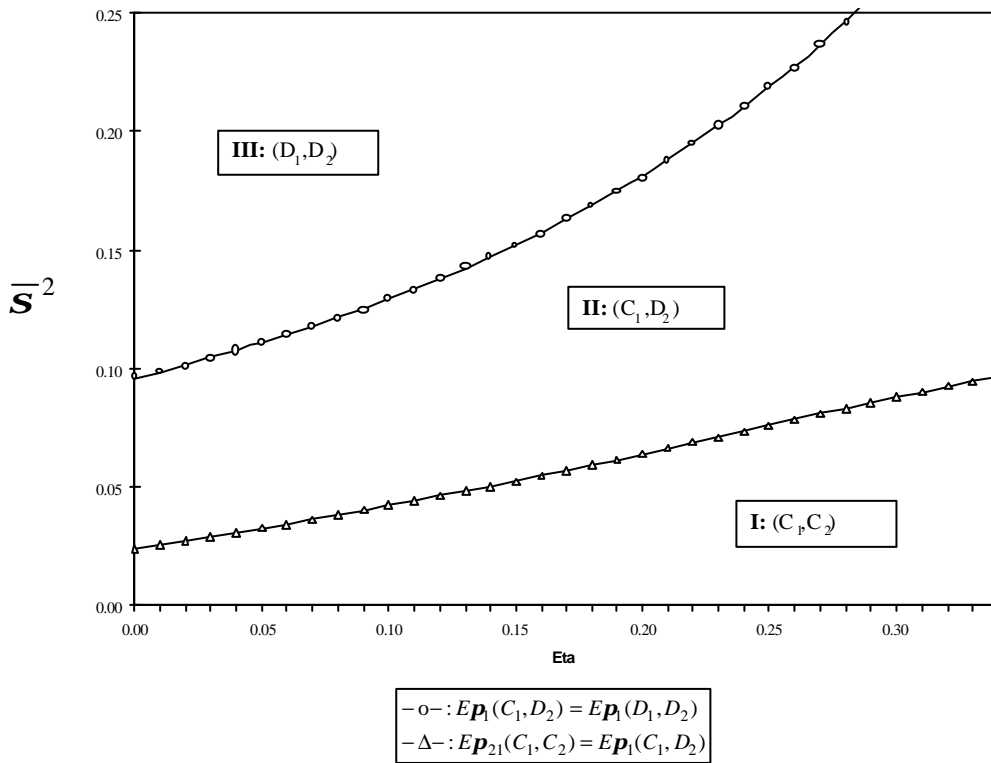


Figure 5a: Market outcomes versus socially preferred outcomes with quick-in-place investment (ACG) for cost symmetry ($A_1=A_2$)

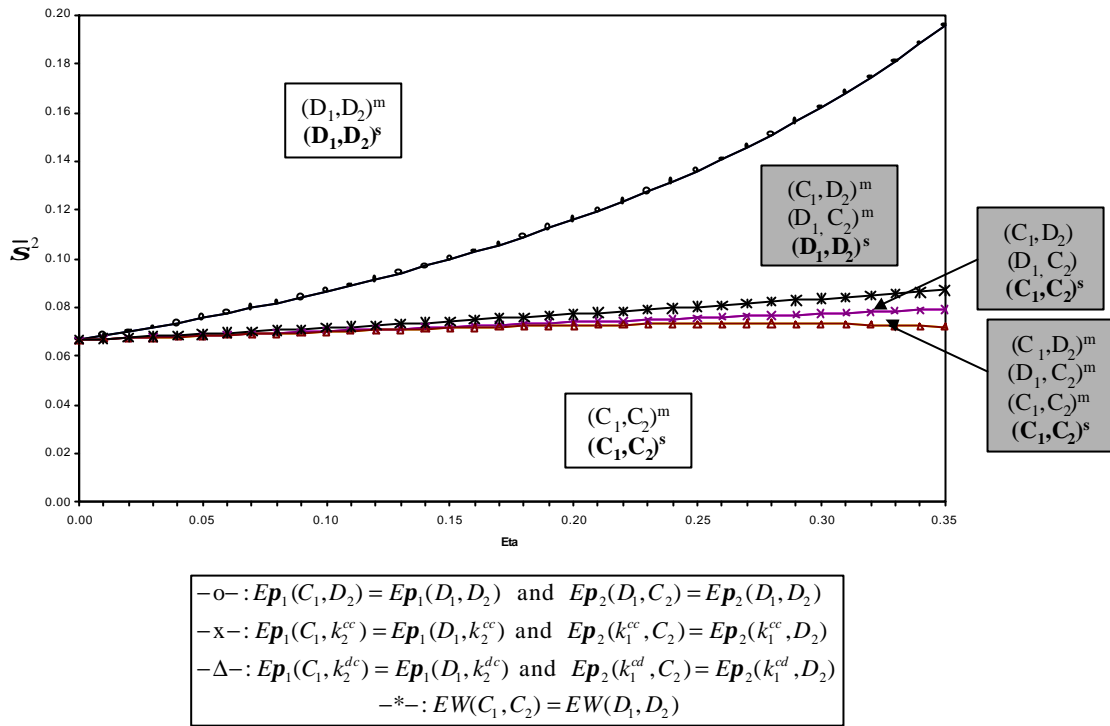


Figure 5b: Market outcomes versus socially preferred outcomes with time-to-build investment (ODG) for cost symmetry ($A_1=A_2$)

