Research Memorandum

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Falling R&D but stable investments by oil companies: why?

A study on R&D and investment in fixed assets in the oil industry

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1. Introduction[1]

In the 20th century, oil has become a critical resource, which has increased economic prosperity considerably in two main ways. First, transport costs fell drastically, because oil is a cheap source of power. Low transport costs have lead to the surge in personal mobility and consequently to more consumer prosperity. Lower transport costs have also lead to changes in production technologies, particularly regarding the increased exploitation of interregional differences in endowments and better use of economies of scale in factories. In fact, reduced production costs resulting from such advantages have outweighed the limited extra costs for transporting the commodities. Second, prosperity grew by the emergence of the organic chemical industry, which is rooted in oil. This industry produces many new materials which are the basics of paints, packaging, and many plastic components in durable goods, like cars and dwellings.

Because oil is a vital resource for the economy, the oil industry is of great concern for policymakers. Practically, this concern appears in the fields of competition, the exhaustion of oil fields and global warming. The Standard Oil case and the recent megamergers (Exxon Mobil and Arco, BP Amoco, and Total Fina) received much attention of several officials on competition policy in order to prevent (abuse of) market power. The expected exhaustion of energy stocks and the two energy crises induced policymakers to secure guaranteed supply. Finally, policymakers have also become concerned about the external effects involved with using oil, such as global warming and pollution.

The latter two issues, i.e. exhaustion of stocks and external effects, suggest that technological progress may be more focussed on the development of new and environmental friendly technologies, fuels and other petrochemicals. New research may even open up the exploitation of new energy sources. But our investigation shows that many multinationals in the oil industry have restricted their R&D-budget and often refrain from research in new areas.

However, the industry can only benefit from such technological progress if the companies are (also) successful in implementing these innovations in the production phase. Therefore they must particularly invest in refineries, drilling platforms, measurement instruments and transport installations that contain such newly developed and environmental friendly technologies. So both investment in R&D and modern fixed

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assets are inimical to technological progress, and can only collectively contribute to the economic prosperity and sustainable growth.

In the last decade, however, the research expenditures in the oil industry have persistently declined. The investments in fixed assets, instead, remained more stable during this period. This paper therefore deals with the following question: Why did the R&D-outlays in the oil industry drop recently, and not the investments in fixed assets? The question is tackled with data drawn from the annual reports of the 13 largest companies in the oil industry and additional patent data. The paper will particularly focus on the world-wide research and investments of multinational oil companies (such as Exxon, Shell and BP Amoco) in all related market segments –i.e. the exploration, production, refining and sales of oil, and the production of other petrochemicals– not on their research and investments performed in specific countries or segments.

This paper builds in three ways on an earlier study on the investment interactions in the electronics-, computer-, chemical and pharmaceutical industry (see Minne (1997) and (1998)). First, the theoretical basis is improved. Second, more types of strategical behaviour are investigated. And third, besides R&D-expenditures, patent data are used in order to find the answers.

The structure of this paper is as follows. First, section 2 analyses the impact of the companies' own key financial figures and competitors' R&D- expenditures (and fixed assets) on their own R&D-expenditures (and fixed assets respectively) according to the approach in Minne (1997) and (1998). Then sections 3 and 4 analyse the R&D-drop. The common decline in R&D can be explained by common expectations among the companies and a dwindling R&D-race. Section 3 further reviews the possible common expectations and check their plausibility by patent-data. Section 4 then raises protection of new know-how as the main reason for the race and underpins this reason with patent-data. Finally, section 5 summarizes the main results.

2. Falling R&D but constant investments: why?

2.1 Facts

The CPB company database[2] reveals that in the last decade the R&D in the oil industry have persistently dropped after the steady development at the end of the 80's (see figure 1a). Actually, in the last decade most oil companies have cut their R&D expenditures – or at most maintained these budgets at a constant level– even though their total sales increased substantially. This decline in research is remarkable viz. the eminent challenge to develop new and environmental friendlier technologies and products. The course of the research expenditures contrasts sharply with the fluctuating course of the investments in fixed assets, as depicted in figure 1b. Actually, over the last two decades these fixed investments maintained at a level of about 8% of total sales. From the diverging developments we may therefore assert that the research strategy and investment decisions seem to be based on different principles. The next two sections will elaborate this issue.

Figure 1a: Research expenditures of major oil companies and engineers

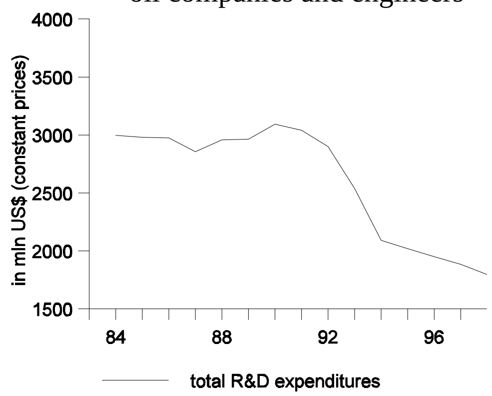


Figure 1b: Fixed investments of major oil companies and engineers

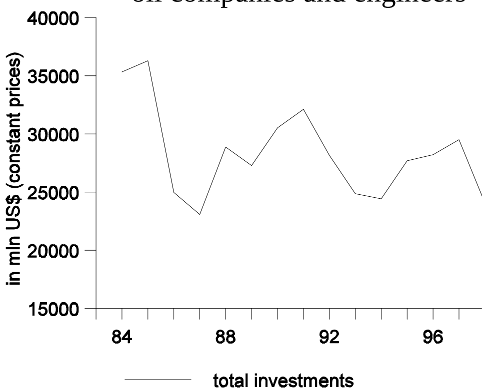


Table 1 lists the companies in the oil industry which we analysed in our research. The table also provides some key data on their "innovative performance" in 1997-1998. In order to make meaningful comparisons between companies on innovativeness, we have calculated for each company its investment intensity, defined as the ratio of total investment in fixed assets to total sales, and its research intensity, defined as the ratio

Table 1 The oil industry and innovation

[2] Appendix 1 gives an extended description of this database.

	Investment intensity 1997-1998	Research intensity 1997-1998	Patents 1997-1998
	in %	in %	number
Drilling services	12.66	3.90	
Schlumberger	15.06	4.69	164
Halliburton	6.54 [d]	1.87 [d]	183
Oil-producers	9.00 [f]	0.49 [f]	
Exxon	6.16	0.42	364
Mobil Oil	8.41	0.37	131
Shell	11.31	0.66	263
BP	8.06 [d, e]	0.32 [d, e]	97
Amoco	9.20 [d, e]	0.42 [d, e]	51
Texaco	8.59	0.36	28
Elf	n.a.	2.76	31
Chevron	10.73	0.50	84
Total	9.46	0.77	29
Petrofina	6.00	0.44	n.a.
Phillips Petroleum	15.02 [d]	0.43 [d]	48

[a] the ratio of total investments in fixed assets in 1997 and 1998 to total sales in 1997 and 1998, nominal data

[b] the ratio of total research expenditures in 1997 and 1998 to total sales in 1997 and 1998, nominal data

[c] for description of patent data see appendix 1.

[d] only for 1997.

[e] the average investment intensity and research intensity for BP and Amoco consolidated is in 1998 respectively 10.69 and 0.60.

[f] average investment- and research intensity without figures for Elf-Acquitaine.

of total R&D expenditures to total sales [3]. In addition, the table includes the number of patent applications of each company in 1997 and 1998. Appendix 1 gives an extended description of investment data of (on average) the last two decades and patent data of ‘87-‘88, ‘92-‘93 and ‘97-‘98.

The table reveals that for each company the R&D intensity is considerably smaller than the investment intensity. This observation indicates that the oil industry is very capital intensive. Actually, the oil companies invest heavily in equipment for their upstream activities, such as exploration (drilling platforms) and production (oil pumps, pipelines and tankers), and in refineries[4]. Part of the capital expenditures in the oil industry combat global warming. Consequently, process innovation is dominant in the oil industry. As a mature industry the oil industry only spends less than 1% of their sales on R&D. However, since most companies are (extremely) large their total R&D effort is still considerable. In fact, the 13 major oil companies and engineers in our study spent about $4,2 bn in 1997.

The table also contains figures on the innovative performance of two drilling companies. These drilling service enterprises, or so-called oil engineers, focus their core-business on the upstream stages in the oil industry, i.e. the exploration and production of (crude) oil (see section 4). They are much more innovative than the oil companies, but their investment intensities in fixed assets are more comparable. So despite their smaller size, these oil engineers still make a substantial contribution to the research in the oil industry.

[3] The industry average R&D intensity and investment intensity are average intensities for both oil companies and oil engineers. These two average intensities are calculated as the ratio of total investments and total sales for those enterprises for which data on investments (and sales) are available. So the enterprises for which the data in some year are missing are not incorporated in calculating the annual average investment intensity of that respective year. The latter reservation particularly holds for Exxon, for which data between 1975 and 1983 are missing. However, simulating by extending the series of Exxon with fictitious but acceptable figures of Exxon back to 1975 does not alter the course of average research intensity in the indicted period. Further, skipping the data for the oil engineers only results in a downward shift of the intensity levels in the whole period (1975-1998).

[4] Source: Annual Reviews.

2.2 The impact of financial structure

Theoretical backgrounds

In this section we investigate whether the differences in financial structure, i.e the combination of the availability of internal funds and creditworthiness, can explain the question why only investments in R&D have dropped and not the investment in fixed assets. Less internal funds, probably due to sustained lower profits, or limited external funds may reduce the firms ability to invest in R&D.

Several arguments plea for the assertion that internal financing is more important for R&D than investment in fixed assets (for elaboration of these arguments see the two boxes below). First, external financiers often have less information about research prospects –such as its potential return, external risks and the efforts and success of researchers– than the company's managers. In fact, the information asymmetry in R&D is much larger than the information asymmetry in fixed investment. So, particularly in case of R&D, external financiers may become a victim of the borrower's potential opportunistic behaviour such as the improper use of funds. If the consequences of this informational asymmetry cannot be removed, then risk averse financiers may restrain from lending funds. Second, the incomplete knowledge of a new technology as an intermediate output of research is unsuitable for solid collateral in cases of economic setbacks. So because of informational asymmetry and lack of collateral involved with R&D, risk averse financiers may charge an extra risk premium and make external financing more expensive, unless they can trust implicitly on the company's substantial creditworthiness (see Hubbard (1998)). Companies would thus be forced to use internal funds for financing risky R&D projects. But without sufficient retained profits and internal funds they may have to refrain from research.

The investments in fixed assets, however, offer more solid collateral and entail substantially less information asymmetry between external financiers and the company's management. So companies may finance their fixed investment more likely with external funds. A higher creditworthiness will improve their ability to borrow external funds. Actually, if firms have less total debt, they can better meet (new) interest obligations and have sufficient free and unpawned collateral – for cases of bankruptcy– if they would take a new loan. Further, firms with lower creditworthiness must more often rely on their own means, thus making new investments more vulnerable to fluctuations in the availability of internal funds (cf. Farrazi, Hubbard and Petersen (1988)).

So from these (theoretical) arguments we would expect that oil companies with more internal funds can better invest in risky projects such as R&D. The empirical research by Hall (1992) on the financing of investments notably confirms the "...unsuitability of debt as a source of finance for R&D-investment...". On the other hand, a company may find it easier to borrow financial funds if its creditworthiness is larger. Therefore we expect that creditworthiness has a significant impact on investment, particularly for investments in fixed assets with safe collateral.

Some analytical remarks on the impact of financial constraints

The relation between investments and internal funds described above looks similar to widely investigated relation between the company's investments and the expected net return on future's investment, also known as Tobin's q (see Hubbard (1998)). However, in our analysis the equity or retained profits refers to the companies' current financial capacity to make investments, not to their expectations on future investment returns in other studies. In reality this return is hardly predictable due to the potential risks involved with the investment.

High potential risks and/or modest returns may even distort the relation between the companies' investments and its creditworthiness in case of external financing. Actually, companies adjust the expected return on investment for risks by subtracting some (weakly defined) risk premium. Now, in case of investments with high risks and low risk adjusted returns, companies are tempted to choose a low level of investments. So then they would only need only a small loan that is fully covered by equity. Companies with plenty cash may even confine with their internal funds and thus abandon from lending. So generally speaking , higher risks and/or less investment returns may weaken the relation between the company's investment intensity and financial structure, particularly between risky R&D and its creditworthiness.

Incentive compatible contracts as a remedy on information asymmetry

The negative consequences of asymmetric information on research performance can be removed by incentive compatible contracts that increase the commitment of the innovative firm or division. Maurer, for example, suggests to use incentive-compatible loan contracts (see Maurer (1999)). Such a contract introduces a periodical test on the firm's profit (or research progress) to decide whether continuation of the loan for the next marked period is appropriate. Actually, if the lending firm is successful and realizes sufficient profits to fulfill its repayment obligations, it can obtain new funds for continuing its research. If it cannot make sufficient profits for repayment, the investor captures all remaining profits and suspends further continuation of the loan.

The European Investment Bank (EIB), for example, resolves to monitor investment projects for which it has granted a loan until completion of the project as well as during the loan repayment period. More particularly, it checks wether "... the funds are used in line with corresponding objectives and forecasts, and keeps abreast of developments concerning the promoter (i.e. the investing company) and his partners..." (see http://www.eib.org/proj.htm).

Aghion and Tirole, however, suggest to combine the loan with a research license (see Aghion and Tirole (1994)). The idea is that firms should give the property rights of a potential innovation to the research unit and subsequently bargain for a license fee for using the innovation. In this way financiers are more prepared to co-finance research projects because the increased financial involvement of the research unit offsets their financial risks. Actually, the research unit has minimal incentives to shirk but will rather try to limit the overall R&D cost.

Specialization and outsourcing of research (cf. section 4) is some kind of the latter concept. In fact, oil companies may stimulate or even commission oil engineers to conduct specific research, e.g. in drilling technologies. The oil engineers then obtain all property rights of the new technology, and make it available to other companies at some compensation fee. They still bear all risks that are related with their research.

Testing the hypotheses on financial structure

To test the previous hypotheses on the impact of the financial strength we use two financial variables that can be derived from the available data set. As a measure for the availability of internal funds we use profitability, defined as the ratio of net profits to total sales and denoted as P/S. We have no data which are directly related to the availability of internal funds, but we are still confident of the explanatory power of the profits because companies raise internal funds by retaining profits. For measuring creditworthiness we use the debt to assets ratio, defined as the ratio of total debt to total assets and denoted as D/TA. The ratio of stockholders' equity to total assets may be more obvious and easier to understand, but its complement –the debt to assets ratio– is more often used in financial analysis. A low (high) debt to assets ratio points to higher (lower) creditworthiness.

The profitability and debt to assets ratio will be used to explain the developments in research intensity and investment intensity. Notice that by scaling each company's net profits and its R&D outlays or investment in fixed assets, we also partly correct the regressions for spurious correlations of R&D trends (heteroscedasticity). In fact, the impact of internal funds on R&D or fixed investments is not influenced by the total sales because both regression terms (R&D/fixed investments and profits) are divided by sales.

The graphical representation and interpretation of the development in profitability and debt to assets ratio gives a first impression on the development of internal funds and creditworthiness and their impact on investments. Figure 2a shows that the oil companies have on average a highly fluctuating profitability rate[5]. Comparing the average profitability development with the oil price development (not included in figure 2a) reveals that the average profitability of oil companies is weakly related to (the margin between) the average price of final oil products and the input price of crude oil. This observation may indicate that oil companies are not only dependent on the oil industry but also have activities in other industries, such as the chemical industry[6]. Figure 2b reveals that the oil companies have lower but more stable debt to assets ratios than the oil engineers.

[5] The average profitability of oil engineers is not included in figure 2a because this profitability fell dramatically from 14,1 % in 1982, via 0,1% in 1983 to -31,3 % in 1984. For this dramatic fall we can not give any explanation.

[6] Notice that the intermediate oil products are particularly used in the chemical industry. A decline (increase) in oil prices – and thus in the prices of intermediate oil products– then entail declining (increasing) profits in the oil industry, but increasing (decreasing) profits in the chemical industry.

By comparing figures 1a and 1b with figures 2a and 2b we may assert that the availability of internal funds and creditworthiness may likely explain the fluctuating development of the investments in fixed assets, but can hardly explain the persistent decline in R&D expenditures in the 90's.

Figure 2a: Average profitability

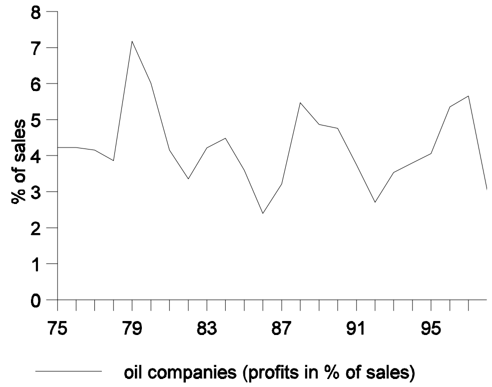
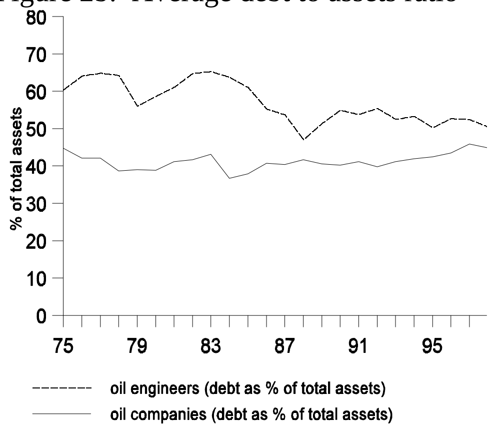


Figure 2b: Average debt to assets ratio



In order to test these theoretical assertions more appropriately we regressed the intensities of R&D and investment in fixed assets for each company on the 1-year or 2-year lagged profitability rate and the 1-year or 2-year lagged debt to assets ratio by simple least squares. For these regressions we used the financial key figures from the CPB database (see appendix 1). In this way we implicitly assume that the investment behaviour of each company remained constant over the estimation period (i.e. at most between 1975 and 1998).

Table 2a and 2b mention all significant and non-significant coefficients which are theoretically correct, i.e. a positive coefficient for profitability and a negative coefficient for the debt to assets ratio[7]. The sign of the latter coefficient results because companies with lower debt to assets ratios are more creditworthy to make new debts for financing new investments.

[7] For those companies for which several specifications with the 1-year-lagged or2-year lagged explaining variables are theoretically correct, we selected the specification with the highest explaining power or R^2.

Table 2a Determinants of investment in R&D

	Profitability [a,b]	Credit-worthiness [a,c]	R^2	Period
	coefficients			year
Schlumberger				76-98
Halliburton				81-97
Exxon		-0.015	0.143	84-98
Mobil				81-98
Shell				76-98
BP	0.022		0.028	77-97
Amoco				76-97
Texaco	0.016		0.023	76-98
Elf		-0.122*	0.342	77-98
Chevron				76-98
Total		-0.018*	0.480	79-98
Petrofina				89-97
Phillips				76-98

[a] a superscript * denotes a significant relationship with (absolute) t-statistic larger than 1.9.

[b] coefficient of 1 year lagged profitability (BP 2 years lagged) on R&D

[c] coefficient of 1 year lagged creditworthiness (Exxon 2 years lagged) on R&D.

Table 2a indicates that the availability of internal funds and creditworthiness have a weak explanatory power on R&D. Only for the French Elf Acquitaine, and to a lesser extent for Total, creditworthiness seems to be significantly related to R&D. This outcome is similar to the results in the previous study investigating the R&D and fixed investment in the chemical industry (see Minne (1998)). The limited impact of internal funds and creditworthiness on R&D outlays thus seem to be solid. The (unpublished) high constants derived from the regressions would imply that R&D expenditures are proportional to sales. However, this result contradicts with our observation that the research intensity is not stable, and so that R&D expenditures and total sales have different time patterns.

Table 2b *Determinants of investment in fixed assets*

	Profitability [a,b]	Credit-worthiness [a,c]	R^2	Period
	coefficients			year
Schlumberger	0.103 *		0.213	76-98
Halliburton	0.246 *		0.602	80-97
Exxon		-0.202 *	0.313	83-98
Mobil	0.323	-0.114	0.209	76-98
Shell	0.551	-0.260	0.239	87-98
BP	0.565 *		0.343	77-97
Amoco	0.051	-0.521 *	0.278	77-97
Texaco				76-98
Elf		-1.044 *	0.813	78-96
Chevron	0.266 *	-0.096 *	0.661	81-98
Total				79-98
Petrofina	1.715 *	-0.138 *	0.588	77-95
Phillips	0.686 *	-0.041	0.502	76-98

[a] a superscript * denotes a significant relationship with (absolute) t-statistic larger than 1.9.

[b] coefficient of 1 year lagged profitability (Amoco, BP, Petrofina and Shell 2 years lagged) on investment in fixed assets

[c] coefficient of 1 year lagged creditworthiness (Amoco, Elf and Exxon 2 years lagged) on investment in fixed assets

Table 2b reveals that the financial structure has more impact on the investments in fixed assets. Notice particularly the relatively high profitability-coefficients for Petrofina and the high coefficient of the debt/assets ratio for Elf Acquitaine[8]. Further, the investments of both oil engineers in equipment are only significantly related to their potentials for internal financing, although to a relatively low extent.

[8] The estimated coefficient of Petrofina may be due to limited available data; for the coefficient of Elf Acquitaine we have no explanation.

In conclusion we may argue that research expenditures, contrary to investments in fixed assets, can hardly be explained by the financial structure. So more internal funds and improved creditworthiness can only contribute to substantial growth through higher investments in fixed assets, not through more research. Obviously, there must be other factors at work which can explain the industry wide drop in R&D-outlays.

2.3 Strategic interactions

This section considers the impact of the strategic interactions between oil companies in their investment strategy. We will particularly find out whether the various strategies for conducting research and/or investing in fixed assets intensify or accommodate competition between oil companies. Bulow, Geanakoplos and Klemperer (1985) and Tirole (1988) developed the basic theoretical concept of strategic interactions and discern two types of interactions (see theoretical background). However, only a few empirical studies explicitly elaborate on this theoretical and fundamental concept. Sundaram et al. (1996), for example, investigated the relations between market interactions, R&D intensity and the firms' expected profitability indicated by the firms' stock prices[9]. Many other studies[10] investigate strategic interactions between companies without explicit reference to the basic theory of strategic interactions. This study, instead, takes the basic concept on strategic interactions as an explicit starting point and applies the concept to explain the drop of the industry wide R&D expenditures.

In this section we leave the oil engineers out of consideration, because the oil engineers and the "regular" oil companies direct their investments on different stages in the supply chain. In fact, section 4 reveals that the engineers specialized in drilling services focus their research on product development in the upstream stage, while the oil companies specialize in the development of downstream technologies.

[9]Actually ,the market interactions refer to strategic interactions in produced quantity levels or market prices. The study by Sundaram et al. shows that companies in concentrated markets often boost competition, while R&D-intensive companies in specialized segments are more likely to accommodate (external) competitive forces. It also showed that the prospected changes in R&D expenditures have not only a straight effect on stock prices, but also an indirect effect via competition and market interactions.

[10] For example studies on R&D and patent races (see Reinganum (1989)) or on industry-wide studies on innovation and diffusion of knowledge (see e.g. Jovanovic and MacDonald (1994a) and (1994b).

Theoretical background on strategic interactions

Competing enterprises may not only base their investment decisions on their financial strength, but also on other firms' investments. More particularly, if some company takes an initial investment impulse[11] in order to improve its market share and profits, competitors may respond with counter-offensive investments in order to restrict their losses resulting from the offensive impulse. The main theory on strategic interactions classifies such reactions into two categories (cf. Tirole (1988)). It calls a strategic response a *strategic complement* if the competitors follow the same investment strategy as the initiating firm. The strategic response is a *strategic substitute* if the competitors follow an opposite strategy by accommodating the impact of the investment impulse on competition.

The strategic interactions in R&D can be based on either strategic complements or substitutes. If, in case of strategic complements, an innovative company conducts firm-specific R&D such that no spillover exist and competitors cannot benefit from the research, competitors will respond by conducting complementary R&D. If the competitors would not respond and would therefore drop behind in technological progress, they might loose their competitive position and some market share in favour of the innovative company. Similarly, if some company decides to reduce its R&D budget since technological advantage has become less compelling, competitors may eagerly respond with a similar or complementary strategy. In fact, if the competitors would not reduce their own R&D-budget they would invest in research that yields insufficient profits and thus would lose their cost-advantage.

But if spillovers do exist and competitors actually benefit from others' research, then – with strategic substitutes– competitors may reverse their own extensive R&D activities into low scale applied engineering necessary to implement others' innovations in their own production process. In this way the rival firms become "free-riders" on the industry-wide R&D since they fully benefit from R&D-results while incurring lower R&D costs than the researching company.

The strategic interactions in investment in fixed assets can be either strategic substitutes or complements as well. The competitors may either take similar investment decisions to boost the competitive pressure (strategic complements), or reduce their investments to prevent industry wide overcapacity (strategic substitutes).

[11] Such investment impulse may be a sharp increase or decrease of investments in research or fixed assets, or maybe even disinvestment of fixed assets.

Besides the classification in strategic substitutes and complements, we may also consider the extent to which firms respond to each other's (re)action. For example, if two firms mutually respond to the others' investments (so called *simultaneous* interaction[12]), they may get involved in a leapfrogging process in which firms keep responding to the other's (re)action. A single initial investment impulse by one of the two firms will be enough to start such an ongoing process. Firms may also engage in a *sequential* or *hierarchal* interaction. In that case only one of the two firms responds to the other's investment impulse, but not the other way around. We say that the non-responding company is the leader and the responding company the follower. Notice that this type of interaction will not result in a leapfrogging process because each firm acts or responds only once.

Within the class of simultaneous interactions we may discern three interaction types. First, in an *investment race* two firms respond one after the other to the competitor's action with a similar move or strategic complement, thereby continuously reinforcing the competitive rivalry (or relief). Second, in the case of *retraction* the initiating firm may partly reverse its initial impulse due to the competitors' harsh response. In fact, the response may boost competitive rivalry to such extent that continuation of the initial investment impulse becomes counter-effective. Finally, in the case of *elimination* one firm (continuously) accommodates the offensive actions of the other, while the latter firm –motivated by the lax response of the first firm– further intensifies its previous actions. The first firm will, consequently, loose its market share in favour of the latter (and offensive) firm. Table 3 mentions all possible types of strategic interactions of two companies in R&D or investment in fixed assets, including the underlying response types (i.e. strategic complements or substitutes).

This theoretical identification of interactions may be helpful to answer the question why the R&D intensity has dropped. For example, the oil companies may walk into the trap of continuously reducing investments if they follow their competitors' strategy to reduce total costs. More specific, if R&D investments would be based on strategic complements, companies may imitate their rivals and cut their research expenses to reduce cost, particularly if the market matures and technological advantage becomes less compelling.

[12] With simultaneous behaviour of two companies we thus mean that the behaviour of the one is similar and affects the behaviour of the other, and visa versa.

Table 3 *Types of strategic interactions*

(re)action	by company[a]	leads to	of company	response type[b]
simultaneous interactions:				
investment-race intensifying	A	complementary response	B	+S
competition	B	complementary response	A	+S
elimination of lax competitor B by the	A	substituting response	B	-S
offensive A	B	substituting response	A	-S
strategic retraction of A's impulse after	A	complementary response	B	+S
B's response	B	substituting response	A	-S
hierarchical interactions:				
A leads,	A	complementary response	B	+Q
B intensifies A's strategy	B	no response	A	
A leads,	A	substituting response	B	-Q
B accommodates A's strategy	B	no response	A	
no interaction:	A	no response	B	
	B	no response	A	

[a] In this table we assume that company A takes the initial investment impulse.

[b] With
- +S significant simultaneous response as a strategic complement
- !S significant simultaneous response as a strategic substitute
- +Q significant hierarchical response as a strategic complement
- !Q significant hierarchical response as a strategic substitute
- blanc no significant response

Procedure to detect strategic interactions

In order to detect such strategic interactions we determine the mutual correlations between the investments of oil companies (see also box below). Thereby we implicitly assume that each company follows a constant investment strategy in the course of time, because we used all available data for determining the correlations. Actually, for each company we now try to explain its investment not only by its financial variables, but also by each competitor's the unlagged, 1-year lagged and 2-year lagged investment of the other firm[13] to identify mutual strategic responses. Then we combine the mutual correlations of competitors' (lagged) investments to a single response matrix. Such a matrix denotes whether companies respond simultaneously or hierarchically on competitors' investments, and whether a simultaneous interaction refers to an investment race, elimination race or strategic retraction. Appendix 2 presents all estimated response matrices on competitors' research and competitors' investments in fixed assets. The next subsection, however, provides the most striking results from these matrices.

Computation of response matrices

The method to calculate a response matrix is similar for both R&D and fixed investments, and contains two steps. First, for each oil company we conduct separate OLS-regressions to explain a company's investment in research or fixed assets. For the explaining variables we extend the significant specifications from section 2.1 with the other competitor's investment intensities in research or fixed assets. Actually, we have added the unlagged, the one-year lagged and the two-year lagged competitors' investment intensities in separate regressions. The t-statistic of the competitor's investment indicates whether the investment response refers to a significant strategic substitute (negative t-statistic with *t*$1,8) or significant strategic complement (positive t-statistic with *t*$1,8).

Then, by pairing the response coefficients for each combination of two companies we may determine the type of interaction between these two companies. In fact, if both response coefficients are significant and positive then the two companies are involved in a mutual R&D race with strategic complements. If one of the two coefficients is significant while the other is not, then the two companies interact hierarchically with one as the follower and the other as the leader. Finally, if both coefficients are not significant then the two companies do not interact (significantly).

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[13] We regress the competitors' unlagged, 1-year lagged and 2-year lagged investments separately due to the lack of data.

Strategic interactions of oil companies

In order to catch the main results from the various response matrices, we calculated the frequency of occurrences of each interaction type (see Table 4) by counting the contents in the cells of the response matrices in appendix 2.

Table 4 Frequency of various interaction types

	R&D interactions			Investment interactions		
type of interaction	unlagged	1 year lagged	2 year lagged	unlagged	1 year lagged	2 year lagged
	in %					
most common interactions						
investment race (+S/+S)	60	42	20	16	0	0
hierarchy (+Q or -Q)	18	33	51	24	27	33
no interaction	20	23	25	58	71	67
hardly occurring interactions						
elimination (-S/-S)	2	2	2	0	2	0
retraction (+S/-S)	0	0	2	2	0	0
total	100	100	100	100	100	100
	in number					
total	55	55	55	55	55	55

The most striking result from Table 4 is that the R&D-race is the dominant type, as in 60% of all cases both companies respond mutually and instantaneously with similar moves. Taking further account of the declining research expenditures, we may assert that the oil companies restricted their research expenditures because all other companies did exactly the same. In fact, in this case they have minimal risks that they would drop behind in technological progress and loose the competitive struggle.

Companies may not only respond instantaneously but also with time lags to make up their losses from the competitor's initial action[14]. Table 4 shows that the dominant type of interaction then shifts from a R&D-race to a hierarchy, while the non-response rate slightly increases. For example, in 51% of all interactions one of the two interacting companies still responds to an action of the competitor after 2 years, while the other has already pulled out.

From the result on R&D-interactions we may finally assert that the drop in R&D outlays could not result from a better use of knowledge spillovers. In the normal case of R&D interactions firms may take advantage of knowledge spillovers if they would adapt their R&D as a strategic substitute. If, for example, some company would expand its R&D activities (and thus R&D-outlays), the competitors may benefit from this additional research outcomes and would therefore reduce their own R&D expenses. In the last decade however, *all* oil companies reduced their research intensities. In that particular case the companies have had minor opportunities to benefit from knowledge spillovers and thus could not respond with strategic substitutes[15, 16]. From the unlagged response matrix (see appendix 2) we can also state that a research impulse of either Exxon or the Francophone companies Elf, Total and particularly Petrofina, provoke less reactions from other oil companies[17].

Table 4 also reveals that there are less significant investment interactions in fixed assets than in R&D. Further, the interactions on investment in fixed assets go more often in one direction. Exxon, in particular, does not respond to any investment impulse of other oil companies. Similar to the simultaneous R&D interactions, the current simultaneous interactions between two oil companies reverse to a sequential (or unilateral) response on competitors' lagged investments.

Most current interactions are (again) based on strategic complements, indicating that most responding oil companies seem to intensify the investment race as well. However,

[14] Notice that the duration of the (long term) R&D-projects has only a weak effect on the period in which companies react on competitors' R&D-changes and decide to start/adapt their own projects.

[15] If the research of some company would revive and the other oil companies would still reply with a strategic complement instead of a strategic substitute, then we may conclude that the oil companies refrain from knowledge spillovers and only intensify the R&D race.

[16] Actually, the two year lagged response matrix shows that only Petrofina responds in opposite direction to changes in competitors' research outlays, but this assertion may be due to the limited availability of data.

[17] On the other hand, Petrofina (and to a lower extent Elf Acquitaine) takes almost no account of the current changes in research outlays by the other companies, but this assertion may be due to the limited estimation period.

the response matrices to the competitors' lagged investments (see tables in appendix 2) reveal that the interactions, particularly with smaller companies, involve strategic substitutes. So after their instantaneous and similar reaction in the first year, the oil companies seem to further accommodate competitors' investments.

Since the response matrices on competitors' investments are sparsely filled we may determine a sequence of leadership in investment interactions. However, our computations showed that the leader/ follower pattern among oil companies is not consistent over time. Therefore we cannot draw any relevant conclusion on the leader/follower pattern in investment interactions.

Concluding this section we discovered that the investment expenditures of oil companies depend significantly on their own financial structure and only to a lesser extent on competitors' current investments. Their R&D-outlays, however, depend hardly on the financial structure but more on strategic complementary interactions. These outcomes are similar to the results in the comparable research in Minne (1997) on the investment interactions in the electronic and chemical industry, and thus seem rather robust.

3. Few research opportunities initiate R&D drop

3.1 Common expectations

Section 2 showed that oil companies base their investment decision in R&D or in fixed assets on different conditions. However, the signalled R&D races may not only refer to purely strategic and competitive behaviour, but also point to common external factors, which may have triggered a R&D-race.

The common external factors are possibly related to the low expected profit to risk ratio of R&D-investments[18]. This section investigates two reasons for this low ratio.

Section 3.2 raises the maturity of oil products as a reason for few new technical opportunities. Then, low expected profits of R&D-investments lead to a reduction of R&D expenditures. This section shows with patent-data that this decline is real, because the productivity in the laboratories did hardly rise to offset the fall of research.

Section 3.3 focusses on the second reason: oil companies may regard research as too risky if aimed at specific new energy sources, which have not taken shape yet[19]. The companies therefore spend their R&D-budget hardly on this kind of research, and wait for each other until the new dominant technology has emerged. They may only bet on promising new energy technologies by subsidizing research projects of universities. This section illustrates this thesis as the oil companies hardly apply for patents in the field of renewable energy sources.

Both arguments lead to the conclusion that oil companies refrain from a leading edge- or pioneering R&D strategy but follow their competitors' sparing and conservative R&D strategy. The box further elaborates on this issue. Technological leadership in the relatively mature industry has become less urgent (see Bleakley et al. (1997)), while the exploration of new technologies or segments may be too risky. Harsh competition then forces oil companies to follow their competitors in reducing research-budgets and keep their total costs as low as possible.

[18] The common expectations argument has been suggested by Richard Nahuis from a theoretical point of view and it became real in our discussions with some oil companies

[19] The box analysing the impact of financial constraints indicated that the high risks involved with new research can partly explain the weak impact of financial constraints on limited research.

Process innovation and -imitation of firms with diverging technologies

In order to strengthen their competitive position, firms can improve their technology by enlarging their knowledge through several types of research (see e.g. Jovanovic and MacDonald (1994a) and (1994b), and Jovanovic and Nyarko (1995)). More particularly, they can conduct applied research and improve their current technology, imitate better technologies of other firms or invent completely new technologies. The choice depends on the balance of early (sunk) investment in existing technologies and the expected returns on adopting new, perhaps risky technologies.

First, (conservative) firms may conduct only applied research in order to optimize their current technology and to learn about the best practice or production method (organization of the work space, type of labour hired and task-assignment, etc.). The expected profits of upgrading to a better technology cannot outweigh the existing profits and an additional gain by conducting applied research. The sunk (capital) investment related to the existing technology will be foregone, while upgrading involves too much risk. However, the gain in conducting applied research will diminish as the firm's experience increases and production converges to the best practice.

At the other extreme, pioneering firms may continuously invent new technologies on the basis of their knowledge on previous technologies. In this way they will show upward jumps in productivity levels or downward jumps in marginal cost. Whereas these firms do not invest in applied research or learning, they will never attain the best practice for each specific technology. The incremental (risky) benefit of research in a potentially better technology may thus be higher than sticking with an inefficient practice of the current technology. Nevertheless, the pioneering firms can continuously decrease their marginal cost and thus may eventually attain a large market share, certainly compared to those firms that have not conducted any research.

The third option is to benefit from knowledge spill overs and imitate high-grade technologies of other firms, thus taking a relative low risk while conducting (low) imitative research. In an awakening segment there are initially few firms to imitate. But when time passes and the segment matures there will be more high-grade technologies and thus more opportunities for imitation . Then the return on imitative effort will rise and overall industry imitative research, particularly by low-tech firms, will replace the inventing research for developing new technologies. Although the initial market share of the imitating firms may be relatively low, they will grow at a faster rate than the innovative and pioneering firms i.e. until they have fully implemented the leading-edge technology and captured a similar market share as the pioneer.

3.2 Real drop in invention

The data on patent applications confirm that higher R&D productivity does not offset the fall in R&D investments. Hence, a decline in research budgets without further compensating R&D productivity growth points to diminishing research outcomes and thus eventually to a slow down of technological development.

The company related productivity in research can be measured as the number of patents (as research output) per mln US$ of R&D-expenditures (as research input). Higher research productivity may have several causes. First, the research laboratories may have become more cost efficient so that more patents can be attained with a million dollars of research costs. Second, since originality is a prerequisite for acquiring a patent, an increase in the number of patent applications may point to improved inventiveness and better development of new and original ideas. Third, companies may follow different policies regarding patent applications[20]. The latter cause, however, is unlikely in the oil industry because the companies resemble each other and make similar products (see section 4). In contrast to high productivity, a low patent to R&D ratio indicates that the laboratories are inefficient or that R&D is mainly aimed at knowledge absorption, so that the research output cannot be patented.

Table 5 presents the various levels in research productivity[21]. The patent/R&D ratio relates the patents of year *t* to the R&D expenditures during the year *t-3*. In fact, the patent data refer to publications of patent applications which are made public18 months after the application filing date. Further we assume that the average duration for a research project is about 1 year. We actually do not know the real average duration[22] of a research project, but calculations of research productivity with longer duration periods point out that varying the assumption on research duration does not severely harm the

[20] They may also, for example for strategic reasons, choose to keep the research outcomes as a company-secret.

[21] Appendix 1 elaborates on the definitions of the patent data, appendix 3 provides a complete version of table 5.

[22] In fact, the duration may vary widely across different research projects.

Table 5 *Productivity of research*

	Patent/ R&D			Percentage change	
	1987- 1988	1992-1993	1997-1998	1987-1998	1992-1998
				annual average	
Oil engineers	0.15	0.45	0.37	9.1	-4.1
Schlumberger	0.11	0.36	0.22	7.0	-9.3
Halliburton	0.38	0.77	0.93	9.4	4.0
Oil companies	0.19	0.26	0.24	2.5	-1.1
Exxon	0.14	0.26	0.38	10.9	8.4
Mobil	0.31	0.55	0.28	-0.9	-12.5
Shell	0.29	0.30	0.21	-3.4	-7.1
BP	0.10	0.10	0.29	11.7	24.0
Amoco	0.17	0.15	0.13	-2.4	-2.1
Texaco	0.14	0.52	0.10	-3.6	-28.6
Elf	0.16	0.05	0.02	-20.1	-20.5
Chevron	0.08	0.11	0.26	12.3	18.1
Total	0.35	0.08	0.08	-13.6	1.0
Phillips	0.32	0.66	0.42	2.8	-8.4

[a] The average ratios exclude Elf because of inexplicably high R&D expenditures.

Note: The deflation of the nominal R&D-expenditures is carried out with the "*US* Deflator for GDP at Market Prices" (source: OECD Economic Outlook) and converted to US $ on the basis of yearly averages of exchange rates (source: OECD, STAN'96, completed with data from CPB, CEP'99). Patent data lack for Petrofina.

figures on research productivity[23]. In fact, the number of patents (or better patent applications or publications) fluctuate more wildly than the research expenditures.

The table shows that, in general, large oil companies have a higher and more steady patent/R&D ratio than the smaller oil companies, which we interpret as higher efficiency or more originality in research. More particularly, Exxon Mobil, Shell and BP Amoco reach (on average) higher research productivity levels than the smaller ones Texaco, Elf and Total. However, the two smallest companies Halliburton and Phillips Petroleum take the lead and have the highest productivity levels across the industry.

More important, in the last decade there was an industry-wide R&D productivity growth of 2,5% per year, albeit that in the last five years productivity has declined with an annual average of about 1%. Exxon, BP, Chevron and Halliburton could maintain their productivity growth over the entire period. Texaco, Mobil and the smaller companies Schlumberger and Phillips Petroleum had only an occasional productivity gain in 1992-1993. Shell and particularly the French companies Elf and Total showed a severe decline in research productivity. Nevertheless, despite the diverging research productivity performances of individual companies we can still assert that the overall cost efficiency or research originality has hardly improved.

However, research productivity may improve if the oil companies and engineers could benefit from increased cooperation. But there are only few R&D-alliances such as research joint ventures or other forms of cooperation. The reason is probably that the companies need much secrecy of their research efforts in order to maintain their firm-specific production processes, as we will see in section 4.

3.3 Little research in renewable sources

Besides the strong overlap in research, the oil companies also have in common that they conduct little research in new and environmental friendly energy sources. Because renewable energy sources compete with organic energy sources, oil companies could have an incentive to thwart this kind of research. But if the potentials of renewable

[23] As a means of sensitivity analysis we also calculated the research productivity assuming that the average research duration varied between one and five years. We could not calculate all the various productivity levels for each company because of missing data on research expenditures (and thus not an accurate time pattern of the industry average productivity level). But those productivity levels of individual companies which could be calculated show that a change in duration does not severely affect research productivity.

energy are high, oil companies may consider the exploitation of this related segment as a challenge rather than a threat.

Still, table 6 shows that the oil companies almost never apply for patents in the fields of nuclear energy or renewable energy, such as wind or solar energy. Further, few patents are applied for in the field of micro-organisms (IPC class C12), but it is not clear whether these patents are related to bio-mass-production. The lack of patent applications thus points to a negligible research on new energy sources. In this respect we can argue that the research on this field could not have contributed to the decline in research intensity.

Table 6 Pattern of inventiveness in renewable sources

Description	IPC-class	European patents		
		'87-'88	'92-'93	'97-'98
		in number		
nuclear physics and engineering	G21	0	1	0
solar energy				
drying solid material by solar radiation	F26B	0	0	0
solar heat collectors and use of solar heat, electric boards	F24J, H02B	1	0	0
use of solar energy	F03G	0	0	0
wind energy				
wind motors and wind mills	F03D	1	0	0
water energy				
water power plants	E02B, F03B	0	1	1

A few oil companies have nevertheless attempted to accomplish some progress this field of science. Shell Solar Energy in the Netherlands, for example, conducts some research on solar energy to "search for the button", but not with great success viz. the absence of patents in this field. Nevertheless, Shell launched in 1997 its "Shell International Renewables"-division, which will focus on solar power and biomass (www.shell.com,24/6/1999). Finally, BP Amoco has recently started to explore solar energy as well (see Annual Review 1998, p.23).

4. Strong R&D-interactions intensify R&D drop

The declining research outlays can thus be explained by common expectations aggravated by an industry wide R&D-race. The regression equations in section 2 cannot discriminate between the impact of both determinants, but probably, both determinants are relevant. A R&D-race is likely because, according to the life cycle theory, companies in a mature and homogenous market mainly compete on production costs (see e.g. Creusen (1997)). In order to survive the intensifying competition, the companies may focus their R&D on company-specific production processes and strongly protect their process innovations. However, the persistent overlap in research and severe protection of the few research outcomes would imply few knowledge spillovers and potential duplication. In this section we use again patent data to determine the main directions of research in the oil industry, and find out if this argument is also valid for the oil industry.

Next to the level of R&D-expenditures and number of patent applications, inventiveness can also be characterized by the specialization in research. More particularly, to which extent do the companies supplement or duplicate each other's research? This question is important because of two reasons. First, from a welfare point of view, duplication of research entails a waste in R&D expenditures and is therefore less desirable than supplementary research. Second, companies with much overlapping research are probably fierce competitors, because they develop products and production processes which are close substitutes. Instead, companies with supplementary research will launch complementary products and services in order to set higher mark-ups. Table7 presents the patterns of research specialization of Schlumberger, Halliburton and the group of oil-companies in relation to the value chain of the oil industry. The measure of specialization is the distribution of the patent-shares in the fields of science of the oil industry in 1997-1998.

The table reveals that, generally, the oil engineers specialize in product development for the upstream part of the oil industry. Mutually, they develop distinct technologies which are supplementary to each other. Schlumberger specializes in the exploration for crude oil and natural gas. It focuses on geo-mechanics, large scale seismic data acquisition, and 3-dimensional visualisation[24]. Halliburton, a specialist in drilling technology, takes the next stage in the value chain, i.e. oil production. This enterprise has much know how

[24] Schlumberger is even such a software specialist that it is able to invent smart cards!

on zonal isolation, sand control and cementing[25]. Table 7 also reveals that the oil companies follow the engineers in the value chain. Compared with the engineers, they specialize in the development of downstream technologies, viz. the fields of refining, petrochemicals and specialities.

Table 7 Pattern of inventiveness in 1997-1998 [a]

European Patents	Drilling service		Oil companies
	Schlumberger	Halliburton	group
	%-share		
Exploration	65	4	5
Oil production	34	93	11
Refining	0	1	30
Petrochemicals	0	1	45
Specialities & life sciences	1	1	9
	100	100	100

[a] See appendix 4 for further explanation

Marketing

Marketing of the petrol-, LPG- and lubricant-brands is another main downstream activity of the oil companies. Inventions in this field cannot be patented. Therefore, table 7 does not contain a row "Marketing". Marketing expenditures, however, promote the brand and boosts the value of company names to high levels. For instance, the branding consultancy group Interbrand estimates the value of the brands BP and Shell at US$ 3 bn and US$ 2.7 bn respectively (Financial Times, June 22, 1999).

Despite the broad range of research fields the research of oil companies is only unique in oil refining. In fact, other companies conduct similar research on the research fields of oil companies: chemical enterprises carry out the main research on petrochemicals and specialties, while oil engineers conduct research on exploration and oil production.

[25] See www.halliburton.com, section research.

Notwithstanding the uniqueness of the research in refining, oil companies spend only about a quarter of their innovative activities on this field (indicated by a 29,6 % share in total number of patent applications).

Still, the oil companies investigate only a few particular issues inside the broad range of research fields. A more detailed listing of research fields (see appendix 4) shows that oil companies only apply for patents in a limited number of IPC-classes, albeit that these IPC-classes are categorized under various main sections.

As a result, the research fields of oil companies –contrary to the high specialization of the engineers– strongly overlap. This assertion is empirically underpinned by two main observations from table 8, which presents the three fields with the highest patent-shares of each company in 1997-1998. First, the table reveals that the oil companies share the main fields of science. It shows that all companies (except Total Oil) concentrate their research on acyclic or carbocyclic compounds (IPC-class C07C). These are bulk petrochemicals (such as olefines and aromatics) and intermediates for downstream stages (like glycols and phenols). In addition, the research is also often targeted at polymers (IPC-class C08), including polypropylene and poly-ethylene (IPC-class C08F). Second, research is generally concentrated in these main fields only. This ensues from the last column in the table, which indicates that the total shares of the three main research fields in the total number of patents are high. The extended version of Table 8 in appendix 4 reveals that the top-3 patent classes of1997-1998 were also very important in 1987-1988. Consequently, the strong overlap has been persistent over time.

The strong overlap in research among the oil companies points to a strong homogeneity of oil products, and thus to strong mutual competition. This conclusion is stressed, because large specialized chemical companies also carry out research in similar fields of petrochemicals. The latter enterprises are therefore competitors of the oil companies as well. Oil companies have therefore focussed their research on improving their own production processes in order to get a competitive advantage, and thus keep these processes secret for competitors.

So there are few spillovers between oil companies and lots of duplication in research. Actually, the patented innovations in the research fields mentioned above are probably modest because they are often based on common basic research, and involve only slight extensions to the vast stock of existing knowledge. Due to lack of coordination oil companies may thus independently conduct similar research with equivalent outcomes. Other, more important and more pioneering innovations might exist as well, but must then be secret and thus become vulnerable to duplication.

The potential duplication in research is wasteful from a social point of view, because knowledge spillovers are insufficiently exploited. The companies, however, do not consider the overlapping research as wasteful because they derive their competitive advantage mainly from their unique production processes.

Strong emphasis on secret process innovation induces complementary R&D with limited spillovers, which is consistent with the high rate of instantaneous R&D races observed in section 2.3. Additionally, due to lacking information on competitors' research, oil companies are forced to focus on the only observable feature of competitors' research, i.e. their research outlays.

Table 8 *Little specialization between oil companies (1997-1998)*

European Patents	Rank main field of science			Share top 3
	1	2	3	%
Exxon	lubricants (C10M)	polymers (C08F)	carb. compounds (C07C)[a]	47
Mobil	layered products (B32B)	carb. compounds (C07C)[a]	cracking (C10G)	60
Shell	polymers (C08G)	carb. compounds (C07C)[a]	drilling (E)	30
BP	carb. compounds (C07C)[a]	polymers (C08F)	lubricants (C10M)	41
Amoco	carb. compounds (C07C)[a]	polymers (C08G)	polymers (C08L)	49
Texaco	carb. compounds (C07C)[a]	synthetic gas (C10L)	analysis properties (G01N)	36
Elf	non-met. comp. (C01B)[b]	carb. compounds (C07C)[a]	geo mechanics (G01V)	58
Chevron	lubricants (C10M)	carb. compounds (C07C)[a]	cracking (C10G)	48
Total	cracking (C10G)	catalysis (B01J)	other operations (B*)	59
Phillips P	polymers (C08F)	catalysis (B01J)	carb. compounds (C07C)[a]	71

[a] Carbolic compounds (C07C)

[a] Non-metallic compounds (C01B)

5. Conclusion

In the mid 90's the main oil companies and oil engineers reduced their R&D expenditures. This study investigates why these research expenditures dropped, while the investments in fixed assets remained stable. The study shows that the main determinants for research differ from those for investments in fixed assets. Fixed investments by oil companies and engineers are strongly related to the availability of internal funds and creditworthiness, and less to competitors' behaviour. R&D expenditures, instead, hardly depend on the company's financial strength, but are liable to reinforcing R&D-races between oil the companies, initiated by common expectations among them.

Despite the differences in determinants, the strategic interactions in research and investment in fixed assets have much in common. Most investment-interactions are races. These are complementary interactions where companies respond with similar investment decisions to the initiator's strategic impulse. Elimination of competitors due to lax reactions, or retraction of earlier investment initiatives, hardly occur. Furthermore, often one company pulls out after its own first (re)action, while the other company continues in its attempt to undo the competitor's actions.

The decline in R&D is probably initiated by two types of common expectations on research prospects. First, in the current mature market oil companies foresee few profitable research opportunities to improve current products and processing, and therefore reduce their research outlays for developing the current technology. The R&D decline is hardly compensated by higher productivity in research laboratories, and thus results in less research outcomes. Actually, between 1987 and 1992 research productivity –i.e. the number of patents per million dollar research– increased by 6% on average per year, but declined subsequently by about 1% per year. So apparently, most oil companies and engineers could not maintain their initial gain in research efficiency and originality.

Second, the companies may regard research on renewable energy as too risky, because they do not know which technology will eventually win. The few patent applications on renewable energy confirm that oil companies have conducted only moderate research on this field.

The mutual R&D-race among competitors intensifies the declining R&D. Oil companies often engage in R&D- races because they can hardly benefit from knowledge spillovers. They mainly apply for patents on similar fields and thus have hardly specialized their research. They often invest in new equipment for upstream activities, such as exploration and oil-production, but focus their R&D mainly on the downstream stage, like development of new and environmental friendlier fuels and innovations in refining.

Further, the innovations on their unique production process are strongly protected because oil companies mainly compete on efficient processing and cost savings. The companies must therefore follow competitors' research strategy in order to prevent technological deprivation, cost disadvantage and loss of market share. But in the last years all companies reduced their R&D without harming their competitive position, because all competitors share the common expectations on the research prospects and thus similarly reduce their R&D-outlays.

The oil engineers, instead, concentrate their research on separate fields in the upstream stages. By specializing they have more opportunities to differentiate on separate markets.

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Enterprises:

BP Amoco:	www.bpamoco.com
Exxon:	www.exxon.com/exxoncorp/index2.html
Mobil:	www.mobil.com
Shell Group:	www.shell.com/home
Shell Nederland:	www.shell.nl
Schlumberger:	www.schlumberger.com

Patents:

IPC Classification:	http://classifications.wipo.int/eng/main.htm
European Patent Office:	www.european-patent-office.org
Bureau voor Industriële Eigendom:	http://info.minez.nl/bie

Petroleum Organizations:

American Petroleum Institute	www.api.org

Journals:

Petroleum-economist:	www.petroleum-economist.com
Energy Journal:	www.iaee.org/enerjor.htm
Energy Policy (Elsevier):	www.elsevier.com

List of interviewed persons

Ms. J. Saetre, Director European Research Centre, Halliburton
Mr. M. Buijse, Scientist European Research Centre, Halliburton

Ms. C. Alma, Manager Corporate External Relations, Shell Netherlands
Mr. R. Tausk, Manager Technology Development,
Shell International Oil Products/ Shell Global Solutions
Mr. J. Verloop, Manager Technology Strategy,
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Mr. M. Verhagen, Head Energy efficiency Manufacturing,
Ministry of Economic Affairs, DG Energy, Directorate Energy Market
Mr. F. Otte, Policy official Liberalized Markets,
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Appendix 1 Data Sources

This appendix discusses the sources of financial data and the patent data. All financial data are drawn from the Annual Reports of the companies. For most companies data are available from 1975 to 1998, but for few companies data is (partly) missing in the fist ten years. They are stored in a database set-up by the CPB. For a further description of this database, see Minne and Verbruggen (1999). Some important oil companies are absent because these companies, such as Gulf Oil and Q8, do not publish data. The financial data are converted to US$ on the basis of yearly averages of exchange rates (source: OECD, STAN'96, completed with data from CPB, CEP'99). Furthermore, in some tables we deflated the nominal R&D-expenditures with the "*US* Deflator for GDP at Market Prices" (source: OECD Economic Outlook). The table below presents the main figures on total sales, physical investment- and research intensity, the number of patent applications, each in 1997 and 1998, and figures on the average profitability and creditworthiness.

Table A.1.1 Key figures of the oil industry

	Total sales		Investment intensity[a]		Research intensity[b]		Patent[c]	P/S [d, e]	D/TA [d, f]
	1997	1998	1997	1998	1997	1998	1997-1998		
	in mln US$		in %		in %		in number	in %	
Drilling services									
Schlumberger	10648	11815	14.05	15.97	4.56	4.81	164	9.4	46.8
Halliburton	8819	NA	6.54	NA	1.87	NA	183	2.9	51.8
Oil-producers									
Exxon	137242	117772	5.39	7.06	0.39	0.47	364	5.4	55.0
Mobil Oil	65906	53531	6.36	10.93	0.36	0.38	131	3.3	57.5
Shell	128026	93507	9.55	13.72	0.52	0.85	263	5.2	48.9
BP	71129	] 68304	8.06	] 10.69	0.32	] 0.60	97	4.2	62.9
Amoco	36287		9.20		0.42		51	6.7	50.4
Texaco	46667	31707	7.77	9.78	0.32	0.44	28	3.3	59.9
Elf	43574	35856	NA	NA	2.48	3.10	31	1.7	64.9
Chevron	41950	30557	9.29	12.70	0.43	0.61	84	5.1	55.0
Total	32742	27053	8.50	10.62	0.67	0.88	29	3.0	59.5
Petrofina	20352	NA	6.00	NA	0.44	NA	NA	1.8	64.9
Phillips	15424	11845	13.25	17.32	0.36	0.52	48	4.8	70.4

[a] the ratio of investment in fixed assets to sales, nominal data
[b] the ratio of expenditures on research and development to sales, nominal data
[c] For description of patent data see below
[d] average of last five years for which data is available
[e] profitability indicated by the profit/total sales ratio
[f] creditworthiness indicated by the debt to assets ratio

The patent data are collected from the PION (Patent Information ON line) data-system of the Dutch patent office (Bureau voor Industriële Eigendom, BIE). The patent data refer to publications of European patent applications. Actually there are two types of publications:

- A publications:
  these publications are publicly available 18 months after the first filing date at either the European Patent Office (EPO) or a (related) national patent office[26].
- B publications:
  these publications appear at the date when the patent is actually granted (mostly between 2 and 5 years after the first filing date

Our data base contains the frequency of A-publications of patent applications by the oil companies and engineers in 1987/1988, 1992/1993 and 19987/1988. From these data we can easily derive the frequency of patent applications according to their filing date. Actually,

- a publication date between 1-1-1987 and 31-12-1988 refers to
  a filing date between 1-7-1985 and 1-7-1986
- a publication date between 1-1-1992 and 31-12-1993 refers to
  a filing date between 1-7-1990 and 1-7-1991
- a publication date between 1-1-1997 and 31-12-1998 refers to
  a filing date between 1-7-1995and 1-7-1996

Finally, for external use all data bases are on request available at the CPB. The financial data bases for each individual company are located in:

h:\a_ti\ondernemingsdatabase\energy\oil,

and the patent database with patent applications is located in:

h:\a_ti\oil\cpb_report\eur_patent_original.wb3.

[26] See www.epo.co.at/epo/obtain.htm#1.

Appendix 2 Response matrices

This appendix presents the response matrices for competitors' unlagged, 1-year and 2-year lagged investments in research and fixed assets. Each response matrix is sorted by the firms' turnover. Consider for example the unlagged R&D-response matrix (table A.2.1). The cells (Exxon, Shell) and (Shell, Exxon) have both a '+S'[27], which indicates that Exxon and Shell would directly and similarly adapt their research outlays in response to the other firm's change in R&D expenditures. So Exxon and Shell would get involved in an investment race after some R&D-impulse. The cell (Amoco, Exxon) contains a '+Q', indicating that Exxon would respond to Amoco's research impulse and adapt its own R&D outlays in a similar way. On the other hand, the cell (Exxon, Amoco) is empty, which signals that Amoco would not (directly) respond to Exxon's own research impulse[28]. The strategic interaction between Exxon and Amoco refers to a hierarchical interaction with Amoco the leader and Exxon the follower. The other response matrices can be interpreted similarly.

[27] In more technical terms, the responses of both Exxon and Shell to the each others' research impulse are simultaneously to the impulse, and can be characterised as a strategic complement.

[28] In more technical terms, Exxon's response to Amoco's research impulse is unilateral or sequential, and can be characterised as a strategic complement.

Table A.2.1: Research responses to competitors' unlagged research outlays

follower leader	Exx	Shl	BP	Mob	Tex	Chv	Elf	Amo	Tot	Phl	Ptf
Exxon (Exx)		+S	+S	+S	+S		-S			+S	
Shell (Shl)	+S		+S	+S	+S	+S		+S	+S	+S	
BP	+S	+S		+S	+S	+S		+S	+S	+S	
Mobil (Mob)	+S	+S	+S		+S	+S		+S	+Q	+S	
Texaco (Tex)	+S	+S	+S	+S		+S		+S	+Q	+S	
Chevron (Chv)		+S	+S	+S	+S		+S	+S	+S	+S	
Elf	-S	+Q	+Q		+Q	+S		+Q	+S		
Amoco (Amo)	+Q	+S	+S	+S	+S	+S			+S	+S	
Total (Tot)	-Q	+S	+S			+S	+S	+S			+S
Phillips (Phl)	+S	+S	+S	+S	+S	+S	-Q	+S			
Petrofina (Ptf)							+Q		+S		

Table A.2.2: Research responses to competitors' 1-year lagged research outlays

follower leader	Exx	Shl	BP	Mob	Tex	Chv	Elf	Amo	Tot	Phl	Ptf
Exxon (Exx)		+Q	+S	+S	+Q	+Q	-S	+Q		+S	
Shell (Shl)			+S	+S	+S	+S		+S	+Q	+S	
BP	+S	+S		+S	+S	+S		+S	+Q	+S	
Mobil (Mob)	+S	+S	+S		+S	+S		+S	+Q		
Texaco (Tex)		+S	+S	+S		+S		+S	+Q		
Chevron (Chv)		+S	+S	+S	+S		+S	+S	+Q		
Elf	-S		+Q		+Q	+S		+Q	+S		
Amoco (Amo)		+S	+S	+S	+S	+S			+Q	+S	
Total (Tot)	-Q						+S				
Phillips (Phl)	+S	+S	+S	+Q	+Q		-Q	+S	+Q		
Petrofina (Ptf)											

Table A.2.3: Research responses to competitors' 2-year lagged research outlays

follower leader	Exx	Shl	BP	Mob	Tex	Chv	Elf	Amo	Tot	Phl	Ptf
Exxon (Exx)		+Q	+S	+Q	+Q	+Q	-S	+Q		+S	
Shell (Shl)			+S		+Q			+S	+Q		
BP	+S	+S		+Q	+S	+S		+S	+Q		
Mobil (Mob)					+Q						
Texaco (Tex)			+S			+S		+S	+Q		
Chevron (Chv)		+Q	+S		+S			+S	+Q		
Elf				+Q	+Q		+Q	+S			
Amoco (Amo)		+S	+S		+S	+S			+Q		
Total (Tot)	-Q						+S			-S	
Phillips (Phl)	+S		+Q		+Q		-Q	+Q	+S		
Petrofina (Ptf)			-Q	-Q	-Q	-Q		-Q		-Q	

Table A.2.4: Investment responses to competitors' unlagged investments in fixed assets

follower leader	Exx	Shl	BP	Mob	Tex	Chv	Elf	Amo	Tot	Phl	Ptf
Exxon (Exx)								+Q			
Shell (Shl)				+S		+S				+S	
BP				+Q	+S				+S		
Mobil (Mob)		+S			+S					+Q	
Texaco (Tex)		+Q	+S	+S							
Chevron (Chv)		+S			+Q					+S	
Elf									+S	+S	
Amoco (Amo)							+Q				
Total (Tot)			+S				+S	+Q			+S
Phillips (Phl)		+S	-Q			+S	-S				-Q
Petrofina (Ptf)			+Q			-Q	+Q	+Q	+S		

Table A.2.5: Investment responses to competitors' 1-year lagged investments in fixed assets

follower leader	Exx	Shl	BP	Mob	Tex	Chv	Elf	Amo	Tot	Phl	Ptf
Exxon (Exx)										-Q	
Shell (Shl)								-Q			-S
BP		-Q									
Mobil (Mob)					+Q			-Q			
Texaco (Tex)	+Q										
Chevron (Chv)							-Q		-Q		
Elf								-Q			
Amoco (Amo)										-Q	
Total (Tot)											
Phillips (Phl)		+Q	-Q			+Q	-Q				-Q
Petrofina (Ptf)		-S									

Table A.2.6: Investment responses to competitors' 2-year lagged investments in fixed assets

follower leader	Exx	Shl	BP	Mob	Tex	Chv	Elf	Amo	Tot	Phl	Ptf
Exxon (Exx)										-Q	+Q
Shell (Shl)	-Q						-Q				
BP								+Q	+Q		+Q
Mobil (Mob)		+Q			+Q					+Q	
Texaco (Tex)	+Q										
Chevron (Chv)	+Q									-Q	
Elf			-Q								
Amoco (Amo)											
Total (Tot)											
Phillips (Phl)			-Q				-Q		-Q		
Petrofina (Ptf)									+Q		

Appendix 3 Developments of research productivity

This appendix gives the extended version of table 5 in the main text. It particularly denotes the assignment of lagged R&D outlays to the patent data due to the 18-month delay between the filing date and the publication date of a patent application. In fact we assume that the research projects in 1984 and 1985 resulted in a patent publication in 1987 or 1988, ...etc.

Table A.3.1 Productivity of research

	Patents '87-'88	R&D '84-'85	Patents/ R&D	Patents '92-'93	R&D '89-'90	Patents/ R&D	Patents '97-'98	R&D '94-'95	Patents/ R&D
	number	mln US$		number	mln US$		number	mln US$	
Oil engineers	180	1171	0.15	433	952	0.45	347	942	0.37
Schlumberger	110	986	0.11	260	727	0.36	164	746	0.22
Halliburton	70	184	0.38	173	226	0.77	183	196	0.93
Oil companies	1150	6036	0.19	1628	6308	0.26	1095	4479	0.24
Exxon	233	1714	0.14	320	1255	0.26	364	954	0.38
Mobil	165	532	0.31	140	255	0.55	131	464	0.28
Shell	384	1305	0.29	485	1608	0.30	263	1259	0.21
BP	75	787	0.10	112	1139	0.10	97	337	0.29
Amoco	77	451	0.17	89	597	0.15	51	379	0.13
Texaco	60	431	0.14	234	449	0.52	28	290	0.10
Elf	55	339	0.16	64	1187	0.05	31	1811	0.02
Chevron	37	452	0.08	53	465	0.11	84	321	0.26
Total	29	84	0.35	21	275	0.08	29	361	0.08
Phillips	90	280	0.32	174	266	0.66	48	114	0.42

[a] The total number of patents, total R&D expenditures and average ratios exclude Elf because of inexplicably high R&D expenditures.

Note: The deflation of the nominal R&D-expenditures is carried out with the "*US* Deflator for GDP at Market Prices" (source: OECD Economic Outlook) and concerted to US $ on the basis of yearly averages of exchange rates (source: OECD, STAN'96, completed with data from CPB, CEP'99). Patent data lack of Petrofina.

Appendix 4 Developments of specialization in research

The table below –an extended version of table 7 in the main text– contains a detailed listing of research fields related to the oil industry. It reveals that the oil companies investigate only a few particular issues inside a broad range of research fields.

Table A.4.1 Pattern of inventiveness in 1997-1998

European Patents	IPC-class[a]	Drilling service Schlumberger group	Halliburton	Oil companies
		%-share		
Exploration		64.8	3.8	5.1
geo mechanics	G01V	17.3	2.7	2.6
communication and network technology	H	14.2	0.0	0.5
electro magnetics	G01R	8.0	0.0	0.1
computer and data sciences	G06G,K	6.8	0.0	0.8
other physics	G*	9.9	1.1	0.8
fluid mechanics	G01F	8.6	0.0	0.3
Oil production		34.0	93.4	11.1
explosives, burners, coolers	F21-42	0.0	0.5	1.0
drilling technologies	E	25.3	84.2	3.8
flame resistant materials	C04B	0.0	5.5	0.4
engines and pumps	F01-04	0.0	0.0	0.2
pipes, valves	F15-17	2.5	1.1	0.7
synthetic fibres	D	0.6	0.0	0.4
removal material from surfaces, anti corrosion	C23F	0.0	0.0	0.1
analysis chemical of physical properties	G01N	3.1	1.6	1.5
other operations	B*	1.9	0.5	2.6
other inorganic chemistry	C01-06*	0.6	0.0	0.4
Refining		0.0	0.5	29.6
catalysis	B01J	0.0	0.0	6.7
cracking hydrocarbon oils	C10G	0.0	0.0	9.1
lubricants	C10M	0.0	0.0	9.5
synthetic natural gas, LP Gas	C10L	0.0	0.5	4.1
other petroleum	C10*	0.0	0.0	0.2

European Patents	IPC-class[a]	Drilling service Schlumberger group	Halliburton	Oil companies
Petrochemicals		0.0	0.5	45.4
separation	B01D	0.0	0.0	1.4
compounds of non-metallic elements	C01B	0.0	0.0	3.6
acyclic or carbocyclic compounds	C07C	0.0	0.0	13.1
hetero cyclical compounds	C07D	0.0	0.0	0.9
other organic chemicals	C07*	0.0	0.0	0.4
polymers:				
- only carbon to carbon unsaturated bonds	C08F	0.0	0.0	11.7
- more than carbon to carbon unsaturated bonds	C08G	0.0	0.0	4.8
- compositions of macromolecular compounds	C08L	0.0	0.5	5.8
- other polymers	C08*	0.0	0.0	3.7
Specialities & life sciences		1.2	1.6	8.9
adhesives, paints	C09	0.0	1.6	1.9
other (C11-30, excl C12) final chemicals	C11-30*	0.0	0.0	0.9
shaping or plastics	B29B,C	0.0	0.0	1.2
layered products	B32B	0.0	0.0	3.4
micro-organisms	C12	0.0	0.0	0.4
biocides	A01N	0.0	0.0	0.0
medical devices, other	A*	1.2	0.0	1.1
		100.0	100.0	100.0

[*] Denotes: rest of the IPC class

[a] IPC-class: the number in the International Patent Classification

Table A.4.2, which similar to table 8 in the main text but now extended for the periods 1987-1988 and 1992-1993, provides more some insight in the development of specialization in research of oil engineers and oil companies[29]. It shows that the overlap in research activities by oil companies has been persistent over the last decade.

[29] For an explanation of the IPC-classes we refer to the previous table (table A.3.2).

Table A.4.2 Development of specialization in research

	Oil engineers		*Oil companies*									
Rank	Schlum-berger	Halli-burton	Exxon	Mobil	Shell	BP	Amoco	Texaco	Elf	Chevron	Total	Phillips
'87-'88												
1st	E	E	C08F	C10G	C07C	C07C	C08G	C07C	C07C	C07C	C10G	C07C
2nd	G01V	H	C10M	C07C	C08G	C08F	C07C	C08G	B01D	C10M	F21-42	B01J
3rd	G*	G06G,K	C10G	B01J	C07D	C08*	C10M	C10M	H	C10G	G01N	C12
%-share	49.1	88.6	42.2	50.9	38.4	43.2	42.9	48.3	48.1	40.5	51.7	45.6
'92-'93												
1st	E	E	C08F	C10G	C08G	C08F	C12	C07C	E	C10G	G01N	C08F
2nd	G01V	G01V	C07C	C07C	C07C	C07C	C08L	C08G	C01B	G01V	C10G	C08G
3rd	G*	C09	B01J	C08F	C08F	C08G	H	C07D	C12	B01J	E	C08L
%-share	62.6	82.1	35.7	39.7	49.0	53.6	48.3	52.4	44.4	50.9	57.1	49.1
'97-'98												
1st	E	E	C10M	B32B	C08G	C07C	C07C	C07C	C01B	C10M	C10G	C08F
2nd	G01V	C04B	C08F	C10G	E	C08F	C08G	G01N	C07C	C07C	B01J	B01J
3rd	H	G01V	C10G	C07C	C07C	C10M	G01V	C10L	G01V	C10G	B*	C07C
%-share	56.8	92.4	48.1	60.3	30.3	50.5	51.0	35.7	58.1	48.2	58.6	70.8

Abstract

In the last decade the world-wide research expenditures of the major oil companies have dropped. This is remarkable since their investments in fixed assets remained stable. This study reveals that the level of fixed investments particularly depend on their financial strength, while R&D mainly relates to competitors' research and common expectations.

The decline in R&D is initiated by common expectations. In the mature oil industry, companies foresee diminishing research potential within the current technology. This is also confirmed by the declining number of patent applications. The high risks of research on renewable energy may lead to wait and see behaviour instead of new research initiatives. Actually, oil companies have hardly applied for patents on renewable energy.

The R&D decline is intensified by a dwindling R&D-race, which is due to a large overlap in research topics. The companies protect their research results because they largely compete on their unique technologies which embody their research results. The research overlap appears from patents: the oil companies apply for patents in exactly the same patent classes.