Technology Frames:

a fourth organisational capability?

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ABSTRACT

In this article, we introduce the concept of the technology frame, which is the firm's self-image of its technological resources, capabilities and opportunities. It is the conceptualisation by which the firm's top managers not only identify and understand these, but by which they assign them worth within a wider corporate strategy. In our analysis, we consider how the frame can influence – and be influenced by – patterns in the firm's technology inputs, outputs and ultimately its operating performance. Using the top 10 integrated oil companies active in the upstream petroleum industry, we test the frame as a heuristic for interpreting the patterns in R&D expenditure, patenting, publications and operating performance metrics according to predicted effects. The panel-data econometric evidence supports most of the predicted effects, with the exceptions arguably affected by longer-term trends or by interesting divergences between firm views and employee behaviours. We conclude that there is evidence to support our view that technology frames matter because they set the boundaries in which firms plan and act, and they provide us with one means of conceptualising 'routines'.

1 Introduction

Nelson & Winter (1982) challenged orthodoxy by arguing that the skill of business lay not in optimisation, as this implied choice and full cognitive awareness, but in skilful behaviour and the automaticity of this behaviour. As they explain, the selection of options is not random but deeply embedded in the underlying skills that have evolved over the life of the firm. Whilst downplaying these implied limitations to corporate strategy, the business press recognises the variety of corporate styles in evidence and the superiority of a few over the many. In the field of technology and innovation, Gary Hamel (2000) refers to the different "innovation styles" of companies and the evolved corporate "configuration" which uniquely binds the company's core strategy and its strategic resources[1].

Indeed, senior technology staff at companies we have interviewed talk freely of the firm's technology frame, philosophy, innovation culture or R&D model. Far from simply being the latest buzzwords, we argue that this concept of a **technology frame**[2] reflects the established company routines described by Nelson & Winter within a broader corporate interpretative framework of how innovation occurs in their industry or at large, and their place within that process.

Personality and automaticity

Scholars of organisational theory have long indicated the distinctiveness of firms based on their characteristics and behaviours. Nelson & Winter (1982) crystallised these arguments in the concept of skilful behaviour in which the firm develops over time distinctive capabilities in its routines and approach, which are difficult to imitate or transfer. In contrast to the orthodox view that firms maximise choice through deliberation, they emphasise the point that firms behave according to routine as well as to strategy.[3] By considering the effects of the automaticity of skilful behaviour, Nelson and Winter widen the focus for study of corporate strategy and performance.

Leonard (1995) also refers to the mindset of the firm which is embedded in the values and norms of behaviour maintained. As Leonard describes, "Rather, one finds a pattern of thought and behaviour that is observable at all levels and that gives the organization its character" (p. 260). Elsewhere, she refers to this as the company's 'personality'. Penrose (1959, p. 5), in her seminal discussion of 'the theory of the growth of the firm', similarly spoke of firm-specific 'images' that relate closely to notions of interpretative frameworks.

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[1] Hamel (2000), p 78.

[2] We have referred to this concept as the "R&D Model" in Acha and von Tunzelmann (2000). However, both elements of that term often led to a misunderstanding of the concept. We have therefore adopted the term "frame" from Teece (2000).

[3] "We, on the other hand, emphasize the *automaticity* of skillful behavior and the suppression of choice that this involves. In skillful behavior, behavioural options are selected, but they are not deliberately chosen." (Nelson & Winter, 1982, p. 94).

These authors indicate that there is a consciousness comprised of habits and beliefs in the firm that belies an orthodox view that there is an automatic response to signals couched within a rational frame in which the choice to maximise is unfettered. Rather, as Hamel suggests in his concept of innovation styles and Teece in his reference to 'frames', the firm's strategy, capabilities and resources arise and progress within such a framework with which the firm interprets its world and its position within that world. However many studies that appear compatible with this approach either exclude technology as a strategic issue, or at the other extreme focus on it practically to exclusion. We see it instead as part of production activity at large (von Tunzelmann, 1995), though here we focus on it rather more exclusively.

The eye of the beholder

"All the choir of heaven and furniture of earth – in a word, all those bodies which compose the mighty frame of the world – have not any subsistence without a mind."[4]

Frames matter because they set the boundaries in which firms will plan and act. The capabilities and resources that result then affect the frame in a co-evolutionary relationship. The frame in turn helps couch the more specific co-evolution between services (capabilities) and resources, of which Penrose (1959) spoke. Because of this interconnectivity, any study of capabilities and resources must address the frame within which they are embedded, and vice versa.

This argument holds in the case of technology capabilities developed in the firm. The concept of the technology frame both reflects and affects the established company routines described by Nelson & Winter and knowledge bases within a broader corporate interpretative framework of how innovation occurs in their industry, the role of technology in that process, the wider innovation system and the firm's place within that. As such, we argue that the technology frame is a strategic capability. Moreover, just as Chandler demonstrated the strategic importance of organisational capabilities (and we would add, frames) of the triptych of manufacturing, marketing and management, it can be demonstrated that together the technology frame and the embedded technological capabilities and resources are a fourth organisational capability. In rather parallel fashion, we have argued that Penrose did not pay great attention to such issues because she was essentially describing the large firm under fairly stable technological conditions, such as largely held good at the time she was preparing her main studies (von Tunzelmann & Wang, 2001).

Structure of the paper

We set our arguments out in the following way. We begin with a fuller presentation of the concept of technology frames and their relevance to organisational and evolutionary theory and industrial dynamics. We then consider how this concept provides an extension to the Chandlerian framework. The fourth section establishes the relationship between the technology frame and technological capabilities and resources. Using the case of the upstream petroleum industry, we then analyse the role of the technology frame as a strategic capability. Finally, we present a platform for further development of this conceptual study and its generalisability to other industries.

2. The Technology Frame

In the *Wellsprings of Knowledge,* Leonard argues that, in order to manage knowledge assets, firms need not just to identify them but also to understand them in depth.[5] We would add to this assertion that firms also need also to be able to **assign worth** to these assets correctly. This obviously also affects therefore the management strategies for encouraging the growth and development of these assets. The technology frame determines how firms assign worth to knowledge and technology assets with respect to the firm’s past and future development and performance. The frame governs how the firm’s managerial leadership construes the dynamics of its industry and the wider economy, its place and potential within that industry, and the role of technology in determining these issues. On the basis of this conceptualisation of the world – this ‘composition of the mighty frame of the world’ – the firm’s top managers not only identify and understand technological capabilities, but they assign them worth within a wider corporate strategy.

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[4] George Berkeley (1710) A Treatise Concerning the Principles of Human Knowledge, pt I, sect. 6.

[5] Leonard (1995), p. xii.

> *"Like an individual, a corporation has a certain style, a unique way of looking at things that mirrors its past and points to its future by indicating ways in which the company will carry out its strategies in the pursuit of its long-term objectives."* [6]

The technology frame is the firm's self-image of its technological resources, capabilities and opportunities. By 'self-image', we draw on the concept developed by Boulding (1956) and used by Penrose to describe the mindset of the entrepreneur.[7] The concept of 'frame' is best considered as the perspective from or a lens through which the firm considers its commercial past, present and future. The frame comprises the firm's appraisal of the competitive value of technology, its own position vis-à-vis its competitors, and its ability to obtain/contain these resources and capabilities.

Because firms have unique and historically developed resources and capabilities, the technology frame is likely to be also idiosyncratic and evolving. The role of the individual, particularly at the top levels of management, is critical in the shaping of the technology frame and its resulting strategies. However, as Penrose argues, there is a complex interaction between the development of resources, capabilities and managerial function and strategy (here the technology frame). Historical resources and capabilities will have shaped the technology frame, but this does not limit the potential for the frame to change according to new managerial emphasis and the strategy for the use and development of capabilities and resources to alter accordingly. The causality runs in both directions.

The technology frame is not static and fixed, but evolving and able to be influenced. Like our own self-images, the technology frame of the firm is not founded only in reality (the facts and evidence of the marketplace) but also in the perceptions, aspirations and/or pessimism of the management. However, this is not to say that commonalities do not emerge across companies over time, trials and observations. As Eisenhardt and Martin (2000) note with respect to dynamic capabilities, "These commonalities arise because there are more and less effective ways of dealing with the specific organizational, interpersonal, and technical challenges that must be addressed by a given capability."[8] This comment could equally apply to sets of technological

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[6] Atlantic Richfield Corporation, Annual Report, 1982, p. 4.

[7] Penrose (1959), p. 5.

[8] Eisenhardt and Martin (2000), p. 1108.

capabilities and the technology frames that guide their development. Our fieldwork indicated that companies study the technology frames of their competitors and respond to those different perspectives by adopting what seems to work or by taking an opposing strategy.

The concept of the technology frame was first raised in an interview with the General Manager of Strategic Research for Chevron[9], who used it to discuss the distinctive company objectives, organisation and conduct of research and development at a given time. He recognised that the technology frame for Chevron had changed significantly over the past decade, resulting in a shift to more and newer forms of collaborative R&D as well as innovations in the internal organisation of technological capabilities.[10] Furthermore, it was clear to this Chevron manager that there were significant differences in the models pursued by the peer group companies. This view has been echoed in other fieldwork and in the industry literature. In a speech in 1998 by the managing director responsible for global Exploration & Production and Downstream Gas & Power businesses for Royal Dutch/Shell, it was argued that technological development, which Shell recognised to be central to upstream strategic success, includes both utilisation and innovation; however, he emphasised that some competitors emphasise only utilisation of technologies whereas Shell believes that both are vital[11]. Certainly, we anticipate that this difference in the role of technology within the firm's technology frame would shape the objectives and conduct of research and development and the development of technological capabilities.

3. Building on the Chandlerian Framework

As Chandler describes in *Scale and Scope,* the evolution of business enterprise was a response to the demands for massive capital investment and the successful management of increasing complexities arising in operations and strategy that were engendered by the second industrial revolution. Chandler argues that the successful firms were those who first and best harnessed the right organisational capabilities in management,

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[9] Telephone interview with Robert Heming.

[10] Detailed case studies of some of the ten companies are being conducted as part of the wider study of the role of technological capabilities in determining upstream performance, on which the present paper is based.

[11] Watts (1998).

marketing and production to meet the business environment. Whilst this analysis of the two-thirds of the 20th century convincingly explains the evolution of business enterprise during that period, it only hints at future directions for evolution of business organisational structure and capabilities. The lynchpins of complexity, co-ordination and risk (implicit in massive capital investment) certainly altered dramatically during that period from previous centuries of socio-economic development. It could also be argued that the final quarter of the 20th century saw a renewed change in complexity, co-ordination and risk, as new industries and business structures emerged and the market landscape shifted.

Determined by the underlying economies of scale, scope and transaction costs, these firms organised functional activities and the managerial staff to supervise, co-ordinate and plan strategically for them, Chandler explains. Within this structure, Chandler identified the development of a smaller, internal research and development department to serve the needs of production, once production and marketing organisations were well in place.[12]. However, his discussion of the developing role of the R&D department does not extend much beyond this. R&D is described as a support activity to production that is strategically important at times, but there is no clear indication of if and how R&D would become a fourth string to the corporate strategic bow.

Building on Chandler's framework, we believe that as the R&D function has grown and developed in risk and complexity, the corresponding managerial function within the enterprise and its strategic importance have evolved to become an organisational capability like those described by Chandler, but separate. Like Nelson & Winter[13] and Chandler, we refer here primarily to firms that are "large and complex", although complexity is most likely the true distinguishing feature. A cursory review of annual reports and the business press reveal the details of senior executives with titles such as Chief Technology Officer and Senior Vice President, Technology, as well as descriptions of the firm's technology strategy and portfolio. In these details, there is a de facto description of this evolved organisational capability, which we have termed the technology frame.

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[12] Chandler (1990), p. 32

In other work we have shown how this behaviour can be linked to meso-level and macro-level indicators of the growing importance of technology to firms both large and small, in the period since Chandler and Penrose were conducting most of their research (von Tunzelmann & Wang, 2001). The proliferation of interest in 'knowledge management' in organizations in recent years, despite the buzzword connotations of the term, to us also indicates real phenomena taking place. Our macro data show how there has been a fall in tangible capital formation in OECD countries offset by a rise in intangible capital formation since the early 1970s.

4. Capabilities, routines and frames

However, the technology frame comprises much more than senior executive representation and influence on high-level corporate strategy, or even a larger commitment to technological resources. As in the case of production, marketing and management, the resources (staff and skills) and capabilities (dynamic processes) for R&D are part of the corporate body of the firm. The processes, the staff and the skills related to technology, better described as the routines – the "organisational repetitive pattern of activity" first described by Nelson and Winter[14] – both embody and shape the firm's technology frame. In this sense, the technology frame provides the conceptual bridge between the Chandlerian framework and the well-known theoretical contributions of Nelson and Winter on the evolutionary nature and dynamics of routines and innovation in firms[15].

The work by Nelson and Winter has been taken forward by many authors, including – and corresponding to the concept of the technology frame – the contributions by Leonard (1995) and Teece, Pisano and Shuen (1997). Teece et al. (1997) argue that the strategic dimensions of the firm are in its managerial and organisational processes (capabilities), its present position (resources) and the paths available to it, where paths are the strategic alternatives available and the attractiveness of future opportunities. In the realm of technological change, the technology frame embodies these strategic

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[13] Nelson & Winter (1982), p. 97

[14] ibid.

[15] Nelson noted that, with hindsight, a greater familiarity with Chandlerian arguments would have greatly benefited the development of An Evolutionary Theory of Economic Change (1982). See Nelson (1991), p. 67.

dimensions and their comprising routines, which have evolved within the firm over time and which condition the paths to future development. This is also indicated by Nelson (1991), who defines the firm by three key features - its strategy, its structure and its core capabilities. "Strategy and structure call forth and mold organizational capabilities, but what an organization can do well has something of a life of its own."[16]

Leonard (1995) defines strategic technological capabilities as "… organic systems of interdependent dimensions that are created over time and can be sustained over time. They are not easily imitated, transferred, or redirected on short notice. And as bodies of knowledge, core capabilities cannot be managed in the same way as are the tangible assets of the firm."[17] This implies that the organisational capability for managing and applying technology and knowledge assets comprises a different set of skills and not simply an extension of the skills and routines established under marketing, production and management. Both Leonard (1995) and Penrose (1959) indicate that the management of these capabilities requires effort at all levels to select correct knowledge sources, to understand how knowledge is developed, acquired and applied, and actively to change these flows according to strategy.

Leonard (1995) identifies four interdependent dimensions of corporate strategic capabilities: employee knowledge and skill, physical technical systems, managerial systems and values and norms.[18] Whilst other authors, including Leonard, have explored the effects of routines, skills and infrastructure at length, she draws much needed attention to the values and norms of the firm and their role in determining corporate competitiveness. "Skills and knowledge, both embodied in people and embedded in physical systems as well as managerial systems all exhibit a particular character depending on what is valued in the company." (Leonard, p. 24)

The technology frame incorporates the 'little *v*' values described by Leonard as those norms of behaviour concerned with the choice of technology, and this reflects the interdependency of the frame with the technological capabilities of the firm. For example, an exploration company that gained prominence through offshore activity

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[16] Nelson (1991), p. 68.
[17] Leonard (1995), p xi.
[18] Leonard (1995), p. 23

develops preferences for the suite of technologies developed and applied extensively through that experience. She describes the manner by which these preferences, embedded in many routines company-wide, serve to reinforce the core technological capabilities. But there is another factor by which established practice (the little *v*s) is challenged (or not) for its assigned worth in present and anticipated market conditions. This factor is the strategic element of the technology frame, and it is this that provides the link from where the firm has been (reflected in its existing resources, capabilities and personality) to where the firm is going.

5. The role of the technology frame

Evidence of the frame

Ultimately, the relationship between technological strength (comprised of capabilities and resources) and operational performance is at the heart of corporate strategy, together with the corresponding relationships between the three Chandlerian organisational capabilities: management, marketing and production. As Helfat (2000) summarised recently, a better understanding of the reasons for firm success and failure will allow a better understanding of the relationship between capabilities and competitive advantage.[19] We argue that the technology frame provides a heuristic by which to explore this relationship more effectively. This view is in accordance with the arguments of Eisenhardt and Martin (2000) on the empirical assessment of dynamic capabilities and routines.[20]

Our earlier study[21] addressed the role of the technology frame as a heuristic to explore the relationship between capabilities and competitive advantage with respect to the upstream petroleum industry, and we concluded there that measuring technological strength through traditional innovation metrics was unhelpful and potentially misleading. Instead of appraising the innovation metrics and drawing conclusions about the company’s technological strength, our analysis suggested that a more dedicated

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[19] Helfat (2000), p. 955.

[20] “In contrast, by defining dynamic capabilities in terms of their functional relationship to resource manipulation, their value is defined independent of firm performance.” Eisenhardt and Martin (2000), p. 1108.

[21] Acha and von Tunzelmann, 2000.

analysis of the technology frame – and thus the technology strategy – of the firm provided the means to interpret the resulting innovation metrics accordingly. In some cases, analysts should be aware that these innovation metrics are not capable of effectively measuring technological strength. In all cases, analysts should also recall that technological strength is comprised of both resources and capabilities. Input measures, like R&D funding, and output measures, like patents and publications, are really only imperfectly capturing the firm's available resources. These orthodox metrics have to be placed in the context of how the firm appraises the competitive value of technology, how it stands relative its competitors, and how far it is able to obtain/contain these resources; in other words, its technology frame.

Frame effects

Because the technology frame is interdependent with resources and capabilities, we expect the frame to influence – and be influenced by – patterns in the firm's technology inputs, outputs and ultimately its operating performance. As a matter of direct correlation, we would expect the effects on these to be declining in strength in the order given because of the effects of other factors, such as the interests of individuals and changes in the market environment. For this study, we consider the effects on technology inputs and outputs and operating performance separately.

Reflecting the organisation itself, the technology frame has some elements that are firm-specific. However, it is possible to identify some common elements that shape it over time. For the upstream petroleum sector, three elements of the technology frame are likely to affect the correlation between the innovation metrics themselves as well as the correlation between the underlying technological capabilities and the operational performance. These elements are the **upstream strategy**, the **nature of the role of technology**, and **the role of formal appropriation of technology**.

The **upstream strategy** defines the nature of exploration and production of hydrocarbons to be undertaken by the company. We can summarise the strategy as either Growth, or Efficiency with targeted growth. A Growth strategy indicates a relatively extensive exploration programme with a primary objective of securing more reserves. This is a longer view strategy that is more tolerant of high-risk and high-cost initiatives in the effort to identify new reserves. An Efficiency strategy reflects a more cautious longer-term approach taken under conditions of persistently low oil prices and natural gas. The strategy is targeted towards efficient (effective and low-cost) exploration and production methods on generally ‘high quality and low risk’ reservoirs[22]. It is essential to pursue some programme of growth (exploration of new reservoirs) in order to counteract the depletion of existing reserves. Therefore, in practice, efficiency strategies are combined with a programme of targeted growth. This programme has typically been dedicated principally (but not exclusively) to the capture of very large (‘elephant’) fields. It is important to emphasise that these strategies are cyclical in nature, reflecting the market conditions and broader socio-economic trends. Therefore, it is likely that there will be some concordance between firms with respect to this element of the technology frame.

We summarise the predicted effects of an efficiency or growth strategy on technological inputs, outputs and performance measures in Table 1.[23] Because the growth strategy involves an acceptance of relatively high levels of risk and investment, we include a gearing ratio (long-term debt as a share of long-term debt plus equity) as a trend indicator of strategy. We also include geological and geophysical costs as a technological input measure because considerable innovation in the understanding and characterisation of a hydrocarbon reservoir[24] derives from this investment. Because these are not completely distinct strategies (given that an efficiency regime includes some strategy for growth), it is anticipated that the differences are likely to lie in the changes in the rates of growth and deceleration.

R&D expenditure and the R&D intensity measure are expected to change in a similar direction, growing or holding steady in a growth period and declining in an efficiency period. In the short term, R&D as a share of Capital and Exploratory Expenditures (Capex) may move in an opposite direction, as changes in other field development

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[22] This practice is known as ‘prospect highgrading’.

[23] In our previous article (Acha and von Tunzelmann, 2000), we considered a wider selection of performance measures. However, the analysis indicated that some variables were overwhelmingly determined by variations in the oil price and that others (ratios) were affected by ambiguity in the changes of the denominator versus the nominator. Therefore, we have used here only the variables that held some explanatory strength.

[24] Fieldwork has confirmed that the understanding and improved characterisation of a hydrocarbon reservoir is a strategically core capability for the oil companies.

expenditures tend to occur more quickly than adjustments in R&D expenditure. The predictions for technological outputs are far more ambivalent, as the correlation between a company's upstream strategy and its choice to publish and patent is expected to be less direct.

In both efficiency and growth regimes, companies are always seeking to enhance performance. Because the nature of the upstream petroleum industry at the end of the 20th Century was such that the majors needed to find reservoirs with substantial reserves to meet economic viability in a low price environment and yet secure their position in the long term, the drivers for performance were cost-efficiency and the securing of major new finds. Therefore, these objectives remain the same under either regime; what changes are the levels of tolerance to risk (higher under a growth regime and lower under an efficiency regime). Therefore, bearing in mind that the companies are bound to some extent in the short term by the nature of their assets, the performance measures can be expected to reflect their risk preferences as well as their success in achieving their goals of reducing costs and securing new reserves through the application of technology as well as other important non-technological factors (such as negotiation capabilities, finance and project management).

Table 1: Predicted Outcomes – Upstream Strategy

	GROWTH	EFFICIENCY
RISK		
Gearing – trends	Increases	Decreases
TECHNOLOGICAL INPUTS		
R&D	Growth in expenditure accelerates or keeps steady	Growth in expenditure declines (R&D expenditure held steady or declines)
R&D/Capex	R&D may temporarily decline as a share (as Capex increases for growth), then resumes trend or increases	R&D share may temporarily rise (as Capex reduced), but then decline
TECHNOLOGICAL OUTPUTS		
Patents - Number	Indeterminate; if R&D increases, may increase emphasis on patenting; expansion provides greater opportunities for novelty, but greater exploration focus may limit potential to patent	Indeterminate; as production focus increases relative (G&G down), possibly increases; as R&D effort reduced, may be less emphasis on patenting
Publications - Number	Possibly increases for companies seeking to position themselves; likely to be independent of growth	Likely to be independent of efficiency focus, as publications not costly to company (but to individual!)
PERFORMANCE MEASURES*		
Exploratory Well Success Ratios	Success ratios can worsen, as companies drill more and take more risks	Success ratios improve
Finding & Development Costs	Increase: R&D targeted at finding and developing new (more) reserves	Decrease; R&D targeted to reduce costs
Reserve additions	Additions likely to increase more rapidly	Additions likely to increase less rapidly

Companies will give either an Explicit or an Implicit recognised role to technology, and this element of the technology frame can be described as the **nature of the role of technology**. The predicted effects of this element are given in Table 2. The Implicit role of R&D and technology signifies a determination by the firm that R&D and technology are part of the infrastructure that allows exploration and production activities to be carried out. Typical signals of a firm pursuing an implicit role regime include the following: R&D and technology are not identified as a strategic advantage in the E&P business; there will be no mention of R&D and technology in the Chairman’s Letter to Stockholders; there will be no dedicated discussion of R&D and technology in the review of operations; there will be no representation of R&D and technology at the executive level. Firms that maintain an implicit role of R&D and technology do not necessarily have lesser technological capabilities, but there is an inherent bias that technological development is conducted for a specific purpose, i.e. for the specific needs of a given field development programme. The role is therefore one of problem-solving, rather than opportunity-making.

Table 2: Predicted Outcomes – Nature of the Role of Technology

	EXPLICIT	IMPLICIT
RISK		
Hierarchical placement	Executive representation; Self-determining technology programme; Serving but equal	No specific executive representation; Technology programme co-determined (determined) by asset needs, business units; Strictly supportive role
Planning horizon	Balance of effort includes greater share of longer view projects (returns in 5 – 10 years), even some 'blue sky'	Balance of effort on short term projects (6 months to 3 years), some medium term, no independent long term
TECHNOLOGICAL INPUTS		
R&D - trend	Growth in expenditure likely to decline less in lean periods, grow more in flush times	Growth in expenditure more likely to decline in lean times; vulnerable expenditure
R&D/Capex	Relatively higher share, as R&D prominent within overall investment programme	Relatively lower share, In part because R&D effort may not be classified as R&D expenditure
TECHNOLOGICAL OUTPUTS		
Patents – Number	Patents more likely; Impetus to produce demonstrable outputs and position capabilities	Patents may be less likely; Value is in application
Publications - Number	Publications more likely; Impetus to produce demonstrable outputs and position capabilities, particularly for less known companies	Publications less likely, particularly where no company policy / incentives to publish

The Explicit role of R&D and technology is found in firms that position themselves purposefully as a 'technology company'. Signals that firms hold an explicit role for technology include a list that is roughly the reverse of that for an implicit role: technology and the strategic role of R&D will be described in the Chairman's Letter to Stockholders; there will be a (at least one) senior Officer with responsibility for technology and R&D; there will be dedicated discussion of the development and application of R&D and technology in the review of operations. These firms will generally describe themselves as firms at the frontier of technological development of the industry. R&D and technology are strategically important to E&P activities, but instead of being subsumed within these activities, there is an acknowledgement that the R&D programme and technology is both informed by these activities but sufficiently apart to look longer term. The balance of effort will include a greater share for the longer view (even 'blue sky' projects).

Companies holding a more explicit role of technology are expected to have a relatively higher share of R&D in overall investment (Capex) as well as a higher propensity to patent and to publish, as patents and publications are useful signals of technological strength both within the firm and to the wider industry. Where the view is one of an implicit role for technology, we would therefore expect to see R&D expenditures to be lower, partially because the effort will not be allocated to an "R&D" budget but rather to the exploration or development costs lines. Where identifiable, it is likely that these expenditures will correlate more closely with trends in lower exploration and production costs. Likewise, the implicit value of technology is finally in its application, rather than in and of itself. This would imply a more collaborative and open relationship to collaborate in R&D with other firms and a fairly weak interest in IPR per se. Hence, we would expect patents to be lower for such firms. Whilst we can make predictions about the impacts on technology inputs and outputs of holding an explicit or an implicit role for technology, we do not have a priori expectations of impacts on operating performance. Rather, we use this analysis to explore these relationships.

The last element of the technology frame to be considered within the boundaries of our wider study is that of formal appropriation of intellectual property. The **role of formal appropriation** of technology defines whether a company seeks to obtain intellectual property rights (IPR) for the profits to be derived from licensing and sales or for the reasons of access and positioning. In practice, and according to industry experts, licensing revenues are not typically commercially significant in the upstream industry, but this strategy is in evidence amongst some oil companies. The upstream petroleum industry is characterised by knowledge and technology spillovers, which are unavoidable given the collaborative nature of the business and the concentrated service company sector. New ideas from one field development are quickly transferred by participating service company staff, by individuals and by the firms themselves. This continuous diffusion is tolerated because many of the oil companies see the value not in the technology itself but in knowing how best to apply it.[25] Therefore, the emphasis may not be to hold IPR to prevent access, but to ensure access by the inventing company, particularly if the patentee is a smaller oil company.

The second strategy is to use IPR to secure access and to position the company more favourably with the governmental bodies granting licences to hydrocarbon regions as well as with other oil companies. The smaller companies may also find that patents help improve their technological reputation amongst competitors and government licensing

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[25] Shell would be an exception to this, and it exhibits one of the more restrictive IPR policies. Other companies (in particular BP of late and the smaller integrated oil companies) argue that it is not the technology that conveys strategic advantage but the knowledge about how and where to apply it. This point of view was put forward by an Amerada Hess Senior Technology Manager at an Institute of Petroleum conference on innovation in offshore developments in February 1998.

bodies. These licensing authorities grant licenses to the best offers from companies that are expected to be able to deliver in an effective, profitable and environmentally sound manner. Larger, better-known companies with track records in dealing with technologically difficult fields have the advantage. Therefore, smaller companies actively seek to improve their positioning in order to gain a place in the running.

The role of formal appropriation can be expected to affect the organisation of innovative effort, particularly of collaborative projects, and the number of patents and publications (see Table 3). It is arguable that its IPR holdings and strategy in other business sectors, like petrochemicals, temper the firm’s strategy for IPR in the upstream sector. In the upstream petroleum industry (as in all others), the choice to patent or publish is a business decision and not an automatic outcome of innovative effort. There are costs and benefits to patenting and publishing that are derived from direct expenditures (such as legal costs) and indirect effects (such as the opportunity to collaborate). Individual firms make these choices based on their underlying preferences and objectives. In our fieldwork with the oil companies, it was a widely shared opinion that the patterns of patenting and publishing were not strategically indicative of success in the upstream petroleum industry.

Table 3 Predicted Outcomes – Appropriation of Intellectual Property (IP)

	IP PROFIT	**IP DEFENSIVE, POSITIONING**
RISK		
Peer Group Position	Leading position in key, marketable technologies with close followers	Generally technology follower, Leading in niche technologies
Technology Value Chain Strategy	Strategy to make returns throughout chain, including sale of technologies to third parties (licensing revenues)	Strategy to make full use of technologies (in-house and external) in operations
TECHNOLOGICAL INPUTS		
R&D – trend	R&D expenditure less vulnerable to market conditions	Impact on R&D expenditure sensitive to need for company positioning
R&D/Capex	Relatively higher share	As far as market conditions allow, increases with need for enhanced positioning
TECHNOLOGICAL OUTPUTS		
Patents – Number	Patents more likely, Continuous levels of patenting	Patents also likely, but sporadic
Publications – Number	Publications less likely, particularly in perceived strategic areas	Publications more likely, for positioning and for collaborative stance

Testing the frame

In order to assess the impact of the technology frame empirically, we have to define identify appropriate proxies for each of the three identified elements of the frame. Recently (Acha and von Tunzelmann, 2000), we addressed the upstream strategy element exclusively. In this paper, we address the upstream strategy element together with the nature of the role for technology.[26]

Here, we provide some illustrations of the technology frame with respect to the top 10 privately-held integrated oil companies over the period 1984 to 1997.[27]. This group comprised the supermajors of the period (Royal Dutch Shell and Exxon), the medium tier majors (Mobil, BP, Chevron, Amoco, Texaco) and the then establishing medium tier companies (Total SA, Elf Aquitaine and Atlantic Richfield). The study is focused solely on the upstream petroleum activities of these firms, that is to say their operations related to the exploration and production of crude oil and natural gas worldwide.

For the upstream strategy proxies, we define a firm as following "*G*" (growth) or "*E*" (efficiency) by assessing its changes in the gearing ratio[28] and the trend in R&D expenditure. For the nature of the role of technology, we collected details for each company over the period of study of the executive representation of technology in the firm (whether there was or was not) and the positioning of technology in the Annual Report. The Annual Report acts not only as an 'autobiography' of the firm for that year but also as a message for investors, staff, industry partners and clients as to the firm's strategic interests. Where technology was given a separate section, the firm was marked as "Annual Report 1". Frequently, technology would receive a subheading within the wider section on the production areas of upstream, downstream and chemicals. In these years, the firms were marked as "Annual Report 2". Finally, some firms did not address technology specifically anywhere in the report. These cases were noted as "Annual Report 3". Where firms included technology as part of operations or not at all in detail,

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[26] The leading indicators for the appropriation element (peer group position and technology value chain strategy) are ones that require detailed information from the companies themselves and industry technology experts; this stage of the study will be pursued in the future.

[27] These are namely (in descending order of the 1997 Petroleum Intelligence Weekly Ranking of the top 50 Petroleum Companies) Royal Dutch Shell, Exxon, Mobil, BP, Chevron, Amoco, Texaco, Total SA, Elf Aquitaine and Atlantic Richfield (Arco).

[28] Gearing is the total long-term debt held by a company in a given year, as a share of the combined sum of total long-term debt and shareholders' equity. In common parlance, this measure is described as debt to total capitalisation. This measure only uses long-term debt (instead of short-term debt) because this is more likely to indicate a change of risk and investment preference.

we argue that these firms are holding an implicit role for technology. Firms that report on technology separately in the Annual Report are considered to hold an explicit role for technology. These proxies would then be used to test the predicted relationships to technology inputs, outputs and operating performance.

Two R&D funding metrics are used as technology inputs: R&D expenditure and Upstream R&D expenditure as a share of upstream capital and exploratory expenditures (Capex). Whilst the R&D intensity figure is the most common metric for R&D expenditure corrected for size, we also use the R&D/Capex measure as an indication of the firm’s investment preference.[29] One advantage of the R&D/Capex measure over the R&D intensity measure is that is not affected by volatility in the world oil prices and oil tax and royalty regimes.

Because the ten companies did not make publicly available the figures for the specific R&D funding dedicated to their upstream activities, we have had to use their total R&D expenditures for the R&D expenditure variable. However, upstream (exploration and production) R&D funding data were made available for the six US companies within the peer group by the Energy Information Administration of the US Department of Energy[30]. Because of the confidential nature of this database, these firms have not been identified nor their actual figures revealed. Instead, using the average annual shares, we have estimated the upstream R&D share of total R&D expenditures for all 10 companies for comparison. Using correlation analysis, we compared the real upstream R&D figures to the estimated upstream R&D figures. The correlation in all but one case was above 0.75, and the average correlation for the group as a whole was 0.733. This provides confidence in the estimated values. However, the one case for which the correlation was poor is an interesting case in point. During the first half of the period, this company was actively increasing the share of upstream R&D significantly more than overall trend in growth in total R&D. This is an example of how technology frames differ even amongst peer companies under very similar market circumstances.

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[29] Case study research has confirmed that the oil companies themselves use the R&D/Capex measure to benchmark their technological effort against the peer group.

[30] This study has benefited greatly from the assistance and advice of Jon Rasmussen and Neal Davis of the Energy Information Administration.

The technology output measures used are the upstream patents and publications of each firm over the period of study. Patent data were obtained from the Derwent Scientific and Patent Information database[31], SubClass H01 Crude Oil and Natural Gas. This subset of patents collates patents granted around the world, assembled to avoid double counting, ascribed to the appropriate business, research or governmental entity[32] and coded by industrial relevance. This analysis has addressed patent counts rather than citations as a first measure of investigation. The publication data were provided by the TULSA database, developed and maintained by Petroleum Abstracts[33] of the University of Tulsa, which is the leading abstracting and indexing service for the upstream petroleum industry. The database contains more than 650,000 entries dating from 1965 to the present and which have been ‘filtered’ to include only high quality and relevant technical literature pertinent to the upstream petroleum industry.

The operating performance variables we use are finding and development costs (FDC), additions to reserves, and exploratory well success ratios. The FDC ratio is a measure of efficiency, in which the sum of the costs of exploration, development and unproven property is set against additions to reserves related to these costs. Well success ratios are the number of productive to total wells drilled (exploratory and development). Additions to reserves are reserves added through extensions and discoveries, improved recovery, purchases and (within company) transfers, before production and sales. Whilst these measures are not solely indicators of technical change, they do reflect technical change. According to recent research, improvements in technology and in technique (or methodology) to predict subsurface geological structures directly improve well success ratios. Likewise, Fagan (1997) has demonstrated for the US industry, technical change is reducing average finding costs at an accelerating rate.[34]

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[31] Derwent Scientific and Patent Information, 1725 Duke Street, Suite 250, Alexandria, Virginia 22314. Dr Donald Walter and Dr Deborah Hansell conducted the analysis.

[32] In the case of a trading group, the patents of the subsidiaries are ascribed to the parent company. In the case of conglomerates, the patents typically will be ascribed to each principal trading company within the conglomerate.

[33] Petroleum Abstracts Service, The University of Tulsa, 600 South College Avenue-HH100, Tulsa, Oklahoma 74104-3189. Carol Guy conducted the analysis.

[34] In her study, Fagan estimated the rate of cost diminution as reaching nearly 15% in 1994 for onshore efforts and 17.6% for offshore. Although there are significant variations in the diminution rates, there is a clear trend (both onshore and offshore) that accelerates from the mid-1980s. While her figures may be more indicative of scale effects rather than a precise estimate, it can be argued that FDCs do reflect the employment of superior technologies and techniques in that these innovations allow for a more informed bidding for unproven acreage, operating cost reductions and prospect highgrading (which is the practice of only going after the sure bets).

Estimation and analysis

We structure the relationships for the technology frame proxies to be tested thus:

1. G = • + • Gear + • R&D + • ExecRep + • Annual Rep1 + • Annual Rep2 + • UpRDCapex + u
2. Exec Rep = • + • UpRDCapex + u
3. Annual Rep1 = • + • UpRDCapex + u
4. Annual Rep2 = • + • UpRDCapex + u
5. Annual Rep3 = • + • UpRDCapex + u

Where **G** = Growth, **Gear** = Gearing; **R&D** = R&D expenditure in real terms; **Exec Rep** = executive representation for technology; **Annual Rep1** = technology given separate section in the Annual Report; **Annual Rep 2** = technology discussed, but within an operating section; **Annual Rep3** = technology not specifically discussed; **UpRDCapex** = share of upstream R&D in upstream capex.

We begin by testing for expected correlates of the dichotomous variable *G*, the growth (rather than efficiency) indicator of the behaviour of firm *j* in regard to its technology frame. The use of random effects in the probit analysis implies that the companies chosen for analysis are randomly chosen among all actual or potential companies. Since our data comprise all the oil company majors for many of the variables, if not all of the observations, this may seem unduly generous. On the other hand, statistical difficulties confront us if we instead opt for a fixed-effects model in a probit context. “There is no command for a conditional fixed-effects model, as there does not exist a sufficient statistic allowing the fixed effects to be conditioned out of the likelihood.”[35]

In Table 4, Equation (1) regresses Growth (*G*) against variables, which include the gearing ratio and R&D expenditures in constant prices. Since these two variables were used to define the value of the frame variable *G*, it would be expected that they be positively related to *G*. The variables *Gear* and *R&D* are indeed significantly positively correlated with the dichotomous variable *G* at the 5% level or better. It is the performance of other variables which is more interesting. The significant finding is for *Ann Rep1,* i.e. where technology is explicit in the Annual Report, which emerges as positively related to *G*. This would suggest that companies would hold a more explicit role for technology during times of expansion. This would be consistent with the explanation that, in times of growth, companies look beyond problem-solving technology efforts to more "game changing" initiatives. Overall, in this equation, the Wald statistic is significant at above the 5% level, but the proportion of total variance contributed by panel-level variance (rho) is virtually zero. Hence in this equation a pooled estimate would be as justifiable as the panel-data approach; or in other words, allowing for company differences adds almost nothing to the fit.

Table 4: Panel-data probit regressions on Technology Frame proxies

Variable	**Eqn (1)**	**Eqn (2)**	**Eqn (3)**	**Eqn (4)**	**Eqn (5)**
Dep Var	**Growth**	**Exec Rep**	**Ann Rep1**	**Ann Rep2**	**Ann Rep3**
Constant	-2.570***	+1.262**	-1.166***	-0.711	+0.637
Gear	+0.049***				
R&D	+0.0024**				
Exec Rep	-0.0815				
Ann Rep1	+0.0850**				
Ann Rep2	+0.3906				
UpRDCapex	-9.484	+4.786	+28.88***	-11.48	-26.81***
LL	-65.38	-34.68	-68.86	-44.68	-65.95
Wald	15.11**	0.10	10.35***	1.27	8.42***
Rho	.000	.786***	.177**	.136*	.180**
N	116	116	116	116	116

Key: Dep Var = Dependent Variable; Gear = Gearing Ratio; R&D = R&D Expenditure; UpRDCapex = Upstream R&D relative to Capital Expenditure; LL = Log-Likelihood; Rho = Ratio of panel variance to total variance; n = Number of observations.
Significance levels: * = 10% or better; ** = 5% or better; *** = 1% or better.

The remaining columns relate the variables proxying whether a technology frame is implicit (Annual Rep3) or explicit (Exec Rep, Annual Rep1) to Upstream R&D relative to Capital expenditure (Annual Rep2 is supposed *a priori* to be uncertain as to its classification). In the probit equations, the signs on the RDCapex variable all turn out as expected, though neither Exec Rep nor Annual Rep2 is significant. The strongly positive relationship for Annual Rep1 and equally strongly negative one for Annual Rep3 are highly supportive of our associated hypotheses. Firms with an explicit role for technology will have higher R&D/Capex shares than firms holding an implicit role. In all of these equations (2) to (5) the adoption of a panel-data approach is justified at some level of significance.

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[35] STATACorp, 417 Unconditional fixed-effects probit models can be estimated but the estimates are biased.

Our predicted relationships for the technology frame proxies and the technology outputs and operating performance variables are be tested thus:

6 Patents = • + • Growth + • R&D + • ExecRep + • Annual Rep1 + • Annual Rep2 + • UpRDCapex + u

7 Publicns = • + • Growth + • R&D + • ExecRep + • Annual Rep1 + • Annual Rep2 + • UpRDCapex + u

8 F&D Costs = • + • Growth + • R&D + • ExecRep + • Annual Rep1 + • Annual Rep2 + • UpRDCapex + u

9 Add Res = • + • Growth + • R&D + • ExecRep + • Annual Rep1 + • Annual Rep2 + • UpRDCapex + u

10 Well Suc = • + • Growth + • R&D + • ExecRep + • Annual Rep1 + • Annual Rep2 + • UpRDCapex + u

Where **Patents** = all upstream patents for firm *j* in year *i*; **Publicns** = all upstream publications for firm *j* in year *i***; F&D Costs** = average finding and development costs for firm *j* in year *i***; Add Res** = additions to reserves for firm *j* in year *i***; Well Suc** = success ratio for exploratory wells for firm *j* in year *i***; G** = Growth, **Gear** = Gearing; **R&D** = R&D expenditure in real terms; **Exec Rep** = executive representation for technology; **Annual Rep1** = technology given separate section in the Annual Report; **Annual Rep 2** = technology discussed, but within an operating section; **UpRDCapex** = share of upstream R&D in upstream capex.

The following set of tables regresses some of the main variables of interest in technology outputs and operating performance against similar regressors to those used in the previous table. Growth appears as an explanatory variable, and is assumed to summarise the effects of Gear and R&D. The estimations here are conducted in four ways: first using a fixed-effects procedure in Table 5A, second using (GLS) random effects in Table 5B, third using maximum-likelihood random-effects in Table 5C, and fourth using Prais-Winsten methods to correct for autocorrelation plus heteroscedasticity in Table 5D.

Table 5A: Fixed-effects regressions on key variables

Variable	**Eqn (6)**	**Eqn (7)**	**Eqn (8)**	**Eqn (9)**	**Eqn (10)**
Dep Var	**Patents**	**Publicns**	**F&D Costs**	**Add Res**	**Well Succ**
Constant	+8.716*	+206.8***	+4.433***	+0.122***	+0.555***
Growth	+3.876	-10.82	+1.709***	-0.0013	-0.060***
Exec Rep	-0.807	+3.112	+0.731	-0.0015	+0.0045
Ann Rep1	+6.093**	-28.01**	+1.333*	+0.0034	-0.0017
Ann Rep2	-0.808	-13.55	+0.877	+0.0079	+0.0233
UpRDCapex	+346.7***	+38.95	-10.51	-0.309	-1.241*
R-sq(W)	.283	.087	.162	.025	.123
R-sq(B)	.027	.130	.576	.108	.242
R-sq(O)	.102	.004	.229	.048	.112
F	7.98***	1.92*	3.39***	0.46	2.57**
Rho	.687	.702	.258	.523	.427
F(panel)	22.95***	17.68***	3.26***	8.21***	7.24***
N	116	116	103	103	106

Key: See previous table. R-sq(W) = R-squared for Within effects; R-sq(B) = R-squared for Between effects; R-sq(O) = R-squared Overall; F(panel) = F-test for significance of panel effects.

Table 5B: GLS Random-effects regressions on key variables

Variable	**Eqn (6)**	**Eqn (7)**	**Eqn (8)**	**Eqn (9)**	**Eqn (10)**
Dep Var	**Patents**	**Publicns**	**F&D Costs**	**Add Res**	**Well Succ**
Constant	+6.933	+200.2***	+4.381***	+0.128***	+0.495***
Growth	+3.296	-23.18***	+2.069***	+0.0009	-0.082***
Exec Rep	+0.559	+10.02	+0.892	-0.0072	+0.056
Ann Rep1	+6.110**	-26.60**	+1.422**	+0.0053	+0.028
Ann Rep2	-0.888	-18.67	+0.794	+0.0166	+0.064*
UpRDCapex	+345.2***	+51.32	-16.76	-0.316	-1.219*
R-sq(W)	.282	.137	.160	.020	.099
R-sq(B)	.042	.142	.621	.239	.668
R-sq(O)	.113	.016	.235	.086	.191
Wald	38.90***	14.96**	25.06***	4.05	18.56***
Rho	.602	.675	.095	.187	.067
LM	216.2***	122.1***	11.40***	35.10***	42.63***
Hausman	3.45	22.29***	3.54	1.61	0.00
N	116	116	103	103	106

Key: See previous table. LM= Breusch-Pagan Lagrangian multiplier test for random effects; Hausman = Hausman specification test for fixed vs. random effects.

Table 5C: Maximum-Likelihood Random-effects regressions on key variables

Variable	**Eqn (6)**	**Eqn (7)**	**Eqn (8)**	**Eqn (9)**	**Eqn (10)**
Dep Var	**Patents**	**Publicns**	**F&D Costs**	**Add Res**	**Well Succ**
Constant	+7.100	+192.9***	+4.345***	+0.129***	+0.544***
Growth	+3.418	-12.23	+1.948***	-0.0005	-0.066***
Exec Rep	+0.281	+9.518	+0.851	-0.0037	+0.019
Ann Rep1	+6.110**	-26.24**	+1.408**	+0.0039	+0.006
Ann Rep2	-0.870	-13.70	+0.824	+0.0110	+0.034
UpRDCapex	+345.5***	+81.53	-14.32	-0.316	-1.244*
LL	-457.9	-617.4	-244.7	204.4	88.27
LR	35.39***	9.04	21.49***	3.04	14.60**
Rho	.662	.667	.177	.465	.362
LR(panel)	87.47***	67.56***	7.68***	29.53***	24.10***
N	116	116	103	103	106

Key: See previous table. LL = Log-likelihood; LR = Likelihood ratio chi-sq; LR(panel) = LR test on panel effects.

Table 5D: Prais-Winsten panel-corrected standard errors regressions on key variables

Variable	**Eqn (6)**	**Eqn (7)**	**Eqn (8)**	**Eqn (9)**	**Eqn (10)**
Dep Var	**Patents**	**Publicns**	**F&D Costs**	**Add Res**	**Well Succ**
Constant	+4.284	+138.2***	+4.509***	+0.124***	+0.455***
Growth	-3.465	-29.42**	+2.401***	+0.004	-0.095***
Exec Rep	+10.44**	+65.34***	+0.996*	-0.015	+0.086*
Ann Rep1	+3.389	-11.68	+1.442**	+0.012	+0.050
Ann Rep2	-2.894	-15.50	+0.697	+0.034**	+0.096**
UpRDCapex	+325.1	+371.9	-24.16	-0.301	-1.228*
R-sqd	.164	.144	.237	.100	.200
Wald	43.73***	16.85***	28.74***	7.97	22.97***
Rho AR1	.686	.622	.524	.628	.355
N	116	116	103	103	106

Key: See previous table. Rho AR1 = rho estimated from an AR1 Prais-Winsten specification.

The last were themselves done in three ways according to the time-based assumptions – with independent errors, AR1 errors, and panel-specific AR1 errors. Only the first of these (which usually gave the strongest results) is reported here.

The four tables tell broadly similar stories.[36] These results can be compared with the predicted effects given in Tables 1-3. Patents and Publications were both seen as rather indeterminately related to a Growth or Efficiency frame; there being arguments for both a positive and a negative connection. The Growth variable turns out to be significant in neither, apart from the GLS random-effects model for publications where it is negative. Returning to the source data, the number of publications is increasing throughout the period for all ten companies, whilst the years 1984 to 1997 saw an overall change from a growth to an efficiency regime for the group as a whole as we found previously. Clearly, the relationship between upstream strategy and publications is tenuous at best.

Both Patents and Publications were predicted to be more likely in an Explicit rather than an Implicit frame. In the first three tables, Patents are significantly and positively related to Annual Rep1 (Explicit) at above the 5% level, with virtually identical coefficients across the tables, and to Upstream RD as a share of Capex likewise at above the 1% level (again, supporting the predicted effects). In the fourth table, using panel-corrected standard errors (PCSE), Exec Rep (the executive representation of technology) instead becomes the significant explanatory variable. The probable reason for which this variable enters only when this method of estimation is used is that companies change their Executive Representation only slowly. Hence over the period of observation most of the included companies either do or do not have a Technology representative on the board. If that is so, then the effects of any contribution from Exec Rep get swallowed up in the standard fixed or random effects relating to the company as a whole. The PCSE approach, with its standardization procedure for the errors, partially avoids this conflation. No other included variables are significant in explaining patents.

We have found elsewhere (e.g. Acha & von Tunzelmann, 2000) that Patents and Publications tended to be negatively correlated in terms of levels in these companies. As described above, patents have the expected positive relationship with the main proxy for Explicitness, i.e. Annual Rep1, but publications have a negative relationship, contrary to our predicted effects. With their different implications, Publications are negatively related to Annual Rep1 at the 5% level, but not to any other included variables except in Table 5D, where there is instead a positive relationship to Exec Rep (explained as above), offset by a negative one with Growth. The overall significance of the Publications equations is lower than for Patents.

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[36] In all equations, the panel effects are strongly significant. Hausman tests suggest that fixed-effects and random-effects specifications are in most cases not significantly different (the exception is for Publications).

Again, the number of publications that a firm produces appears to follow an independent trend, perhaps related to a change in the industry towards more collaborative technological development (where IPR is heavily controlled and resisted, but joint papers are encouraged) and to the fact that papers are essentially the activities of individuals, not firms. Fieldwork with some of the 10 companies has confirmed that, in most cases, papers are written outside of office hours and in addition to the individual's regular workload.

Finding and Development Costs (using the 3-year moving average) are positively and strongly related to a Growth frame, as could be expected. Under a growth regime, upstream petroleum firms are taking on more ambitious projects and are more aggressive in finding new sources of additional reserves. Unsurprisingly, these often result in relatively higher exploration and development costs per barrel found, and thus the FDC trend increases. FDCs are also positively linked to Annual Rep1, with the significance here being greater in the random-effects rather than the fixed-effects equations. This is consistent with the earlier finding that firms in a growth regime often hold an explicit role for technology. Likewise, we find that Exec Rep is again significant though less strong in the PCSE equation and positively related to FDCs.

Additions to reserves are difficult to explain from these variables, and the overall fits are poor. There is some positive relationship with the ambiguous Annual Rep2 variable when expressed in PCSE form to allow for heteroscedasticity across the panels. In the GLS random-effects equation, the Annual Rep2 variable also shows a slight positive impact. Returning to the source data, we see that there was stability for all companies in reserve additions over the 1984-1997 period, but some indications of a later rise. Growth in reserve additions declined from 1984 to 1986 sharply, recovering in 1987 and then continuing on a deceleration path or no growth in reserve additions until 1993. However, since 1993, reserve additions have grown rapidly once again. The single year recovery in 1987 is an example of how the accounting ('booking') methods may affect the data, as companies sometimes manage the booking of reserves to achieve best financial effect. The significant variation of the companies in the growth of reserve additions is consistent throughout the period, and this probably reflects their different stages of asset development. We conclude that it is the field cycle of assets that is the dominant effect here; and though changes in technology frame will affect the development of assets in the long run, our period of analysis is insufficient here to draw any conclusions.

Finally, Exploratory Wells Success is negatively and strongly related to Growth, and negatively but less strongly related to Upstream RDCapex. The implication is that firms under a growth regime and with an explicit role for technology drill more dry wells than the efficiency firms holding an implicit role for technology. Certainly, drilling is the most expensive element of the upstream petroleum activity; therefore, drilling dry wells is never good and less tolerated under a drive for efficiency. This is achieved by technology and prospect highgrading, as discussed earlier. However, this implies a lagged relationship between investment in R&D and results in exploratory well success. Some industry pundits have argued that the good success ratios in recent years are the payoff of years of investment in R&D; but as this investment in R&D (R&D as a share of Capex) declined in the 1990s (when the implicit role for technology dominated these ten companies), it has become more uncertain whether these success ratios can be maintained. Obviously, the continuation of the analysis of these firms into the future will help determine the reasons for the relationship between exploratory well success and the technology frame.

Summary and future applications for the frame

We believe that these findings provide support for our conceptualisation of the technology frame and its interdependent relationship with resources and capabilities, providing the mechanism by which the frame can influence – and be influenced by – patterns in the firm’s technology inputs, outputs and ultimately its operating performance. We have specified three of the dimensions of the technology frame, namely growth vs. efficiency, implicit vs. explicit, and profiting vs. positioning in intellectual property. The panel-data econometric evidence offered on the first two dichotomies supports most of the predicted effects, with a growth frame being correlated with an explicit frame, and the role of technology dichotomy with upstream R&D relative to capital expenditure. Correlations of other key variables like patents or finding and development costs with the frame indicators are generally as expected, with the exceptions of some of those related to some longer trends (additions to reserves) and to interesting divergences between firm views and employee behaviours (publications), both of which should be explored further in subsequent research.

Overall there is a basis for arguing that the technology frame is correlated with the patterns of technological inputs, outputs and performance measures evidenced by the firms over this period, and therefore there is interconnectivity between the technology frame and the resources and capabilities underlying these efforts. By using the technology frame as a heuristic, the patterns of patenting can be explained through the implicit or explicit role for technology, whereas, as we have demonstrated elsewhere, there is no simple correlation with R&D expenditures or with publications.

As stated previously, frames matter because they set the boundaries in which firms plan and act. As we have demonstrated in this industry example, frames affect the way the firms decide whether to publish or patent. More critically, the frames will affect the operational goals and parameters that the firms establish and which guide the paths to be taken. They provide us with one means of conceptualising ‘routines’.

In principle, the concept of a technology frame is likely to span industries and countries, although further research is necessary to explore this premise. Indeed, differences and dynamics encountered would help to elaborate the concept of a technology frame more satisfactorily. Likewise, firms will hold not only technology frames, but also management, marketing and production frames. Another valuable aspect for study would be to compare how these frames interact and co-evolve.

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