

**PRODUCTION COMPETENCE AND COMPETITIVE ADVANTAGE
IN PROCESS INDUSTRIES**

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Production competence and competitive advantage in process industries

Abstract

New technological innovations and customer demands have forced process industries to adapt their traditional emphasis on operational efficiency and embrace the challenges faced by emergent manufacturers and service sectors. These will only be met if process industries are able to integrate disparate production-related functions to accommodate new technology. This paper investigates how production competence enhances technology-based competitive advantage in process industries. A survey of the literature and a preliminary study of 20 process firms raised a series of questions that were investigated further using two case studies. The analysis demonstrates that competitive advantage requires integration between operations, technology and asset management through matching production requirements with the inherent capability of equipment and an understanding of equipment of functionality. Production competence is acquired through a learning mindset, which relies on an investigation of critical unknowns. Competitive advantage derives from tacit knowledge, and complex interdependencies between novel technology and organisational elements, and is enhanced by informal exploration and testing.

Key words: competitive advantage, operations, physical assets, knowledge

Introduction

Strengthening a manufacturer's competitive position requires an innovative use of physical assets, the acquisition of production competencies through collective learning, and establishing organisational routines (Lynskey, 1999). The challenge for the researcher is to develop theory that will "identify unique, proprietary, and special abilities and understand how competencies that lead to competitive advantage both occur and are capitalized upon in the firm" (Coates and McDermott, 2002: 438).

The objective of the study is to investigate the relationship between production competence and competitive advantage in process industries. An initial survey of 20 process manufacturers established what issues were important for achieving competitive advantage from new technology. These were considered in greater depth in two case studies. The findings suggest that competitive advantage derives from tacit knowledge, and complex interdependencies between novel technology and organisational elements. It is enhanced by production competence that emanates from a learning mindset and informal exploration and testing of critical unknowns by operations and maintenance staff. The effective use of technology requires that engineers match production requirements with the inherent capability of equipment, and that operators and maintenance staff understand the functionality of the technology.

The paper is structured as follows: after a discussion of appropriate literature, the methodology is presented. A preliminary survey identified important items pertaining to production competence and competitive advantage. A number of postulates are formulated and tested using case studies (Meredith, 1987). In our study three postulates are derived from the literature and the preliminary survey. Two case studies are used to assess the validity of each postulate. The study benefits from a longitudinal case analysis conducted between 1997 and 2003. The postulates are evaluated, limitations are discussed, and conclusions are presented.

Production competence, operations and physical assets in process industries

Process industries are not monolithic, and cannot be analysed as a single entity since each has its own idiosyncrasies (Ketokivi and Jokinen, 2006). However, process manufacturers share certain general characteristics. They are rather more capital-intensive than discrete-part

manufacturing, and capacity utilisation correlates strongly with profitability. Product variety is comparatively lower than in discrete manufacturing, because process technology tends to be more dedicated to a narrow range of products (Wheelwright and Hayes, 1985). This makes the achievement of higher capacity utilisation rates more challenging since alternative products to fill capacity may not exist during times of low demand. Further, product changeovers in process manufacturing may be both time-consuming and expensive (Hill et al, 2000). Process industries are characterised by carefully developed production methods, long-established markets, well-informed customers and rivals, and widely used technologies. Procedures are formalised under tightly controlled work programmes with regular variance reporting. Stable products and established quality standards introduce degrees of inertia that solidify existing arrangements and discourage alertness in responding to change (Jelinek, 1996). For competitive advantage firms must move beyond adherence to quality standards and delivery requirements and increase the level of knowledge about their processes (Ferdows and De Meyer, 1990). Process industries now face many of the challenges that confront high velocity firms, such as rapid and discontinuous change, intense competition, new technology, and regulation (Dennis and Meredith, 2000). Cutting-edge expertise, quick responses to new developments, agility, opportunism and resource flexibility are no longer the domain of only the high velocity sector (Thompson and Strickland, 2004). The challenge for process industries is to exploit unanticipated opportunities and learn quickly as new markets and non-traditional competitors appear (Govindarajan and Trimble, 2004). Employing a strategy with no distinctive features that can easily be imitated leaves a company 'stuck in the middle' with obsolete skills, and few options for improvement (D'Aveni, 1994).

In terms of the strategic choice theory classification (prospectors, analysers, low-cost defenders, differentiated defenders, and reactors), process industries are often viewed as low-cost defenders that preserve existing products and procedures, and concentrate on efficiency improvement and cost reduction. It is of course insufficient to adopt only a defensive approach since competitive advantage requires a more aggressive developmental action. Firms in process industries that fail to respond to short term trends and events will rarely be at the forefront of new developments, and will remain reactors (Hult et al, 2006).

Employees who understand how something is made are better able to manage manufacturing practices than those who deal only with the symptoms of the underlying process (Gourley,

2006). Organisations introducing new processes and technologies require an environment where knowledge assimilation and sharing generate continuous learning capability, which the literature refers to as absorptive capacity (Tu et al, 2006). A firm's competitive advantage is embedded in its constituent production-related activities, and its physical and knowledge technology base. It has long been suggested that equipment performance is dependent on production competence (Leonard-Barton, 1995). The ability to execute the physical part of manufacturing will assume greater importance as equipment reliant on new technology and knowledge becomes a significant driver of strategic direction.

The profound changes at an operational level are also transforming the management of physical assets. Technology is relied upon to increase output, ensure more efficient energy use, and meet customer value through a closer relationship between maintenance and product quality (Campbell, 1999). Facilities operating in a just-in-time regime require higher plant availability and reliability (Nakajima, 1989). Competition demands strict cost control, since maintenance accounts for an increasing share of operational costs (Paz and Leigh, 1994). Safety and environmental disasters are increasingly attributable to equipment failure (Manion and Evan, 2002), leading Moubrey (1998: 12) to comment: "The worst consequences of the incorrect or irresponsible custodianship of physical assets is that people die, sometimes in very large numbers".

Methodology

There are two components to this study. A pilot study for a preliminary survey was initiated in 1995 to ascertain individuals' views of what influences the introduction of new equipment for competitive advantage. One organisation in each of the following UK process sectors was selected: chemical, food, refinery and steel. Respondents were chosen to obtain as broad a perspective as possible with data collected from areas of expertise rather than on the basis of job title. The sample included 4 managers, 8 supervisors, 4 engineers, and 15 operators/maintenance craftsmen. The survey commenced by asking 31 individuals in these firms:

What issues do you consider to be important for competitive advantage when introducing and operating new technology?

It was to be expected that responses from this sample would be biased towards technology. Once we had clarified what the respondents had wished to convey in naming these, and overlapping items were eliminated, a list of 59 items formed the basis of a wider survey.

In order to expand the study, contact was made with a production or maintenance manager in 28 process manufacturing plants to establish whether the firm: (1) was prepared to take part in the research and grant access to all levels, (2) had acquired substantial new technology (such as a major new machine, production line or control system) in the previous 3 years, and (3) had introduced the technology to upgrade operational processes and capabilities to improve performance, output, flexibility, and quality, or reduce costs or processing time. The twenty plants that met these requirements were in the following sectors: chemical (3), food (5), paper (4), pharmaceuticals (3), refineries (2), and steel (3).

A total of 154 participants were then asked to score the importance of the 59 items on a five-point Likert scale. Factor analysis of quantitative data yielded 48 items grouped into 8 factors. Factors refer to clusters “that could be measuring aspects of the same underlying dimension” (Field, 2000: 423). Details of the factor analysis are discussed in the next section, with quantitative results shown in Table 1. A qualitative dimension was added by conducting 30 minute follow-up interviews with at least one respondent in each firm to clarify emerging results.

The second component of the study follows the approach of Meredith (1987) in using the literature and other sources to derive postulates and test these in real organisations. A “manageable set” of three postulates (Wall et al., 1990) was selected. Process industries are steeped in ‘antecedents’ (McCutcheon and Meredith, 1993), which change over time, so a longitudinal analysis of the postulates was undertaken in two case studies. Qualitative data was obtained through in-depth interviews conducted on three occasions between 1997 and 2003 to explore the development of themes and relationships affecting competitive advantage and production competence.

By their nature longitudinal studies mean that early data will be several years old when final conclusions are drawn. This does not necessarily negate initial results or render case studies

redundant. Some studies have found remarkably few changes in patterns of technology adoption over the last 10 years (Sohal et al., 2004).

Results of preliminary survey

Table 1 contains results of the preliminary survey: factors from the factor analysis using a rotated component matrix, percentage of total variance explained by each factor, item descriptions, importance scores, and factor loadings. Using Field's (2000) guidelines for factor acceptance (point of inflexion on a scree plot, eigenvalues greater than 1, and the requirement that a factor is reliable with 4 or more loadings greater than 0.6 and a sample size of more than 150), 8 factors and 48 associated items are shown (reduced from an initial 10 factors and 59 factors), explaining 75% of total variance. Reliabilities of the data, as assessed through Cronbach's alpha, were above 0.80 for all factors.

Table 1

Important factors in enhancing competitive advantage through new technology (factor analysis grouping of items)

From Table 1, the most significant factor was the management of the physical components of the technology, explaining 17.5% of total variance. The highest item importance score was understanding functionality and consequences of failure on the overall process, reflecting respondents' views that the effective management of physical assets requires integration of production and maintenance since staff from both disciplines should understand how equipment operates. Operational items explained 14% of the total variance. Understanding performance parameters and equipment capability had the highest importance score, supporting the first physical asset management item: it is essential to know what a machine's design capability is, and what the user wants it to do. Knowledge (explaining 12.8% of the total variance) was the third most significant factor. Respondents recognised that their lack of knowledge and understanding was a hindrance to good operating and maintenance. The remaining variance is explained by the other five factors in Table 1 and those excluded from the factor analysis results.

The preliminary survey suggests that production competence is a necessary condition for competitive advantage. The main components contributing to production competence are physical asset management, operations and knowledge.

Postulates for integrating operations and maintenance for new technology

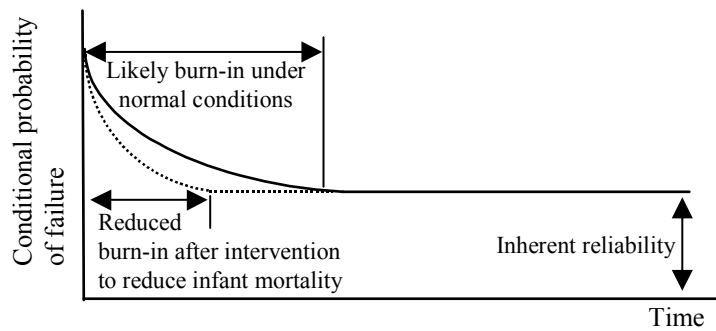
This section follows the approach of Meredith (1987) in deriving a number of postulates from the literature and other sources.

1. Production competence and inherent capability of technology

The management of physical assets encompasses “all activities necessary to restore equipment to, or keep it in, a specified operating condition” (Pintelon and Gelders, 1992: 301). This suggests that the starting point for determining requirements for physical asset management lies in establishing the intended functions of a system, machine, or item, by quantifying desired performance standards in the operating context, and matching requirements and capabilities (Moubray, 2000; Stock and Tatikonda, 2000). The next stages are a failure mode and effect analysis, and consequence evaluation to identify potentially critical unknowns (Swanson, 1999). Proactive intervention requires a task to be ‘applicable and effective’ (Nowlan and Heap, 1978). ‘Applicable’ addresses technical feasibility (maintenance tasks and intervals), and ‘effectiveness’ assesses whether maintenance is worth doing and whether proactive maintenance deals successfully with the consequences of failure in terms of meeting safety standards or cost effectiveness.

As assets become more complex they increasingly exhibit the failure pattern shown in Figure 1 (Nowlan and Heap, 1978) where the highest conditional probability of failure occurs when equipment is newly installed or shortly after overhaul. Correct installation, operating and maintenance should aim to reduce the ‘burn-in’ period (indicated by the dotted line). Complex equipment requires knowledge of the technology in operation and additional maintenance skills.

Figure 1 Failure pattern showing ‘burn-in’



Maintaining assets can only rectify a situation where degradation has resulted in capability falling below desired performance standards, and cannot improve the inherent (design) reliability of equipment. The implication is that the initial capability of equipment should be known, and matched with the desired performance requirements (Moubray 2000).

This discussion leads to the first postulate:

Postulate 1: Production competence requires integration between operations, technology and asset management, which necessitates matching production requirements with the inherent capability of equipment through an understanding of equipment functionality.

2. Operations

Coates and McDermott (2002: 443) define competence as “a bundle of aptitudes, skills, and technologies that the firm performs better than its competitors”. Govindarajan and Trimble (2004) speak of the need to explore skills and technologies, and learn about ‘critical unknowns’. Despite comprising similar equipment, apparently identical manufacturing lines often reflect a remarkable uniqueness, necessitating the accrual of “a plethora of incremental fixes and adjustments ... (requiring) individual line optimizations” (Katz et al., 1996: 99). Explicit technological characteristics are the easiest to transfer through training, first-hand observation and interaction, but even codification of processes dependent on technological subsystems requires subtle skills and expertise (Von Hippel, 1994).

This discussion leads to the second postulate:

Postulate 2: Production competence is derived from ambiguous predictions and information and requires a learning mindset to explore critical unknowns.

3. Knowledge

The success of a technology depends to a large degree on the competencies of personnel (Nonaka and Takeuchi, 1995). Managers should encourage learning that follows from diligent analysis of disparities between predictions and outcomes (Govindarajan and Trimble, 2004). The management of collective knowledge and the ability to work together to convert knowledge into customer value are essential competencies for competitive advantage (Liedtka, 1997).

Stock and Tatikonda (2000) see uncertainty as the result of novelty, complexity and tacitness of knowledge. Other scholars (see Grant, 2002) point to the competitive advantage that can result from mastery of these when they can provide first-mover advantage and prevent imitation by competitors. Technology novelty is the degree of previous experience with, and the amount of change relative to, prior technologies. Technology complexity is the level of interdependence between components in the technology and elements external to it. Tacitness is the degree to which knowledge is physically embodied by the technology and the extent to which it is codified and complete. Among the reasons for inadequate knowledge (tacit and explicit) is a firm's over-optimism about knowledge of its own processes, and its inability to build, debug and operate new processes (Bohn, 1994).

Physical asset management information systems have been developed for decades and support maintenance intervention through soft and hard integration (Jonsson, 2000). The 'soft' component relies on less tangible knowledge, autonomous maintenance and self-managed teams. The 'hard' aspect is represented by computerised maintenance management systems (CMMS). It is questionable how much useful data is stored in these (Hipkin, 2001), and Nowlan and Heap (1978: 66) doubt whether sufficient data exists to determine preventive maintenance intervals: "The development of an age-reliability relationship requires a considerable amount of data. When the failure has serious consequences, this body of data will not exist, since preventive measures must of necessity be taken after the first failure". The determination of proactive tasks therefore relies on experience, intuition and exploration.

This discussion leads to the third postulate:

Postulate 3: Competitive advantage derives from tacit knowledge and complex interdependencies between novel technology and organisational elements, and is enhanced by informal exploration and testing by operations and maintenance.

Case study descriptions

A paper mill and an oil refinery were selected from the companies in the preliminary survey for detailed analysis. These were selected as they offered contrasting operating contexts, with different approaches to the use of operations, technology and maintenance. Significantly, they offered access to rich and comprehensive insight into many of the features identified above, and had specifically emphasised the importance of production competence.

Paperco

The paper mill comprised several paper machines, coaters and a finishing department. The new coater was intended to improve flexibility and reduce setup times to meet a variety of coatings and quality specifications. The mill was implementing a reliability-centred maintenance (RCM) programme which requires performance standards to be documented as part of the description of equipment functionality. Failure modes and effects should be defined precisely. Preventive action is evaluated in terms of applicability and effectiveness. Review groups revised many of the suppliers' maintenance recommendations. Managers attributed improvements in plant availability to the significant plant knowledge acquired through RCM.

Refco

Upgraded plant in this refinery included a new coker heater unit, comprising the heater, flue gas, combustion air, and shutdown systems. Maintenance contractors were used as was the practice elsewhere on the refinery. Task teams were set up to study suppliers' maintenance recommendations, and analyse possible failure modes. The result was a list of hundreds of failure modes. As it was impossible to define appropriate maintenance for all, the refinery maintenance management team categorised these into critical, operational, and less significant failures (to be attended to on a breakdown basis), but operators roundly condemned the recommendations, so the exercise was repeated with operators in attendance, using total productive maintenance (TPM).

Case study analysis

Shortly after commissioning their new lines case study respondents were interviewed using semi-structured interviews based on the preliminary survey topics and postulates. The same individuals (or their replacements) were contacted on two further occasions between 1997 and 2003. Initial interviews established a basis for comparing subsequent actions for the new installations. Later discussions sought to identify changes in production competence, and explored opinions and experiences in relation to each postulate.

Postulate 1: Production competence requires integration between operations, technology and asset management, which necessitates matching production requirements with the inherent capability of equipment through an understanding of equipment functionality.

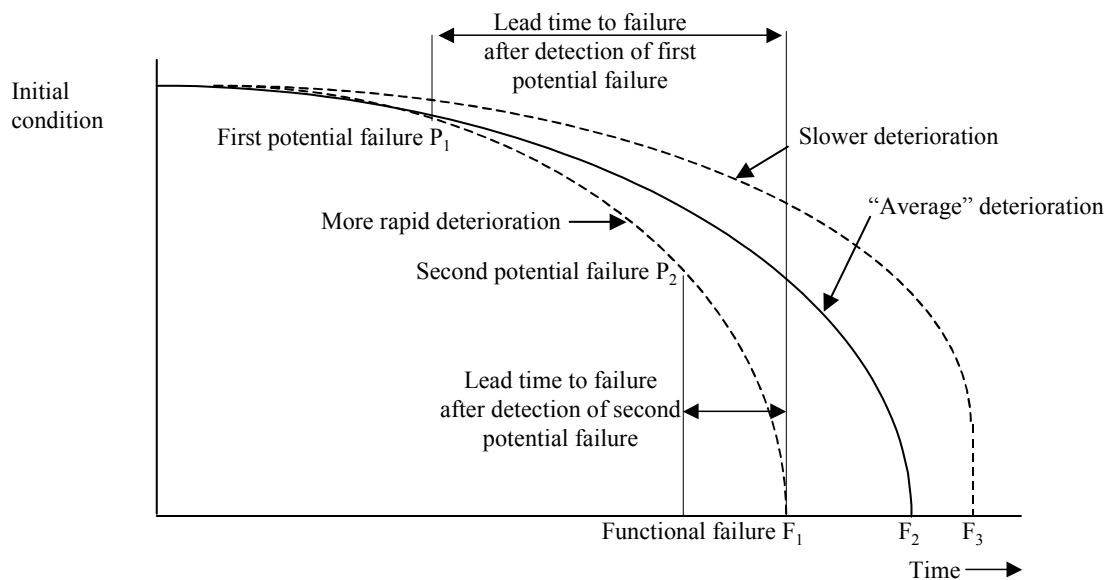
At first reading this postulate appears obvious, but a great deal of ignorance was evident in both cases. Operators in Paperco were unable to provide coatings specifications or acceptable sheet moisture content requirements. Frequent comments were made to the effect that “the computer is programmed to apply the correct weight of coating. We don’t have to know precisely what coating weights are required”. The result was an inability to define functional and failed states (including acceptable/unacceptable quality), or identify failure modes and effects, and failure consequences.

The rigour of RCM required a precise definition of failure effects and consequences (damage and costs). Determining a condition-based proactive task required an understanding of the failure pattern of an item and an estimate of its lead-time to failure (the time between a potential failure (P_1 or P_2) and a functional failure (F_1) shown in Figure 2).

Respondents gave many examples of how knowledge of plant operations had increased as a result of the RCM analyses. This enabled them to determine the frequency of condition-based inspections and scheduled preventive tasks, rather than relying on manufacturers’ recommendations, past practice on different equipment, or arbitrary intervals that conveniently corresponded to production schedules. By the end of the study period, condition monitoring activities were implemented in Paperco to establish early potential failures and efforts were made to establish failure data for critical components. At this stage operators and maintenance staff were familiar with quality and performance standards, and were using

engineering judgement and experimentation to investigate functionality where knowledge had initially been lacking.

Figure 2 Illustration of potential and functional failures, with lead-time to failure



At the beginning of the study operations staff at Refco were unaware of many performance standards and operating practices associated with the newly installed heater. One particular control valve had failed several times, so the TPM group recommended a 6-monthly check for all similar valves. Following a later analysis of this system, operators discovered that if the by-pass valve was opened within 4 minutes of hearing the low flow alarm, the heater could be kept on line and the faulty valve replaced without affecting production. A supervisor noted that they did not know (1) if the 6-monthly inspection was ‘applicable’ (if the valve provided a reasonably consistent warning of imminent failure, and/or whether it exhibited age-related failure characteristics), and (2) whether the task was ‘effective’ in the operating context, or whether safety considerations would override cost effectiveness. Initially, no one realised there was no need for a proactive task, as opening the by-pass valve avoided the consequences of the failure of the control valve. This example (and many others) illustrates the importance of knowing how a system is designed to perform (inherent capability) and understanding functionality if high availability is to be achieved.

Postulate 2: Production competence is derived from ambiguous predictions and information and requires a learning mindset to explore critical unknowns.

In seeking solutions to the kind of example discussed under Postulate 1, staff encountered significant difficulties because of misunderstandings of ‘critical unknowns’ (Govindarajan and Trimble, 2004). Respondents in the first set of interviews were asked how certain systems functioned in order to assess their familiarity with equipment. Responses relating to a feedwater system at Refco are summarised in Table 3. This contains function statements in the left hand column, and a ‘yes’/‘no’ to indicate which staff categories could provide functionality and performance requirements. Maintenance staff and the process engineer were unable to state the flow rate. Operators were able to supply most performance standards. Lack of knowledge among maintenance staff led to incorrect settings of level switches in tanks, or alarm and shutdown temperature protection, with potentially serious safety and operational consequences.

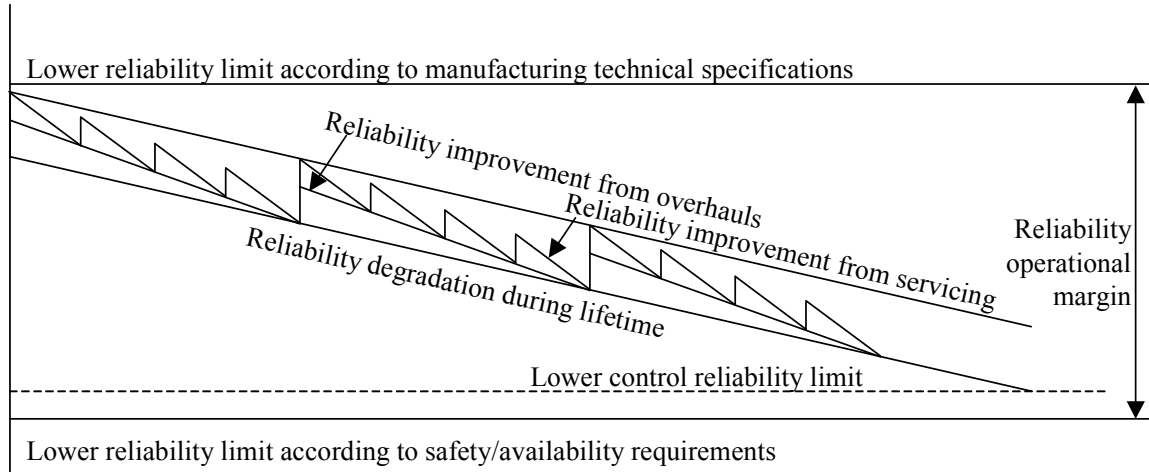
Table 3 Responses of respondents to questions about feedwater system functionality

Function (Feedwater supply)	Production supervisor	Maintenance supervisor	Operator	Craftsman	Electrician/Inst techn	Process specialist
To provide feedwater via 3 multistage pumps and independent lines to ST1 at a rate of 200l/min	yes	yes	yes	yes	yes	yes
	yes	no	yes	no	no	no
To cool process to 200°C and maintain plant in hot standby condition for a minimum of 24 hours	yes	no	yes	no	yes	yes
	yes	yes	yes	yes	no	no
A minimum of 30,000l is required in T7 and a minimum of 60,000l in backup tank T8	yes	no	yes	no	no	yes
	no	no	no	no	no	no
Make-up from T7 to T8 is through a locked closed manual gate valve and gravity feed piping	No	no	no	No	no	No

Similar results to those in Table 3 were found at Paperco, although at the end of the study period the knowledge of individuals involved with RCM had improved considerably. TPM implementation at Refco was useful in addressing broader maintenance issues from an organisational perspective. Respondents in both firms recognised that preventive tasks such as servicing and overhauls did not always restore original resistance to failure. Predictions of the ‘life’ of components did not necessarily take into account reliability degradation during the life of the system. This is illustrated in Figure 3 (adapted from Nikolaev and Gourinovich,

1996). Failure data records did not capture such failure complexities, so personnel relied on a ‘learning mindset’ to estimate the unknown longer term failure patterns of critical systems.

Figure 3 Impact of maintenance on equipment reliability over time

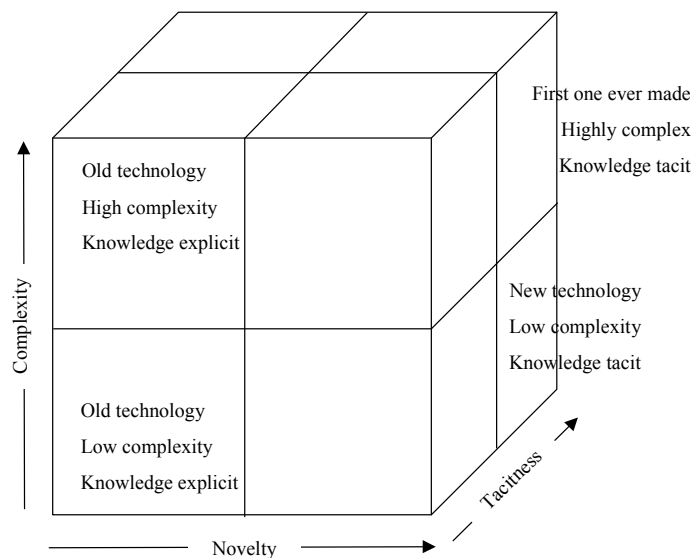


Postulate 3: Competitive advantage derives from tacit knowledge and complex interdependencies between novel technology and organisational elements, and is enhanced by informal exploration and testing by operations and maintenance.

Knowledge creation and diffusion take place through an intricate set of interdependencies between operations and maintenance. Some benefits from formal training were apparent in the cases, but ‘islands of knowledge’ acquired by individuals from the equipment supplier, or developed through their own experiences were not widely diffused, apart from discussions in the RCM review groups and TPM teams. Failure data in the CMMS was, with some notable exceptions, of limited use for developing maintenance information and knowledge. For example, the complexity and novelty of certain critical items meant that neither firm possessed the data that would describe the deterioration of wearing components that were subject to servicing and overhaul, as depicted in Figure 3. Experienced staff recognised such deterioration trends, but acknowledged that no one performed the detailed analysis of inspection reports that would be needed to produce the knowledge to make accurate failure predictions. The only way to gain this was through informal exploration. Figure 4 suggests a number of possibilities that could arise with varying degrees of complexity, novelty and tacitness.

The left hand lower quadrant (old technology, low complexity and explicit knowledge) offers certainty, but little competitive advantage. The uncertainty of old, highly complex technology (upper left hand quadrant) would not be a sensible strategic option. The situation with potentially the greatest competitive advantage (least chance of imitation) would be the quadrant where technology is totally novel (first item ever made) and complex, where knowledge is tacit. The operational challenges of such positioning demand a high degree of production competence, thereby giving a firm a technological lead over competitors who have to acquire the novel technology, master the complexity and access the tacit knowledge.

Figure 4 Complexity, novelty and tacitness



During the second series of interviews respondents illustrated how experience and know-how had led to some knowledge transfer. At Paperco, weekly intervals had been recommended for applicator and backing roll gearbox inspections on the erroneous reasoning that the gearboxes “failed fairly often”. Eventually the RCM review group was persuaded that lead-time to failure was the basis for determining the frequency of inspections and agreed that lead-times to failure were considerably longer than 2 weeks (the interval between P and F depicted in Figure 2). A decision was taken to lengthen the inspection interval. Further analysis revealed that when a certain viscous coating was applied over an extended period, it built up around the grease fittings preventing lubrication of the pivot bushing (understanding leading to knowledge). A cynical manager argued this was no more than a sound engineering

investigation, but was unable to explain why no one had established the true cause of many similar failures on other machines over the years.

Respondents in both cases repeatedly attributed improvements in availability and reliability to a change in emphasis from documented instructions to greater comprehension and, in the words of an operator “being able to get inside the minds of the designers”. However, limited use was made of explicit knowledge in the form of CMMS failure data and instruction manuals. Learning was unstructured, and as one supervisor noted “We have benefited from being able to analyse and discuss in an open and constructive environment free from our managers’ narrow performance measurement mentality”.

Discussion of postulates and implications for managers

Although the preliminary survey was conducted several years ago, respondents reported that production competence became even more important over the study period. Respondents believed competitive advantage would result from meeting all operational performance standards, through ensuring functionality, availability and reliability of equipment, and that these could only be achieved through production competence. It could be argued that competitive advantage arises from a broader range of capabilities, but participants specified these items as the major contributors.

The three postulates are fully supported by the research:

1. Matching production requirements with the inherent capability of equipment requires integration between operations, technology and asset management in order to understand functionality of equipment.
2. Production competence is enhanced by formal instruction and training, but a fuller understanding requires a learning mindset and exploration of critical unknowns.
3. Novel and complex technology deters imitation, but further competitive advantage derives from accessing and utilising the tacitness of technology.

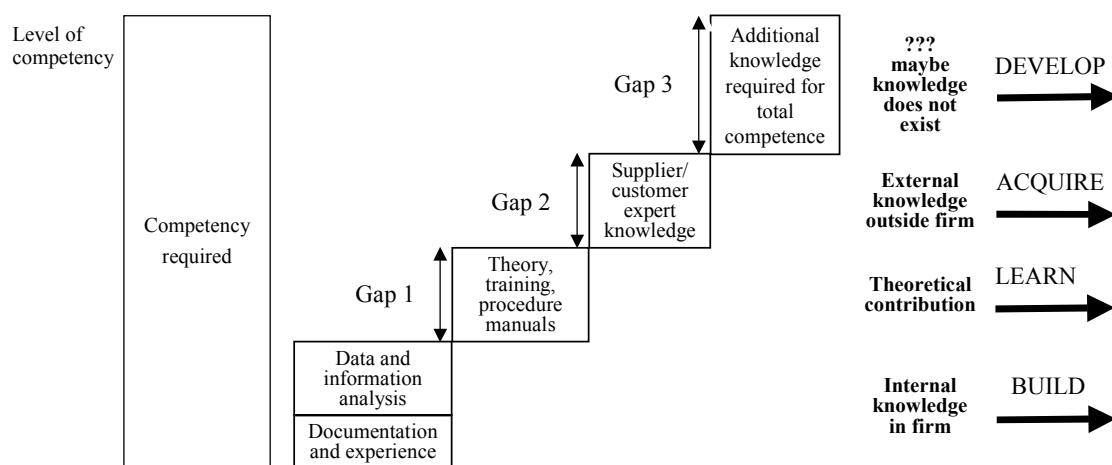
The development of competencies requires crossing boundaries between operational disciplines to understand functionality (Cleveland et al., 1989). Beyond the formal integration of operations and maintenance knowledge lie the incremental fixes and adjustments (Katz et al., 1996) that make allowance for different operating contexts, best known to operators and

maintainers. Champions enhance production competence by going beyond training and lending support to a learning environment that seeks to address the many unknowns that persist long after technology has been installed.

At the time of the final round of interviews (5 years after ‘new’ technology had been installed), the two case organisations had addressed poor reliability attributable to infant mortality, as depicted in Figure 1, but many parameters remained unknown, and the cases were some way from achieving the position of greatest competitive advantage shown in Figure 4. Failure data came from suppliers, or was derived from incorrect assessments of the nature of failure, and did not take different operating contexts into account. Codification of data, information and knowledge followed routines that addressed some of the knowledge deficiencies highlighted in Table 3, but did not permit thorough experimentation and investigations. Attempts to diffuse the considerable intangible knowledge that had accrued since the equipment was installed were informal, and much knowledge remained tacit.

Figure 5 (adapted from Prusak, 1997) is a conceptual illustration of the competences needed to operate and maintain production equipment, and the possible sources of relevant knowledge. The first three stages of augmenting production competences took place in a number of ways in the cases.

Figure 5 Knowledge gaps in achieving production competence



Managers initially assumed existing competences would form the foundation for building new expertise, but made no efforts to identify critical unknowns or encourage learning.

Maintenance interventions enhanced knowledge acquisition and diffusion, but organisational barriers arose. Managers' attempts to invest in explicit knowledge through theoretical and practical training, procedures manuals and CMMS led to data capture in documents, databases and software, but knowledge creation and learning were restricted. External knowledge was acquired through contact with technology suppliers and specialists, but benefits were limited as suppliers were frequently not aware of the operating context in which their technology functioned. Whatever additional (unknown) knowledge is required to develop total competence cannot be quantified, and perhaps does not exist. The study suggests that the most likely source is internal, provided the organisational context encourages the development of production competencies.

Longitudinal studies provide insight into events as a series of 'packages'. Learning and integration of operations and maintenance appeared to take place in bursts, triggered by early successes. While it was not possible to measure the impact of knowledge directly, many instances were recounted in the final interviews of improvements in operations and maintenance because systems were better understood. Serendipity played a role in that the maintenance interventions provided invaluable vehicles for diffusing tacit knowledge. By the end of the study period, it was clear that managers in both cases had "legitimized familiarization activities" (Dimnik and Johnston, 1993) by effectively granting the RCM and TPM groups authority to implement their findings and to experiment, but enthusiasm remained within the teams, with little overt encouragement from managers.

The case study findings strongly corroborate the three postulates. Managers initially proposed strategic justifications for technology to be an innovative solution in response to the competitive challenge, but new equipment did not constitute a major strategic reconfiguration of activities. The change of emphasis from strategic to production-oriented management control and reporting routines suggested that new equipment was to achieve competitive advantage through operational goals. Respondents felt that the most favourable organisational context for competitive capabilities arose from operations and maintenance initiatives in an informal and investigative learning environment not constrained by performance myopia.

A Paperco manager commented that technology was generally installed in process industries to provide sustainable competitive advantage through low cost production and other

operational benefits, whereas in high velocity environments technology provided unique competencies that facilitated change, speed and flexibility (agreeing with Vilkmam and Keil, 2003). A crucial aspect of competitive strategy is the creation of a set of firm-specific differentiated technological skills, complementary assets, organisational routines and unique capacities that will prevent imitation (Aharoni, 1993). This requires the contribution and leverage of agile resources and competencies to reshape skills and structures, and cultivate technological capabilities that should be rooted in knowledge, the organisation and people (Lynskey, 1999). In the case studies traditional and risk-averse attitudes by hesitant and reluctant managers were countered by operators and maintainers who were keen to learn and discover how full functionality could be achieved. Paradoxically, once managers had provided the RCM and TPM structures, operators and maintenance staff used their initiative in exploring and investigating beyond the strict confines of their specific jobs.

Limitations, areas for further research and conclusions

This study has investigated production competence and competitive advantage using a preliminary survey and postulate testing through case study analyses. To some extent the postulates lack conceptual richness as their main function was to focus respondents' minds on what had been highlighted as challenges for competitive advantage. The postulates addressed three topics, and the analysis was limited to two case studies. Like all case-based research, the study presents limited conclusions derived from a small sample. Despite the progress revealed in this longitudinal study, improved knowledge can take years to reveal tangible benefits. There is considerable scope for surveying a larger number of organisations, in a wider range of industries. We have only attempted to identify importance factors for production competence; we have not measured the strength of this relationship with successful implementation of new technology. Further investigations require detailed study, with particular emphasis on high-technology equipment with a potential strategic contribution.

A common feature of process industries is that competition obliges firms to improve quality and reduce costs, as excess global capacity depresses selling prices. A percentage point reduction in operations and maintenance expenditure can be worth tens of millions of dollars. The impact of poor operating and inappropriate maintenance on profitability is even more dramatic when costs of unacceptable quality and lost opportunity due to equipment unavailability are taken into account. With increasing complexity, it is no longer possible for

one person to possess complete knowledge about a machine or process. Acquiring new knowledge requires the workforce to explore ways of diffusing information and “change requires a reappraisal of what is captured in procedures, norms, and the paradigms that shape peoples’ thinking” (Jelinek, 1996: 809). Support for the postulates, and confirmation of items identified in the preliminary survey suggest that competitive advantage through production competence requires understanding and knowledge of functionality through joint learning and interpretations of operational and maintenance requirements, and fostering a learning and investigative culture.

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Table 1 Important factors in enhancing competitive advantage through new technology (factor analysis grouping of items)

FACTOR AND ITEM DESCRIPTION	Importance score	Factor loading	FACTOR AND ITEM DESCRIPTION	Importance score	Factor loading
PHYSICAL ASSET MANAGEMENT (% of variance explained 17.5%)	4.3		STRATEGY (% of total variance explained 9.7%)	4.1	
Understanding functionality and consequences of failure	4.6	0.954	Market demand drivers for new technology	4.2	0.842
Appropriate maintenance intervals	4.3	0.927	Technology to be globally competitive	4.0	0.833
Lead time to acquire spares	4.3	0.928	Technology enables revisit of vertical integration	4.5	0.828
Safety	4.2	0.903	Move from product to process base	4.0	0.819
Specialised maintenance equipment and techniques required	4.3	0.892	Specific objectives to be achieved from technology	3.6	0.782
Availability and reliability of equipment	4.4	0.858	New relationships with stakeholders	4.0	0.763
Appropriate maintenance tasks	4.2	0.845	Technology to provide competitive advantage and distinctive competency	4.6	0.638
CMMS	4.4	0.777			
Cost effectiveness of maintenance	4.3	0.746	TECHNOLOGY CHARACTERISTICS (% of variance explained 7.1%)	3.7	
Infant mortality and 'burn-in'	4.2	0.718	Use of expert systems	3.5	0.865
			Process optimisation	3.4	0.863
OPERATIONS (% of variance explained 14.0%)	4.1		Novelty of technology	3.8	0.808
Understanding performance requirements, equipment capability	3.9	0.884	Uncertainty concerning technology	3.9	0.792
Installation and commissioning	4.2	0.862	Complexity of technology	4.1	0.581
Training operations and maintenance staff	4.2	0.854			
Short term operational returns expected from technology	4.3	0.856	COMPETITIVE CAPABILITIES (% of variance explained 6.1%)	4.5	
Champions essential for implementation of new technology	3.7	0.776	Meeting customer requirements	4.6	0.917
Change management for new processes	3.7	0.750	Production output	4.6	0.893
Labour union cooperation	4.4	0.718	Quality of products	4.7	0.857
			Technology to be accommodated in existing context	4.2	0.682
KNOWLEDGE (% of total variance explained 12.8%)	4.2		Technology transfer and assimilation to permit product modifications	4.2	0.648
Failure data from suppliers	4.1	0.914			
Codification and documentation of data, information and knowledge	4.1	0.892	COOPERATION & INTEGRATION (% of variance explained 4.6%)	4.6	
Documentation and use of failure modes and effects analysis	4.1	0.891	Interfacing with IT systems	4.5	0.894
Diffusion of intangible knowledge	4.4	0.856	Management of contracts	4.5	0.836
Understanding principles behind new technology	4.3	0.831	Integration of new and existing systems	4.6	0.823
Analysis of data and information to produce knowledge	4.0	0.829	Cooperation between engineering, operations and maintenance	4.7	0.791
			SUPPLY CHAIN (% of total variance explained 3.7%)	3.9	
			B2B applications in supply chain management	3.8	0.930
			Use of supply chain in equipment acquisition	3.6	0.898
			Long term dependence on supplier for technical assistance	3.6	0.879
			Relationship between technology user and supplier	4.4	0.616

Scoring: 1 - least importance; 5 = greatest importance

Other factors not listed account for 25% of total variance

