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A Real Options Approach to Managing Resources and Capabilities

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Abstract

The resource-based view (RBV) and the dynamic-capabilities approach (DCA) have emerged as two important frameworks in strategic management that seek to explain why firms are different. In recent years operations management scholars have sought to integrate both RBV and DCA within the field's epistemological orientation to provide normative frameworks for practising managers. This paper argues that the structure of resources and capabilities are such that they present impediments to normative prescriptions. Using ideas from complex systems we argue that any framework for thinking about resource accumulation and capability development must take account of uncertainty and knowledge imperfections in the system. We contend that the real options framework is an appropriate heuristic for managing the process of capability development and a case study of a manufacturing operation is used to illustrate our ideas.

Keywords Resource-based view, Dynamic-capabilities approach, Real options, Open Systems, Case study

Introduction and overview

RBV and DCA constitute two separate yet highly related streams of research in the strategic management literature. A fundamental question in the field of strategic management is how do firms create and sustain a competitive advantage (Rumelt *et al.* 1991). The resource-based view and the dynamic capability based approach have addressed this question in different ways. According to the RBV, competitive advantage and durable performance differences between firms are accounted for by asymmetric resource endowments with differential productivities (Wernerfelt, 1984; Barney, 1986; Conner, 1991; Mahoney and Pandian, 1992; Amit and Schoemaker, 1993). In contrast, from the dynamic capabilities perspective performance differences across firms and over time are accounted for by differences in the capacity of firms to accumulate, deploy, renew, and reconfigure resources in response to changes in the external environment (Nelson and Winter, 1982; Teece *et al.* 1997; Eisenhardt and Martin, 2000; Winter, 2000). Capabilities constitute individual skills, tacit forms of knowledge and social relations that are embedded in a firm's routines, managerial processes, forms of communication and culture. In either case, resources and capabilities have characteristics that make them difficult to trade or imitate; hence performance differences between firms are to be expected, as they are a natural outcome of the idiosyncratic and path dependent histories in which resources and capabilities have evolved.

Both approaches have proved to be attractive for operations strategy scholars for numerous reasons. The introverted orientation of both RBV and DCA enable them to emancipate the neglected strategic importance of operations. Since RBV and DCA represent two leading efficiency approaches in strategic management, they enable us to understand resources and capabilities embedded in operations as something more than strategizing around product market positioning.

Amundson (1998) has argued for RBV to be used as a driver of field-based research in operations management. However, operations strategy scholars have made use of both approaches when discussing the intellectual foundations of operations strategy (Hayes and Pisano, 1994; Mills *et al.* 1995; Clark, 1996; Roth, 1996; Swink and Hegarty, 1998; Gagon, 1999; Slack and Lewis, 2001). It is difficult to find genuine empirical research driven by RBV and DCA in the field of operations management. Recently, Schroeder *et al.* (2002) explored links between manufacturing resources and performance. In addition to conceptual discussions on revisions to the traditional operations strategy concept, RBV and DCA enter the general discussion within the field of operations management more explicitly (Lewis, 2000) or more implicitly (Spina *et al.* 1996; Spina, 1998; Bartezzaghi, 1999) when different best practices are discussed. For operations management scholars RBV and DCA presents an opportunity to establish the identity of the discipline around identification, transfer and application of different best practices. It seems, however, that scholars have not sought to identify themselves with exploring *why* capabilities or best practices emerge in the first place, *how* they develop and *why* they develop. The operations management literature acknowledges the evolutionary paths of capability or best practice development processes as a logical characteristic and recognise contingency factors that make these processes idiosyncratic, yet it is somehow assumed that development of best practices and valuable capabilities is a result of rational decision making about adopting a particular best practice or developing a certain capability. This way of thinking is congruent to the operations management field's epistemological orientation on *how to get thing done*, which reflects the importance the field attaches to the utility of research for practising managers. It leads operations strategy scholars to a research agenda that makes RBV and DCA approaches operational. Both approaches should, therefore, help to develop prescriptive frameworks and universal principles for managing capabilities and applying best practices. This stream of thought largely neglects the point that choice decisions related to capability development are subject to uncertainty due to the complex, ambiguous and even paradoxical nature of organisational phenomenon. The real challenge in managing capabilities does not lie in identifying different best practices, exploring co-relations between them and performance, and studying contingencies that influence applications. The real challenge is to accept the problematic nature of the phenomena and begin the process of learning how to cope with uncertainty, ambiguity and complexity in the capability development process.

Capability development has parallels with the application of the real options heuristic to strategy (Bowman and Hurry, 1993; Kogut and Kulatilaka, 2001; Bowman and Moskowitz, 2001; Kyläheiko *et al.* 2002), whereby a firm's resources, capabilities and knowledge create options for future exploitation. Investments in resources and capabilities are choice decisions made in the context of uncertainty, and as Loasby (2002) reminds us, it is the combination of time and uncertainty that makes real options potentially valuable. Real options are investments in physical and intangible resources that provide the firm with contingencies in an uncertain environment. The ability to alter a course of action in the light of new information is valuable and it is this *flexibility* that is captured by real options analysis. Following the seminal work of Black and Scholes (1973), Merton (1973) and Cox *et al.* (1979) in financial option pricing, the field of real options has expanded rapidly over the last two decades, culminating in a wide range of applications (e.g. Dixit and Pindyck, 1994; Trigeorgis, 1996; Amram and Kulatilaka, 1999; Copeland and Antikarov, 2001). All of these applications make extensive use of the Black-Scholes-Merton (BSM) model and its refinements in transferring financial options to the real options domain. However, as noted by Loasby (2002), in a BSM world uncertainty is transformed to manageable risk in a closed system where every contingency can be specified with known probabilities. In such a setting decision makers have perfect knowledge and choice is reduced to a logical operation (Loasby, 1999).

Our approach to real options follows a different line of reasoning by viewing firms as networks of reserves (Loasby, 1991; 1999; 2002), a pool of resources and capabilities (Kyläheiko et al. 2002), which generate flexibility in a world of incomplete knowledge where no-one knows how to specify appropriate contracts. Following Potts (2000), we adopt an open systems approach made up of elements and the connections between them but where the connections are incomplete. Uncertainty implies that knowledge changes with the passage of time and endogenous change involves reconfiguring connections, and constructing new connections, as knowledge about the system grows.

In the next section we develop a set of arguments to demonstrate that complexity and uncertainty are inherent within capability development, and given the evolutionary nature of the process, we argue that they constrain managerial actions; making both RBV and DCA less amenable to the development of normative prescriptions. Then, we discuss the appropriateness of real options concept for interpreting and managing the process of capability development in an open systems environment. Next, we present a case study of a manufacturing facility that illustrates the capability development process using the real options lens. This is followed by a discussion where we integrate the results from our case study with ideas from the literature on complex systems and real options. Finally, we provide some concluding remarks.

Impediments for normative prescription

Strategy scholars are constantly challenged to prescribe how to achieve competitive advantage. However, it is logically impossible to formulate a set of rules to systematically create a competitive advantage. The intrinsic logic of both RBV and DCA and their emphasis on complexity, path-dependency, and the idiosyncratic nature of the phenomena produce impediments for any model that is used as part of some normative prescription. Our contention is that the RBV and DCA literatures has made a significant contribution in explaining why some firms are more successful than others but is less powerful in prescribing how to manage resources and capabilities. Operations management as a field of study, like other management fields, seeks to develop frameworks and procedures that can help us to frame problems that can offer guidance for practice, but any framework with ambition to guide action will have to confront the properties of the phenomena being investigated. To examine the phenomenon of capability development it will be helpful to adopt a classification based on system complexity and process complexity.

System complexity

We argue that the complexity of a capability is in its structural composition. A capability is never a singular or a distinctive item. It is comprised of a series of nested systems and each subsystem may deal with a different external environment. In other words, elements that constitute a capability do not exist in isolation from each other; they only have meaning and value when linked. This suggests that complexity in any system is a manifestation of the number and diversity of the elements in the system and the nature of the connections among those elements (Potts, 2000).

To motivate our discussion of system complexity it will be instructive to consider some definitions from the strategic management literature. A resource is often defined in terms of assets that a firm owns or has access to (Warren, 2002). Resources can be tangible assets such as facilities and process technology, or intangible, such as patents, brand name, reputation and trade secrets (Hall, 1992). If a resource is understood as a more or less a firm-specific asset to which a monetary value can be attached, a capability refers to a firm's capacity to deploy and reconfigure resources. Makadok (2001) refers to a capability as a special type of a resource whose function improves the productivity of other resources. This implies that resources can represent a cluster of elements that constitutes a capability. In the Wal-Mart case study documented by Stalk *et al*. (1992), a firm's assets, such as real estate, trucking fleet and information technology productively linked to other resources constitute a powerful logistic capability. Capabilities are often discussed in terms of level. For example, Verona (1999) classified capabilities into functional and integrative capabilities. The former allows a firm to deepen its functional knowledge, such as R&D expertise, manufacturing knowledge and marketing expertise. The latter binds different functional capabilities and additionally absorbs critical knowledge from external sources. It is difficult, however, due to system complexity, to develop an unambiguous hierarchy of capabilities and resources. Brand name and corporate reputation are likely to be the outcome of a system of functional and integrative capabilities rather than a resource that underpins a marketing capability. On the other hand a firm-specific advanced process technology developed in-house may be an outcome of R&D and manufacturing expertise, but such a resource in turn can support a basic manufacturing capability and different integrative capabilities, such as quick new product development or flexibility in responding to customer demands. An integrative capability can refer to a firm's ability to use external resources productively. Gulati (1998) defines network resources as entities in networks that provide informational advantage. Through the network firms can obtain access to resources that create value and capabilities that would otherwise require time to develop. This means that something that is seen as a capability from the perspective of the firm can be interpreted as a resource from a network perspective. Furthermore, a firm's network is an idiosyncratic resource, created through a path-dependent process and is therefore, more akin to a capability.

Loasby's (1998) interpretation of a capability as a particular kind of *knowledge how* puts even more weight on the system and complex nature of a capability. Within a discourse of knowledge a capability is depicted as collectively held knowledge (Spender, 1996), which arises from integration and co-ordination of specialised knowledge (Kogut and Zender, 1992; Grant, 1996). As Penrose (1959) noted, capabilities depend on team activity in which the knowledge and skills of individuals are transformed into the integrated knowledge of the organisation. A capability is therefore a system where dispersed knowledge is integrated. The integration is achieved by the co-ordination of different levels of knowledge. Conceptualising a capability as a system of integrated knowledge leads to acknowledging uncertainty as an intrinsic characteristic of a capability. Tsoukas (1996) argues that firms confront radical uncertainty, since nobody knows what patterns of knowledge integration is relevant in particular circumstances. This implies that causal ambiguity – an organisational phenomenon well documented in the strategic management field (Lippman and Rumelt, 1982; Reed and DeFillipi, 1990; Collis, 1994) – is a particular form of uncertainty and refers to the fact that the knowledge of the capability's underlying structure is always incomplete. If this is the case then the link between resources, capabilities and competitive advantage will not be readily decipherable. System complexity reveals bounded rationality, since managers encounter limited capacity when considering different patterns of knowledge integration. They confront limitations when the numerous possibilities of different patterns of integration are considered as well as when consequences of a particular integration are validated. The inability to know in advance what kind of knowledge integration is likely to be relevant introduces uncertainty as a result of the dynamic characteristics of the capability development process.

Process complexity

System complexity is characterised by a high level of interdependency among elements that constitute a capability but the ambiguous structure of the system is not the only obstacle in the path of managers. DCA scholars (Dierickx and Cool, 1989) argue that capability development is a highly dynamic phenomenon. The evolutionary nature of the phenomenon is powerful in revealing how managers are constrained in their action to manage the process. The avowed dynamism of capability development is acknowledged by the operations strategy research community, however the accompanying uncertainty is largely ignored. An identified best practice is understood as a valuable capability, which has to be disaggregated into constitutive elements. When such a *design* of the new best way is revealed and contingencies determined, it is just a matter of time when this dominant *knowing how* will become widespread among other firms in the market place. What is neglected is the fact that a capability is not something that can be identified at the beginning of the process and they do not resemble phenomenon waiting to be discovered. Capability development is a generative process and capabilities are identified through retrospective sense-making as knowledge of organisational processes and markets evolve.

Winter (2000) argues that capabilities emerge in primitive forms. This implies that system complexity might be low in the initial phase of capability development, but process complexity could be high; managers will be confronted by causal ambiguity in that they will have little understanding of the direction in which a process is likely to evolve or how market uncertainties are likely to be resolved. Thus, firms are unlikely to be able to identify in advance which resources or capabilities, if any, will become valuable, or how resources and capabilities should be integrated, or what configurations the market will value in the future, for as Loasby (1998) reminds us, resources and capabilities represents conjectures to be tested in the market, and like any conjecture, they may be false. During the capability development process system complexity is likely to be increasing and by the time a capability is identified, system complexity is high. Whilst during the process causal ambiguity might have given way to causal understanding, knowledge of causality is always incomplete.

Causal understanding about the structure of a capability is due to the dynamic nature of the process and is always achieved *ex post*. The same holds true for a best practice. This suggests that the value of a particular practice can only be recognised *ex post* and cannot be planned *ex ante*. A firm's current stock of resources or capabilities depends critically on conditions that prevailed and decisions taken at some previous time. Since with the passage of time circumstances and knowledge about those circumstances change, a firm's stock of resources and capabilities at any moment will always be less than desired given the knowledge the firm now has.

Our argument is that operations management and operations strategy scholars have not sought to confront the uncertainty that surrounds choices about what future paths of resources and capabilities the firm should commit to. Uncertainty related to the complexity of a capability's structure and to dynamic complexity of the process has been implicitly recognised, yet largely neglected. Furthermore, the uncertainty associated with the subjective nature of the choice decision, so relevant for organisational theorists, has been largely ignored by operations management scholars. This avoidance undoubtedly does not contribute to the development of normative frameworks for managing the capability development process.

Real options and capabilities

Starting from the premise that any resource or capability is embedded in a much larger system, we explore the interplay between systems and process complexity, and real options, through a more precise discourse based on the open systems approach proposed by Potts (2000) in his detailed study of complexity in economic systems and the recent work of Loasby (2002), who has elaborated on some of these ideas. A system consists of both elements and connections between them and though a system in itself can be a complex entity, it can serve as a building block for higher-level systems (Potts, 2000). We can distinguish between closed and open systems. In a closed system every element is connected to every other element, whereas in open systems, the set of elements and the set of connections between them are incomplete, and only a fraction of the possible connections may be operational (Loasby, 2002). In an open system change occurs by rearranging connections, or by constructing new connections, which produce different sets of sub-systems or a hierarchy of systems. For example, rearranging connections may involve some reconfiguration of a firm's value chain and will involve the strengthening of some relationships whilst weakening others, such as would be the case in a supply chain by moving from parallel to single sourcing. Interpreting the firm as webs of multi-layered sets of connections is more meaningful than the idea that a firm is simply an endowment of resources with differential productivities. Different connections form different systems and managerial activity will involve experimenting with these connections to form new entities with new routines, capabilities, and social behaviours (Potts, 2000). As in our earlier discussion, a specific set of connections constitute a firm's competences (Potts, 2000) and capabilities (Loasby, 2002); they are also resources, but they are a particular type of knowledge resource. It is the epistemic phenomena of knowledge that is to be emphasized, in that they are instances of specific connections that seem to work in particular environments.

The suggestion is that the development of resources and capabilities follow a time consuming process by adding and rearranging connections. As a result, managers have to decide what resource and capabilities to commit to ahead of when they might be needed and at a time when their future value is uncertain. Faced with this situation firms will want to invest in resources and capabilities that have value in a range of circumstances. We contend that the real options approach has three redeeming features that offer some potential in thinking through this problem. First, the real options logic recognizes there is value in delaying investments by waiting for market and technological uncertainty to diminish before making a larger commitment. Second, many investments can be undertaken in stages and the real options logic is able to exploit the incremental learning associated with phased investments. Third, options provide a non-linear payoff structure in that purchasing an option enables a firm to take advantage of any upside potential whilst avoiding the downside risk. An option holder has the opportunity to take an action in the future should the situation prove attractive, but not the obligation, should events become unfavourable.

It follows from this discussion that the possible different combinations of connections (which can be thought of as different configurations of the value chain system) represent different option sets (Loasby, 2002). A system moves through state space by rearranging connections, that is, by making differential investments in different value chain configurations. This explains why firms are different. When an option is exercised (a deepening of a commitment in a specific set of resources and capabilities), the resulting configuration will yield a different option set for future exercise. Resource accumulation and capability development are the outcome of a sequential process of striking options, and throughout their history, firms will have taken different decisions about which option sets to strike.

As the density of connectivity varies, it is possible to trace out different system structures, which are characterised by different dynamical behaviour (Waldrop, 1992; Kauffman, 1993; and Potts, 2000). A highly connective structure is 'dynamically unstable', producing 'transient states', as changes in one part of the system can produce 'waves' that 'wash back and forth' throughout the entire system (Potts, 2000, p. 90). If the density of connections is extremely low such that there is a high degree of independence between elements, the system 'freezes up' and the systems dominant behaviour is a continuation of the pattern that is frozen into the system. This structure is referred to by Potts (2000) as the 'ordered state' and it is likely to exhibit a high degree of inertia, making it difficult for the system to respond to change. High quality structures, according to Potts (2000), require the coexistence of both stability and flexibility. This is the state of 'complexity' - a balance between established routines and capabilities being 'usefully' locked into a system and continual experimentation with new ones (Potts, 2000). The real options approach makes explicit the need to maintain system flexibility so that new routines and capabilities can be adapted and absorbed within the system.

Methodology

This research was designed to allow information gathering for the purpose of interpreting decision-making relevant for capability accumulation within the setting where uncertainty is inherent. Consistent with this research intent, an in-depth case study research strategy was followed (Eisenhardt, 1989). Such a strategy is appropriate when dynamic phenomenon is studied (Langley, 1999) and when little prior research has been conducted (Yin, 1989). We have chosen to address the dynamics of the phenomenon by conducting one in-depth longitudinal and retrospective case research.

Research setting

To adhere to the logic of theoretical sampling (Glaser and Strauss, 1967), a business unit within the aero-engine division of Rolls-Royce plc was selected, with the aim of providing a setting where the process of interest is transparent. Civil aerospace is a cyclical industry and the commercial cycle is unpredictable; many factors influence the pattern of new aircraft orders. Civil aero-engine manufacturers make large commitments to design and R&D in engine technology and manufacturing processes. For these reasons manufacturers will forge alliances with risk-sharing partners to collaborate on development work and manufacturing. In addition, all manufacturers have extensive sub-contract networks. The success of Rolls-Royce as the major rival to GE Aircraft Engines is attributed to its strengths in gas turbine technology and its product range (Rolls-Royce has the largest portfolio of engines and powers more types of civil aircraft than any other manufacturer). The industry business context denotes new product development as a core business process; therefore, the capability to develop a wide range of engine types represents a crucial capability. Avowed flexibility in meeting customer demands, illustrated by the extensive product range, significantly influences the process of new product development. Large commitments under conditions of uncertainty to functional capabilities, such as R&D, manufacturing expertise, and investments in resources, necessitates the formation of alliances.

Data collection

A long and ongoing consultancy relation with the company enabled the research team to negotiate access for two researchers over a period of 2 years. In the field research archival documents and interviews were used as sources of evidence. Interviews with the key managers were the primary data collection method since these provided the richness and depth of data, particularly regarding managerial decisions. Twenty interviews were conducted with 5 senior managers. We conducted one group interview with 4 informants that lasted 4 hours. Other interviews typically lasted 2 hours. The interviews were tape recorded and transcribed in the hours immediately following the interviews. Additional observations were noted at the time of the interview. Some short follow-up interviews were made by telephone. Much useful data emerged from informal conversation with managers and engineers. The majority of interviews were open ended, although a list of core questions was prepared to address the relevant questions. A sample of the core questions include:

- What decisions were made and what actions were conducted?
- What were the key events?

- Why were these decisions made and what influenced these decisions?
- How were these decisions brought about?
- How did these decisions and actions influence the process of capability development?

In this research extensive use was made of archival documents such as business plans, strategy documents, capital expenditure scheme proposals, and internal memorandums. A retrospective mode of research did not allow for a real time observation of how decisions were made and how they influenced capability development.

Data analysis

At the very first stage of our research some preliminary interviews were conducted in order to develop an understanding of the business context and to identify a particular project, whose development had to be traced. We were looking for a project with the following characteristics:

- multiple decision points
- incremental investments in resources and capabilities
- trial and error learning and knowledge generation
- irreversible commitments, and
- identifiable outcomes of capability developments.

When an appropriate project was identified, interviews were conducted and archival documents were used in order to develop a chronological picture of relevant events, decisions and actions. Identification of the process also determined key individuals for interviewing. A visual graphical representation (Miles and Huberman, 1984) was prepared for a group interview. This interview was used to enrich the visual map. The relevant events, decisions and actions were mapped chronologically. Context of each event and motivation for each decision were discussed. Effects of decisions and actions on capability development processes were indicated. Such a visual map represented an intermediary step between the row data and a more general understanding. The group interview was followed by additional interviews were a general interpretation of the studied process started to emerge. The entire analysis was, therefore highly iterative and involved moving back and forth among the data as the concepts emerged during the inductive mode of the research.

The Case Study

The case covers the period 1992 until early 2001 and describes the decisions that were taken by NGV Machining (NGVM), a business unit within the Rolls-Royce Aero Engine Group employing 170 engineers and support staff, to develop a 'world's best' capability in the design, manufacture and testing of nozzle guide vanes (NGVs). There are several manufacturers of NGVs and components are sourced from a network of suppliers. NGVs are precision-engineered parts, designed to reduce the operating temperature of the turbo-fans by directing cold air pulled into the fan rotor from the air that by-passes the combustion chamber.

During the period 1989 – 1992 NGVM experimented with the concept of the multi-skilled engineer (MSE) based around team working and simplified material flow. This initiative led to a number of performance improvements, such as reduced inventory and non-conformance, culminating in cost savings of £2.6 million over the period. Demands on the system brought about by more exacting engineering standards from a new generation of engine designs, and spurred by the success of MSE, the senior management team of NGVM sought category 'A' status (core business for Rolls-Royce) for NGV manufacturing and applied for financial support to expand the in-house facility. In 1992 the application to develop this facility was approved. Table 1 identifies events and the major decisions that were taken by NGVM over the period 1989 - 2001.

Phase One, 1992 - 1996

In 1992 NGVM set out a strategy to expand the manufacturing facility for NGV components that were to shape capability development for the next ten years. The background to this decision lay in an earlier period, 1989 – 1992, when in response to a drive to improve performance by the parent department, Turbine Aerofoil Manufacturing, the existing set of machine tools were reconfigured to form a machining cell and through initiatives such as multi-skilling, multi-machine manning and in cycle working, working practices were changed. These changes created a set of reserves by generating greater mobility and flexibility in the system. Reserves have option value because they are a form of contingency enabling NGVM to respond more effectively to a broader range of unforeseen events. Reserves constitute a timing option as they provide an opportunity, but not the obligation, to make a range of adjustments in the future.

The decision to expand was made against a background of considerable market and technological uncertainty. By 1992 the economic cycle for aircraft deliveries had moved well away from its peak in 1990 and both the UK and USA were still in recession. Although the cyclical nature of the industry is well understood, forecasting the length and magnitude of these cycles is problematic. There were two sources of technological uncertainty for NGVM; uncertainty associated with the integration of new machine tools and a related problem associated with performance uncertainty of NGV components for new engines during simulations and testing. In response to both types of uncertainty a decision was made to stage the investment and extend the application of MSE cells, where some successes had been achieved.

A phased investment constitutes an option set, where each phase completed (investment in an additional machining cell plus the learning associated with cumulative production), gave NGVM the option to invest in the next phase. Options within the set evolve along a trajectory as opportunities to invest in subsequent phases are accelerated, deferred, or abandoned, depending on how market and technological uncertainties unfold. NGVM's managers were not passive in this process. By making the investment, undertaking production and making adjustments in real time, they generated learning options, where current costs of production become an option on future production, the payoff from which is a reduction of future costs and other productivity benefits, such as reduced inventory, lead times, and non-conformance. It is learning by doing and using. Accumulated learning in cellular manufacturing reduced the risk for NGVM of introducing new technology and falsely moving to a new state and having an inappropriate set of capabilities. By the end of 1994, the first full year of operation for the new cells, cost savings from avoiding the network amounted to £4.2 million, lead times had been reduced from 21 to 14 weeks on average, and there were significant reductions in both inventory and non-conformance.

Phase Two, 1996 – 1997

In late 1996 a decision was made to accelerate investment in a second phase by adding a third cell. This decision was taken largely as a result of an unprecedented upsurge in demand for aircraft; a combination of the delivery cycle moving from its trough in 1994 and the market share gains being made by Rolls-Royce. Approval was granted in early 1997 and the cell was fully operational by early 1998.

Projections of load-capacity comparisons indicated that without this additional investment, in-house capacity would be half that of total task by the year 2000, but offloading this amount of work onto the sub-contract network raised two important issues. First, the network had become severely capacity-constrained and could not absorb this amount of offload. Second, further investments in the in-house facility had widened the performance gap, as implied by the productivity improvements given above.

The network constitutes a pool of resources and capabilities, which provide NGVM with the flexibility to defer its own investments by making use of the network. A decision made in 1992 to reduce NGVM's dependence on the network in order to prove the viability of the second cell, meant that network benefits could be forfeited if these activities are internalised. To make available the real options in a network requires investment and continual maintenance of the relationships by the network partners. By incurring network costs, largely coordination costs, NGVM effectively purchased a set of options on the network. The network options provide NGVM with the opportunity, but not the obligation, to participate in a range of network benefits, including the opportunity to defer its own investments. Foregoing these investments effectively kills-off the network options but such a decision has to be balanced against the investments that had been made by the mid 1990s in developing the in-house facility, and the preferential access this gave NGVM to make further investments for returns they believed would be more favourable than could be obtained on the network. By early 1998 NGV manufacturing in the UK had become a two-tier system, with NGVM sourcing all the high value added, high volume components for the new generation of engines (category A parts), whilst the network sourced much of the remainder.

Phase Three, 1997 - 2001

In late 1997 the senior management team revisited the load-capacity issue and their projections indicated that without further investments there would have to be offloads for category 'A' components. With some reduction in both market and technological uncertainty a decision was made to accelerate investment and a proposal was prepared that set out the case for investing in three additional cells. The proposal also made the case for an investment in state of art machine tools using technology currently being developed in-house by Rolls-Royce and its technology partners.

Investments in phases one and two represent capability development through cumulative incremental improvements as NGVM increased its capabilities in combining cell teams with proven machine tool technology. The proposal for the third phase represented a much greater degree of experimentation with new and as yet unproven technology. At this point NGVM were faced with a dilemma because in spending time and funding on exploration it could create a diversion of resources, which could slow down its accumulation of learning with the current technology. At the same time, engaging in exploration reduces the possibility of inertia and the path dependent constraints associated with incremental investments and local learning. Experimenting with the new technology during the period 1998 – 2001 created a 'switching option'. Switching in this case means having the ability to extend the different uses of the cells. Such an investment requires higher sunk costs but the payoff is the ability to produce a diverse product range and the ability to meet different performance standards, with the minimal sacrifice in operating costs compared with more conventional technology.

Capability development in NGVM combined with the advances being made through the integration of advanced machine tool technology produced productivity improvements in contiguous processes, such as engine design and testing. This is an example where advances being made in one part of the system can generate options in other parts. NGVM's emerging capability in machining high precision sculptured components created product options for engine designers. Product options are created from perceiving an opportunity to create a new or improved product and where a business has the resources assembled, and the capabilities, to develop and produce the product. An example is swept fan aerofoil technology, unique to Rolls-Royce (to be used for the first time in the Trent 900 engine to power the Airbus A380 when it comes into service in 2006), became possible as a result of advances in high precision measurement and inspection, drilling and machining in areas such as NGV manufacturing.

Discussion

We have argued that resources and capabilities are embedded in much larger systems and that real options offers a heuristic for understanding capability development in complex systems, where knowledge is partial, ambiguous, and where uncertainty can never be completely resolved. A case study was used to illustrate how a real options lens can provide a better understanding of the way in which resources were accumulated and capabilities had been developed in a manufacturing environment where market and technological uncertainty remained high throughout the period of the study. As discussed below, the case study integrates prior literature and provides some insights for strategic management and operations management in particular.

Complexity and the Evolving Nature of the Process

In a recent paper Kogut and Kulatilaka (2001) suggested that the real merit of the options heuristic is in the potential to know the value of a change in capabilities in moving to a different point in state space. It would be useful to know the value of different configurations of capabilities and real options has the potential to do this. As Kogut and Kulatilaka (2001) explain, the value of changing resources and capabilities requires an evaluation of the uncertain costs of changing position against the future unknown reward. The real options approach to capability development would do this by computing expected values of changing position in the future based on current market values (Kogut and Kulatilaka, 2001). However, the knowledge required to undertake such an evaluation should not be underestimated. Consistent with the literature (Penrose, 1959; Loasby, 1999), the case revealed that a firm may start from a position of considerable ambiguity about the direction of change, and from this, knowledge grows by purposeful trial and error from constructing connections, to yield capabilities to make further connections. Knowledge accumulates as a firm operates with its current stock of resources, and increases in knowledge raise the prospect of extending the range and amount of services available. The case illustrated that experience and knowledge acquired by NGVM over the period helped to form new connections by building routines and capabilities centred around MSE and cellular manufacturing, which enabled them to develop more productive resources and capabilities, accumulate further knowledge from pushing out the boundaries in using machine tool technology, and so on.

Resources that provide a broader range of services can afford a firm some flexibility, which is especially valuable when the future evolution of opportunities is unknown. Flexibility has option value, which suggests that a useful heuristic would be for managers to build flexibility into the system. Prior literature (e.g. Kauffman, 1993; Potts, 2000) suggests that a state of complexity represents a balance between stability and the ability to remain flexible, such that there are routines, standard operating procedures, skills and habits, the competences or capabilities of a firm, that are enduring, yet can be adapted to a range of uses. This brings us to the notion of viewing the firm as a set of reserves (Loasby, 1991 and 2002), which create options, and the importance of acquiring and developing reserves as a response to a range of threats and opportunities in an uncertain world. We did find the idea of firms-as-reserves figured strongly at several points over the period documented in the case, particularly in the initial phase, 1989 – 1992, where it was a motivating force for change, and again in the third phase, 1997 – 2001, when state-of-art technology was introduced as a means of reconciling conflicting demands from the need to maintain volume production of high-precision engineered components and the need to provide a fast response to engineering and testing. In completing the investment for phase three we can view NGVM has an adaptive system utilizing capabilities and resources in different input combinations, or converting inputs into outputs at different conversion rates, making it more responsive to market demands and changing competitive conditions.

When the direction of change is unknown prior literature (Brown and Eisenhardt, 1998; Potts, 2000; Kogut and Kulatilaka, 2001) has emphasized the merits of exploration through investing in probes, by adding to or rearranging the present set of connections. To reduce the risks for a firm in adopting radical change in its capabilities, Kogut and Kulatilaka (2001) suggest recombination; that is, exploring connections that recombine current resources with new ones. We can relate this point to our earlier discussion on complex systems. In a complex system a balance can be maintained, such that if one part of the system is in an ordered state the other part can be free to behave with more freedom, or, in the context of our discussion, experimentally (Potts, 2000). The suggestion is that as a firm develops capabilities and gains confidence in one part of the system it may be able to experiment with other parts without jeopardising the entire system. Our case lends some support to this idea. During the 1990s, a distinctive set of capabilities evolved in design, manufacture and testing of high value added components, and this increase in confidence prompted a series of adaptive experimentations, in both work practices and machine tool technology.

One might argue that NGVM identified the options that were the most obvious to exploit, as they tended to involve transitions to adjacent states. This brings us to what is seemingly an obvious point, but an important one, that options have to be recognised (Bowman and Hurry, 1993) before they can be evaluated, and the options that are recognised are likely to represent a small proportion of the options that are potentially available. Recognizing options is concerned with making sense of situations, and as Loasby (2002) remarks, ‘sense is to be made rather than revealed’ (p. 8). We can make a connection here to one of the central contributions of Penrose (1959); the concept of subjectivity of productive opportunities, which combines the idea of the environment as an ‘image’ in the entrepreneurs mind, with the insight that the ‘productive opportunities’ are the possibilities that managers conceive and ‘can take advantage of’ (p 31). This suggests that options are the product of mental conceptions, but as Witt (1998) observes, conceiving in organisations is not an individual act, but the outcome of ‘socially shared interpretations and patterns’, and these emerge from the experiences and knowledge generated within the firm.

This suggests that a capability is a socially constructed phenomenon since managers impart meaning and value to the knowledge a firm possesses. Managers largely influence the process of capability development and their decisions are framed by their cognition about the value of a capability and its productive opportunities.

Cognition, however, is also an evolutionary process and accompanies the capability development process. Within this cognitive process, mechanisms such as sense-making (Daft and Weick, 1984), interpretation (Thomas *et al.* 1993) and imagination (Witt, 1998) play an important role in coping with uncertainty.

Networks

Our case study suggests that processes within NGVM, its routines, operating procedures, habits and skills, are generators of knowledge and this knowledge is a major influence on the real options that become available as well as the timing of these options. The process is emergent and unpredictable, as NGVM cannot know what knowledge it will possess in the future and the uses it is likely to make of such knowledge. Equally, the case suggests that the subcontract network and the variety of collaborative arrangements are also generators of knowledge and make available a variety of real options. It is well understood in the literature (Richardson, 1972; Coombs and Metcalfe, 2000; Madhok, 2002) that different governance structures lead to differences in their potential to generate knowledge, and consequently, their potential to accumulate capabilities and generate options. Different modes represent different bundles of resources and capabilities, and as suggested by Madhok (2002), if a firm possesses the appropriate governance skills, it can select a production set from a range of possibilities and is not restricted to its own production technology. The literature has emphasized the benefits of networks over internal organisation (Coombs and Metcalfe, 2000; Madhok, 2002), suggesting that networks provide benefits that could not be available to a single firm. From an options perspective this conclusion should be treated with some caution.

Our case study suggests that NGVM were not facing the kind of optimisation problem suggested in the real options literature (e.g. Sanchez, 2000), where the problem is to maximize the value of the different option sets over all governance modes. Our discussion of both systems and process complexity should alert us to the difficulties of performing this task. Different governance modes (internal organisation and the subcontract network) have embedded in them different sets of options, so that in choosing to develop its internal capabilities, NGVM sacrificed the value that could be made available by developing the network. As illustrated by the case, NGVM made commitments to build capabilities in support of a particular mode of governance, the in-house facility, and the resulting expenditure represented a sunk cost, in that it was specific to a particular governance choice and could not be fully recovered. The irreversibility inherent in this decision, coupled with the uncertainty, is what makes the option valuable. Irreversibility imposes what Argyres and Liebeskind (2000) refer to as a 'governance switching constraint', which suggests that governance modes are the outcome of idiosyncratic and path-dependent processes.

Whilst we can agree with Madhok (2002), that networks provide substantial scope for learning, it does not follow that it will always be the preferred mode when market and technological uncertainty is high. In addition to the idea of firms as reserves, Madhok's (2002) argument overlooks the benefits of a modular organisation structure, such as was developed by NGVM, as an alternative approach to organisational and technological problem solving based on decomposability. Whilst the principles of modularity for managing technological design are well known, the application of the idea to organisational design is more recent (e.g. Sanchez and Mahoney, 1996; Langlois, 1999; Baldwin and Clark, 2000). Decomposability reduces the number of connections in a system by partitioning tasks, but the benefits of separability for NGVM were not fully realized until phase three, when three more cells were added. Modularity is a response to the problems of dispersed and tacit knowledge – inherent features of complex systems. Connections between cells can be kept low and knowledge need not be communicated to all parts of the system. Within modular structures the whole system may not be consciously designed, but emerges as an adaptive process. Modularity is compatible with staged investments, it enables the firm to learn, and as the firm learns and develops its capabilities, it creates options to benefit from emergent and unforeseen events.

Conclusion

According to RBV and DCA resources and capabilities with differential productivities are a source of performance differentials across firms. From this perspective it is natural for both researchers and managers to enquire into *how* the resources and capabilities with the desired attributes can be identified, developed, and managed. Our contention in this paper has been that many of the strategically important resources and capabilities are embedded in dense and highly complex clusters both within and across networks of firms. Systems complexity would suggest that attempts to identify and then isolate specific resources or capabilities for development is fraught with difficulties. In making the connection between resources, capabilities and knowledge our paper highlights the second phenomena we discussed, process complexity. Resources and capabilities develop and change over time as knowledge changes. The process of how a firm acquires its capabilities cannot be separated from how it acquires its knowledge. Much of the knowledge we have been concerned with comes from experience as managers learn to solve problems and in doing so accumulate knowledge and acquire capabilities which are used to build up the firm's resource base.

Knowledge is problematic, and therefore tentative, it accumulates through a process of purposeful trial and error. In this respect, the knowledge acquired by the firm represent conjectures, and like any conjecture, they are fallible, as they are subject to continuous testing in the market. In highlighting the problematic nature of knowledge and capability development the paper makes a potentially important contribution to the operations management literature. Our examination of complex systems within the context of a manufacturing operation offers a cautionary note to research that either explicitly, or implicitly, assumes that managers have knowledge they could not reasonably be expected to have. Formulating prescriptions on the basis that managers have perfect, or near perfect, knowledge can only lead to outcomes that are misleading and over-simplistic as guides for action.

When systems and process complexity are significant, we contend that a real options approach provides a useful set of tools for thinking about capability development. We illustrated these points using a case study describing incremental investment in a strategically important manufacturing operation for a large aerospace company where difficult governance choice decisions had to be resolved. The case was interpreted using the real options lens and we discussed the contribution of real options in building flexibility as a response to uncertainty and systems complexity.

This paper explicitly addresses the capability development process and more implicitly networking and investment decisions in manufacturing technology. All these present phenomena of interest for operations management. These phenomena however are socially complex, ambiguous and subject to uncertainty, and therefore, less amenable for producing prescriptive knowledge for improving short-term organisational performance. Operations management scholars should not hold back in their study of such phenomena for it is only in developing this knowledge can the field provide managers with a touchstone when confronting an ambiguous situation. This may require researchers to lessen their ties with the field's intellectual foundation and integrate their research with other management fields. If such research does result in the creation of conceptual knowledge, it will lead to the operations management discipline having a firmer identity.

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Table I. Chronology of events and decisions taken

Dates	Events	Decisions and actions taken	Comments
1989 – 1992	Turbine Aerofoil seek cost reductions and other performance improvements from its business units.	Introduction of MSE and formation of NGV manufacturing cells.	New experience curve – creation of learning option.
1992 – 1995	Some successes with MSE experiment – cost savings of £2.6 million over the period 1989-1992. Introduction of new generation of aero-engines i.e. the Trent family, raise engineering and technical standards for core components. Aircraft delivery cycle moves from its 1990 peak.	Funding sought to expand the facility by adding a second cell. Funding approved 1992 and second cell comes on stream in 1993. Bid to receive 'A' category status for NGV manufacturing. Decision taken to reduce dependency on the network.	NGV designated a 'core' component by Turbine Aerofoil Creation of compound option – opportunity for 'follow-on' investments 1994 - cost savings of £4.2 million in first full year of operation for second cell. Implications for the viability of some units within the network – abandonment of network options.
1996 – 1997	Unprecedented surge in demand for aircraft as economic cycle moves out from its trough in 1995. Network becomes capacity-constrained.	Sought approval to expand the facility by adding a third cell using technology already proven in second cell. Funding approved 1997 and third cell comes on stream in 1998.	Growth option created. Two-tier system emerged for NGV manufacturing, and category A parts sole sourced by NGVM.
1997 – 2001	Economic expansion in North America continues to fuel world airline growth and number of orders increase. Substantial gains made in operating performance but need greater flexibility and to drive down lead times. Latest generation of Trent engines raise the bar for engineering, i.e. measuring, inspecting, drilling and machining. Offloading certain category A parts to the network.	Sought approval to expand the facility by adding two more cells and a welding facility. Funding approved 1998.	Decision made to use state of art machine tools rather than source from the market. Machine tool technology becomes proprietary. Lengthens profit window and increases option values. Growth, switching and further learning options created. Technical problems delay the development of machine tools and computer programme writing. Additional cells scheduled to come on stream early 2000, delayed until mid 2001.