The Problems of Embeddedness: Knowledge Transfer, Coordination and Reuse in Information Systems

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Abstract

This research examines the knowledge management challenge underlying technology use. It proposes to examine the key question: how can knowledge management problems and technology adoption difficulties be analysed through experts' practices embedded in their work contexts? The problems of knowledge transfer, coordination and reuse are investigated by examining experts' practices and work contexts. The inquiry is grounded in a qualitative case study of a knowledge management system designed to support maintenance work performed by two groups of engineers in a semiconductor-fabrication equipment company. The findings illustrate two contrasting outcomes: the equipment engineers found the system to be useful; the field engineers considered it to be irrelevant to their work contexts. An analysis of the fabrication process (the technical context), engineers' professional communities (the social context), and the pace of product/process innovation (the innovative context) helps us to understand the main problems underlying knowledge transfer, coordination and reuse. Significantly, we propose a specific definition of knowledge and suggest a way to examine practices and work contexts that can help to uncover new difficulties in knowledge management system adoption. The theoretical and practical implications of the study are discussed.

Keywords: practices, work context, knowledge transfer, knowledge coordination, knowledge reuse, embeddedness, knowledge management system, semiconductor-fabrication equipment

Introduction

Contemporary knowledge management research has collectively examined three major concerns: how to disseminate knowledge (knowledge transfer problems), how to locate knowledge holders (knowledge coordination problems), and how to exploit existing knowledge (knowledge reuse problems) (Huber 2001; Sambamurthy and Subramani 2005). Generally, researchers have found that knowledge is 'sticky' and contextualized, and therefore it might not be readily transferable (Szulanski 1996). However, in spite of this recognition, two primary concerns persist. First, most studies analyse these knowledge management problems with little consideration of knowledge attributes (Alavi and Leidner 2001). Second, they examine largely how knowledge barriers can be mitigated to achieve better technology acceptance

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(e.g. Purvis et al. 2001), but they are relatively insensitive to exploring how work contexts may affect knowledge management problems, which make knowledge sticky and difficult to decipher (Huber 2001).

Lack of understanding of these two concerns may significantly impede future knowledge management research. Researchers appear to treat knowledge barriers as universal, irrespective of whether the knowledge under investigation is an object, a cognitive state, or a capability (Gherardi 2000; Orlikowski 2002). Moreover, insufficient attention is paid to understanding the ways in which knowledge is 'sticky' in a given context. It should be acknowledged that different expert groups may employ different types of knowledge within different work contexts (Bogenrieder and Nooteboom 2004). In different work contexts, knowledge can reside in physical processes, social communities and industrial contexts (Lam 1997; Tyre and von Hippel 1997). Therefore, detached from work contexts, the analysis of knowledge barriers and technology acceptance will only yield information about the conditions of transfer and cannot explain why one expert group can employ technology to transfer, coordinate and reuse knowledge effectively, while another group encounters insurmountable difficulties when using the same technology (see the critique in Huber 2001).

In light of this theoretical gap, we seek to examine the use of technology-enabled knowledge sharing by paying special attention to knowledge attributes and their relationship with work contexts. In this study, we conduct a qualitative case study, and examine two different types of engineers (equipment engineers and field engineers) who are responsible for maintaining semiconductor-fabrication equipment in the same company. We propose an analysis of the following question:

How can knowledge management problems and technology adoption difficulties be analysed through experts' practices embedded in their work contexts?

The second part of the paper explains three different attributes of knowledge (knowledge-as-object, knowledge-as-cognition and knowledge-as-capability). We examine three particular work contexts and suggest an analytical framework for guiding our analysis of experts' practices. The third part explains how we applied this framework to data collection and data analysis in a leading semiconductor-fabrication equipment company. The fourth part provides first-order analysis by examining the practices of the equipment engineers and field engineers. The fifth part conducts second-order analysis by examining the way in which the engineers' practices are embedded in the respective technical, social and innovative contexts. This analysis helps to identify the problems of knowledge transfer, coordination and reuse; further, it proposes the reasons for the successful use of the knowledge management system by the equipment engineers, and the apparent irrelevance of the same system for the field engineers. The final section discusses the theoretical and practical implications of the research.

Theoretical Background

Three Knowledge Attributes

The current literature generally identifies three categories of organizational knowledge: knowledge-as-object, knowledge-as-cognition and knowledge-as-capability (Alavi and Leidner 2001; Gherardi 2000; Orlikowski 2002). For example, Ford Motors can encode the best practices of automobile assembly into structured 'objects' and disseminate them to different production plants through a public database. Management consultants are able to share their 'cognitive understanding' through unstructured stories and case reports, while technicians may transfer their know-how through 'learning-by-doing'.

Knowledge-as-object

The first type of attribute considers knowledge as tangible objects that can be converted and transferred directly to users. However, the major problem of transferring knowledge-as-object is conversion (Nonaka 1994). For example, effective knowledge transfer requires the use of different codification techniques to make tacit knowledge explicit. Although tacit knowledge may resist structured codification, a different set of techniques, such as cognitive maps, may be used to convert such knowledge. From this perspective, knowledge is transferable from one place to another with less appropriation. The role of technology is related to how to codify, represent and convert knowledge, the main challenge of which is to identify possible facilitating/inhibiting factors to knowledge transfer. These may include issues pertaining to motivation, a sharing culture and the ability to transfer knowledge from source (Purvis et al. 2001; Szulanski 1996).

Knowledge-as-cognition

The second type of attribute regards knowledge as experts' cognitions socially distributed in human networks (Tsoukas 1996). Knowledge is better shared through person-to-person communications. As such, different expert communities may hold conflicting belief systems and thus engender incongruent interpretations of a given item of knowledge, resulting in communication breakdown (Boland and Tenkasi 1995). In sharing knowledge, for example, a strong social network may be better than one that is weak, as the building of trustful relationships is achieved more easily (Pickering and King 1995). The challenge is related more to knowledge coordination problems — how to understand the pattern of knowledge distribution (who-knows-what and where the expert can be found; Hansen 2002). Information systems such as groupware can be used as a people finder or as a discussion forum to establish virtual communities that facilitate a personalized mode of communication (Hansen et al. 1999).

Knowledge-as-capability

In contrast to the previous form of attribute, this type considers knowledge as capability generated from experts' work activities (Barley 1996). It is also referred to as 'situated knowledge' because experts must acquire such knowledge by participating in different working situations (Lave and Wenger 1991; Tyre and von Hippel 1997). In other words, knowledge is created through a dynamic interaction between experts' practices and the work context — a concept referred to as 'knowing' (Cook and Brown 1999: 387). As such, knowledge cannot be taken away from practices by transferring it from one place to another as objects, nor can it be shared as individual cognition. As Orlikowski (2002: 253) contends, since knowledge is a 'capability', its transfer involves a developmental process of people's competences, so as to enact 'actionable practices' in a specific context.

Additionally, engineers rely on three generic types of cognitive knowledge to build capabilities: device, procedural and strategic knowledge (Gott et al. 1993). For example, through device knowledge, engineers learn how to maintain circuitry-related problems in a machine; through procedural knowledge, engineers learn how to follow a troubleshooting process; through strategic knowledge, engineers learn how to make decisions, what to do and when to do it. The role of technology is thus to support collective competence-building through learning-by-doing in various work situations (Barab et al. 2001), and to facilitate interactions within communities-of-practice (Brown and Duguid 1991).

Placing Practices in Contexts

A less explored issue involves examination of the three knowledge attributes in specific work contexts, and exploration of the way in which knowledge management problems may occur collectively (Sambamurthy and Subramani 2005). Knowledge, be it object, cognition or capability, must be enacted from people's practices and reside in a particular work context (Orlikowski 2002). In view of this, to understand knowledge management problems, analysis of experts' actions in situ is necessary, as this will help us to examine how experts' practices are embedded in, and shaped by, work contexts.

Barley (1996) suggests a useful framework for examining practices and contexts, which he terms *empirical interface*. As shown in Figure 1, in a maintenance situation, the expert liaises between the domain of 'material' (e.g. a dysfunctional machine) on the one hand and the domain of 'representation' (e.g. experiment data, a test result, or a lab diagnosis) on the other. Depending on the occupation, the 'material entity' may consist of fabrication machines, computers or micro-organisms. Relevant 'representations' consist of information extracted to symbolize problematic situations by using different diagnostic techniques, which may require device, procedural or strategic knowledge. When the expert performs repair practices, he or she first has to examine the machine (i.e. the material domain) and conceptually analyse the problems. The expert then has to 'transform' the machine problems and analyse them by means of certain device, procedural and strategic knowledge through specific diagnostic techniques (i.e. in the representation domain). This process is called 'transformation' in Barley's terminology. Subsequently, having rationalized the problem through the chosen diagnostic techniques, the expert is able physically to repair the machine, a process labelled 'caretaking' by Barley. For example, through the use of various instruments to reduce biological phenomena into data charts (transformation), a science technician is able to employ the data charts to fix the problematic machine (caretaking).

According to this framework, the expert has to perform maintenance practices in three related work contexts: technical, social and innovative. First, repair of a machine requires the expert to become involved with the production process in which the machine is embedded (the technical context). Second, to maintain the machine in different stages of the production process, it is necessary for the expert to work with other groups of experts specialized in different subject domains (the social context). Finally, when engaged in data diagnosis, the expert should also be concerned about whether the repair principles may be outdated, as innovations are incorporated into the new machine model (the innovative context). It is important to discuss these three contexts in greater detail.

Practices Embedded in the Technical Context

The experts' practices are embedded in the technical context. For instance, Tyre and von Hippel (1997) reported that laboratory technicians have to perform their repair tasks embedded in the electronics-manufacturing system. It is necessary for technicians' practices to be adapted to the technical context, for example by searching for problem-solving clues, data-gathering skills, and by using local tools. In her analysis of knowledge transfer between

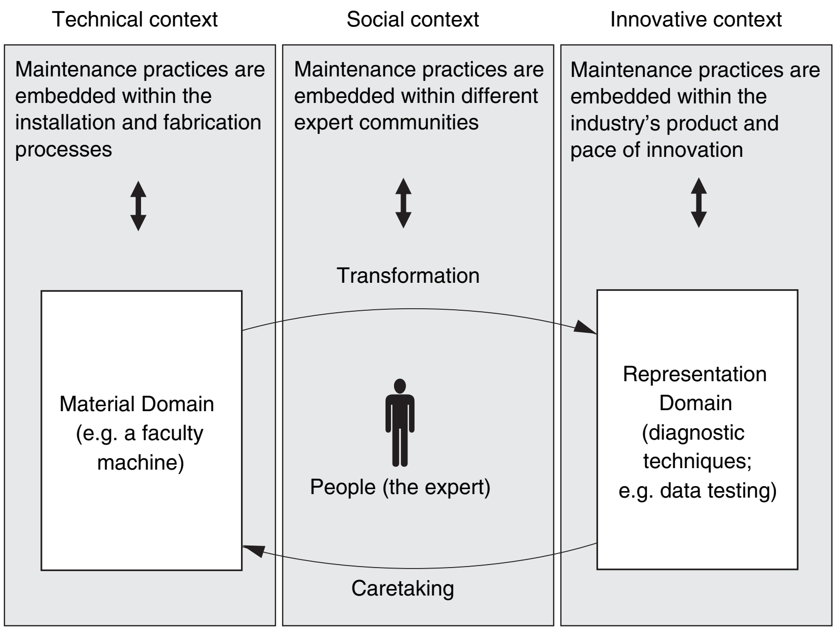

Figure 1. Analysing Practices within Three Work Contexts

Japanese and British engineers, Lam (1997) found that the latter's design practices are embedded in a technical context characterized by a sequenced product-development process. In contrast, the Japanese engineers' practices are embedded in a technical context characterized by a diffusive, overlapping product-development process. As a result, while it is easier for British engineers to articulate product-development practices in formal documentation, it is relatively difficult for Japanese engineers to explain what the relevant collective practices comprise.

Practices Embedded in the Social Context

As Lave and Wenger (1991) suggest, the expert learns his or her practices through 'legitimate peripheral participation'; that is to say, knowledge transfer requires adaptive learning through participation in repair situations within communities-of-practice. Based on different work contexts, the expert may need to collaborate with different professional communities (Brown and Duguid 1991). For instance, Lam (1997) found that British engineers work quite independently in their social network and consider formal documentation to be the preferred method for sharing knowledge. In contrast, Japanese engineers' practices require collaboration in a close-knit social network, and as a result knowledge transfer requires the engagement of engineers in intensive socialization that cannot easily be codified. Additionally, certain repair tasks require knowledge sharing among multiple expert communities spanning different disciplinary boundaries (Levina and Vaast 2005).

Practices Embedded in the Innovative Context

The representation domain is closely linked to the pace of product/process innovation in a particular work context. This is because every new product/process design will invariably affect repair principles — such as the type of diagnostic information that is gathered. The pace of innovation may vary in different industries. In a stable innovative context, for example, the development of a new product often follows a continuous technological roadmap (e.g. consumer products). However, in high-velocity industries such as computers or semiconductors, the intensified competition may trigger a rapid, discontinuous innovation in product and process. Consequently, it is important for repair practices to be renewed frequently, rendering it increasingly difficult for experts to accumulate past maintenance experience. It is therefore difficult to document such fluid knowledge. For example, Pentland (1995) reported that the decision-support system designed to share energy-audit engineers' practices was significantly limited, as many of the software algorithms were quickly outmoded. This was due to the increasingly diversified energy-audit regulations in the USA and the rapidly updated new audit processes. This is clearly illustrated in the case of Florida cooling systems, which required updated documentation before being deployed by public utilities in Florida, owing to the differences between these cooling systems and those in northeastern USA. As the engineers found it difficult to incorporate constant knowledge renewal into the system, the continued relevance of knowledge content could not be guaranteed.

The knowledge management literature acknowledges that people and their practices cannot be isolated from the embedded work contexts (Cook and Brown 1999; Lam 1997; Tyre and von Hippel 1997). Neither is it possible to examine knowledge without referring to the participatory contexts in which these practices were acquired (Lave and Wenger 1991; Orlikowski 2002). The current literature, however, neglects the question of how practices may be shaped within work contexts, thereby inducing knowledge management problems and resulting in difficulties with regard to technology adoption. In this research, we attempt to investigate this issue through the analysis of 'embeddedness' (i.e. how practices are embedded in work contexts). On this basis, we conduct an in-depth case study and examine why the knowledge management system in question was readily adopted by one expert group, while it was rejected by another.

Research Site and Methods

Case Background

This research is based on ChipFab (all names appearing here are pseudonyms), the Asian office of a leading US-based semiconductor-fabrication equipment provider (based in Taiwan). The firm employs 750 people and has installed 2,500 fabrication systems in 30 client firms based at science parks in Taiwan. In setting up a typical microchip fabrication, roughly 60% of the investment is spent on fabrication equipment. ChipFab's after-sales support thus plays a major role in making or breaking a fabrication project. To remain competitive, it is necessary for ChipFab to help clients to sustain a high level of production capacity (in terms of how many wafers are fabricated) and to minimize the defect rate (i.e. the production of rejected wafers).

In ChipFab, there are two types of engineer: equipment engineers (numbering 100 at the time of this study) and field engineers (numbering 400). The equipment engineers' main responsibility is machine installation, while the field engineers perform on-site troubleshooting. It soon emerged that there were two major problems in knowledge sharing. First, the repair engineers were distributed around client sites and were unable to share their knowledge easily. Second, owing to conflicts of interests, engineers were unable to share their repair practices across different client accounts. Any sharing of repair know-how needed to be mediated through the RPM (Regional Product Management) Centre. It had become obvious to ChipFab that codifying the engineers' practices and putting them in a generic repository should greatly facilitate knowledge transfer.

In July 2000, the head of the Human Resource Department incorporated a KM (Knowledge Management) team, which built a knowledge repository, called 'Discover', to disseminate the best practices of machine maintenance. Typically, an engineer would record maintenance tips, following a structured format: (1) abstract; (2) introduction (symptoms of the problem); (3) results and discussion (lessons learned from repairing the machine); (4) conclusion and further references. The tips were then submitted to a central clearinghouse managed by a committee consisting of 18 'knowledge champions'. A domain expert was appointed to review the relevance of the content, and two independent reviewers (selected from the knowledge champions) were asked to judge the usefulness of the tips. Each tip, once approved, would be acknowledged as a 'best practice' tip and stored in the Discover database. The engineer would receive an acknowledgement at an annual corporate meeting, along with a cash bonus of US$500–1,000 for each tip submitted.

Between early 2001 and mid-2002, a senior technical manager took over as head of the KM Team, with the aim of enhancing the knowledge content. This involved improving the knowledge codification protocol and elaborating the 'lessons learned' for each submitted tip. By the end of 2001, the KM Team reported encouraging results: (1) the submission of best practice tips had increased from 18 to 72 items per month; (2) the frequency of knowledge searches in Discover had increased from 117 to 1,176 times per month; (3) machine installation time had reportedly been reduced from 45 days to 30 days. Although the equipment engineers could see the benefits of Discover, their enthusiasm was not shared by the field engineers, who constituted the majority of users. The field engineers typically had the following concerns:

> 'What is stored in Discover only reveals one piece of the jigsaw. Most of the time, when solving a problem, I have to keep several balls in the air while receiving more balls from other people … Discover is pretty static and not very applicable to my work.'

At the end of 2002, despite the provision of more training sessions by the head of the KM Team, with the aim of helping field engineers to better 'decode' (interpret) the tips, field engineers still showed no interest in Discover. In April 2003, the KM Team was dissolved, owing to the lack of support from the key stakeholders — the field engineers.

Why did the equipment engineers find Discover useful, while the field engineers considered Discover inapplicable to their work practices, even though they supported the KM initiative generally? This question becomes the core of our investigation. This case is relevant to the analysis of the problems of knowledge management and technology adoption for two reasons. First, as the project lasted for more than two years, it provides a rich context for understanding system adoption difficulties. Second, the complexity involved in the field engineers' troubleshooting tasks provides an opportunity for analysis of the complex relationship between practices and work contexts.

Data Collection and Analysis

In analysing the engineers' practices and work contexts, we adopted a process-tracing method to guide our theoretical development (Langley 1999). Following an ethnographic approach (Golden-Biddle and Locke 1993), our data gathering was concentrated on engineers' practices — i.e. machine maintenance and troubleshooting activities (Orlikowski 2000). Personal interviews were conducted with the managers, equipment engineers and field engineers in the company's offices and those of its clients located in Taiwan

Table 1. Summary of the Interviews Conducted

Numbers of Interviews (Frequency)*	March–April 2002	May–November 2002	January–August 2003	January–May 2004	Total
Knowledge management department	3	1	3	0	7
Field engineers based in ChipFab and field engineers based in the client firm	10	5	14	2	31
Equipment engineers	5	0	9	6	20
Total	58 persons (78 times)				

* Some key respondents were interviewed more than once.

(see Table 1). On average, each interview lasted between one and two and a half hours, during which field notes were taken. Since the interviews often involved confidential information, most of them were not tape-recorded.

There were three major data-collection rounds. First, managers (KM heads, consultants and administrators) were consulted, in order to understand the company background, transfer conditions and system performance. Through such discussions, it was established that ChipFab engineers had a friendly knowledge-sharing culture and were receptive to many previous technological innovations. Additionally, the company incorporated a steering committee consisting of four senior executives, the purpose of which was to secure top management support. A volunteer change agent was appointed in each department to promote the submission and retrieval of best practice tips in Discover.

Second, the knowledge stored in the system was examined. Through our access to Discover, where 'best practice' tips were posted and shared, providing us with important information about knowledge content, we learned that the tips were of the knowledge-as-object type. For the equipment engineers, the system stored tips relating to their installation practices (e.g. how to assemble a machine for a particular fabrication process). The field engineers were asked to document tips regarding 'device knowledge' (e.g. how to repair circuitries) and 'procedure knowledge' (e.g. the steps involved in diagnosing a wafer defect).

Third, data were gathered to interpret engineers' practices through two reiterative stages: first-order and second-order analysis (Van Maanen 1979). In the first-order analysis, the practices performed by the two groups of engineers were traced. Based on the 'empirical interface' framework (Figure 1), data were coded according to the three contexts: (1) in the technical context, we examined how engineers maintained an individual machine and the way in which the machine might be affected by the whole production system (i.e. installation vs. the fabrication process); (2) in the social context, we examined how engineers collaborated with other communities-of-practice to solve problems stemming from individual machines and the production system; (3) in the innovative context, the way engineers dealt with the changing relevance of repair principles was examined. In each interview, the engineers were asked to describe their maintenance stories. These questions included, for example: (1) In a repair task, when you could not find any problem with the machine, what did you do? Why did you choose to inspect another machine? How did these machines relate to the whole maintenance process? (2) Who did you work with to solve the problem? Why did you ask these experts to join the troubleshooting task? What did these experts contribute respectively to the troubleshooting project? (3) How did the new product-design and fabrication processes affect your repair task? The practice-related data were analysed by reconstructing a generic process in which the engineers maintained machines (Tables 2 and 3). To make the complex repair processes understandable, the work sequences were demarcated by artificial time periods, to illustrate how a typical troubleshooting process might be affected by fabrication processes, human collaboration and product innovation.

With the equipment engineers, personal interviews were conducted and directive documents were reviewed to understand the installation process. Since we were unable to follow the engineers on-site, in each interview, they were asked to recall a recent maintenance task, draw out the installation process, and explain the detailed activities involved. For the field engineers, a different technique was employed, as their troubleshooting practices were more sophisticated. One troubleshooting project (out of eight) was selected for in-depth investigation, owing to the more complete nature of the data (e.g. data could be found on project participants who were based in different departments, regions and disciplines). The 'wafer high-particle' project, which ran for approximately 45 days (Table 3), was used to illustrate a typical repair practice conducted by the field engineers. It took roughly six months for the main participants (in ChipFab and its client sites) to be traced.

On average, on-site observations were conducted on a weekly basis during May to November 2002, January to August 2003, and January to May 2004, during which time we traced selected troubleshooting events and talked to participants over lunches and dinners. To understand better the engineers' repair tasks, check data validity with the informants, and ensure that the analysis of 'embeddedness' aligned with the experiences that engineers had gained in their work process, discussions were developed with selective interviewees by telephone or email, as well as through an in-house seminar with senior executive and field engineers on the Singapore site (about 25 persons). The field engineers affirmed the authenticity of the case scenario and the technology adoption problems that were also encountered in the Singapore and Malaysia sites. Their inputs helped us both to improve our interpretation of the engineers' practices and to detail specific practical implications. However, there was a potential weakness in our analytical method: our understanding of work practices came primarily from the tracing of repair incidents through personal interviews and on-site observation. We were unable to participate in the engineers' work practices in situ, leading inevitably to limited analysis of those practices (cf. Tyre and von Hippel 1997).

The second-order analysis explored the patterns in which practices were embedded in the three work contexts (Table 4). The data (two sets of practices) were coded according to three themes suggested by Barley's (1996) framework: the technical context (linear vs. dynamic production processes), the social context (single vs. multiple expert communities), and the innovative context (stable vs. rapid pace of innovation). On this basis, knowledge transfer problems were analysed in the technical context, knowledge coordination problems in the social context, and knowledge reuse problems in the innovative context. Understanding these three problems helped us to assess the applicability of Discover in the two work contexts.

First-Order Analysis: Practices within Work Contexts

The first-order analysis traced the developmental process of the engineers' practices within three working contexts. The engineers' practices were analysed in relation to the division of labour, the boundary-spanning activities within the expert communities, the transparency of work, and location issues. Although the description of maintenance work included a number of technical terms, we attempted to use generic terms where possible, in order to clarify the terminologies.

The Equipment Engineers' Practices

Equipment engineers assemble the major components of a fabrication machine in-house and, upon completion of preliminary testing, they install the machine at the client's site. On average, machine installation takes one month of full-time employment for an engineer. The installation process is divided into three-tier stages involving a sequence of assembly tasks (Table 2).

At the first-tier stage, equipment engineers devise the physical layout according to the fabrication site. The task involves setting up utilities such as water, electricity, ventilation and gas. At the second-tier stage, equipment engineers install the mainframe and chamber of the machine following a sequential order. The installation task requires collaboration among three expert groups specializing in mechanical, chemical and electronic engineering. At the third-tier stage, equipment engineers fine-tune the machine's operating parameters with regard to voltage, water, temperature and gas. These parameters are adjusted in order to support the pilot testing of microchip fabrication. Equipment engineers refer to the third-tier practice as a 'marathon', often involving more than three engineers working in shifts to monitor the fabrication machines for three to four weeks. A pilot production usually lets the machine fabricate 2,500 wafers, for which test data will be extracted to assess the machine's performance. In these activities, equipment engineers depend on the SOP (Standard Operation Procedure) and other directive documents to perform machine installation. As one engineer noted:

> 'This is the groundwork for us. The SOP documents help [us] accumulate battle experience [i.e. installing the machine]. The SOP is the Bible for [our] learning-by-doing … More than 80% of the problems can be tackled by using the SOP.'

Table 2. The Typical Practice of an Equipment Engineer

Period	Practice	Issues Observed from the Working Context		
		Technical context	Social context	Innovative context
Period 1: Days 1–2	In the Tier 1 stage, the equipment engineer investigates the physical layout of the fabrication site and sets up utilities.	The engineer follows a standard procedure to lay out the physical settings.		The industry has outlined standard procedures for machine installation.
Period 2: Days 3–9	In the Tier 2 stage, the equipment engineer installs the ‘mainframe’ and ‘chamber’ of a machine. The installation task follows the directive manuals. Three groups of experts work together and assemble the machine in a sequential order.	The engineer follows SOP to assemble the fabrication machine.	Experts from mechanics, chemistry and electronics work together to assemble the machine.	The three groups of experts follow a consistent set of repair principles set by the manufacturing company.
Period 3: Days 10–30	In the Tier 3 stage, the equipment engineer fine-tunes the machine’s operating parameters with regard to voltage, water, temperature and gas. These parameters are adjusted to support a series of fabrication tests.	The engineer examines test results, identifies any cause–effect relationships, and decides how to adjust assembly or maintenance work.		The engineer communicates findings through structured written reports.

Discover proved to be a useful source for searching relevant ‘recipes’ for machine configuration. In setting up machines for a fabrication process, equipment engineers must fine-tune a set of parameters, known as a ‘recipe’, before test-running a machine. Each machine requires a set of optimal recipes to perform smoothly. For instance, to set up a thin-film processing machine (which implants ions into semiconductors), equipment engineers need to control two important parameters: voltage and the implanting angle. If the voltage is too high, the implanting ions will spoil a wafer; if they are too low, the rate of implantation of ions will be slowed down, possibly threatening the quality of the wafer. Through trial-and-error, equipment engineers may identify a set of ‘optimal recipes’ for machine installation. When an optimal recipe is documented as a best practice tip, it can save time in fine-tuning the parameters in another similar machine set-up.

For the equipment engineers, Discover provided an effective method for documenting step-by-step procedures, applying explicit measures (e.g. how long N_2 gas should stay in the chamber), and assessing generalizability (how this tip could be applicable to other machine models). The Discover tips were also used to mentor junior engineers and shorten their learning curves. As one senior engineer explained:

> ‘The tips are systematically organized in Discover by model types and installation procedures. I can easily find relevant information to assist my troubleshooting. For example, if there is a gas leakage problem, I can follow the tips to inspect five possible sources of dysfunction sequentially … Normally it would take us one year to train a PVD (Physical Vapour Disposition; see Figure 2) engineer. With Discover, we only need eight months now.’

The Field Engineers’ Practices

Field engineers undertake maintenance through on-site troubleshooting, maintaining machines operating within a dynamic fabrication system. The microchip fabrication process consists of four generic modules (Figure 2). (1) In the Diffusion module, the insulating oxide films are deposited on a wafer (a thin disk) of silicon to create the transistors. A photosensitive coating, called photoresist, is spun over these films. (2) In the Photo (or lithography) module, the photoresist is exposed with a machine called a stepper, which projects light through an optical lens, via a mask, to print patterns of electronic circuits repeatedly onto the wafer. Each pattern is printed on one microchip — typically, more than 200 chips can be fabricated on a wafer. Subsequently, the lithography procedure removes the exposed photoresist, delineating the spaces where different conducting layers interconnect. (3) In the Etching module, the areas unprotected by photoresist film are etched by gas or liquid, so that the oxide film is cut through, and electronic contacts to transistors can be produced. (4) In the Thin-film module, these areas are implanted with ions to create transistors. The transistors are connected by adding metallic layers and insulators through similar cycles (repeating modules 2–4). Depending on the complexity of wafer design, a microchip product consists of 100–400 combinations of fabrication procedures, applying the four generic modules.

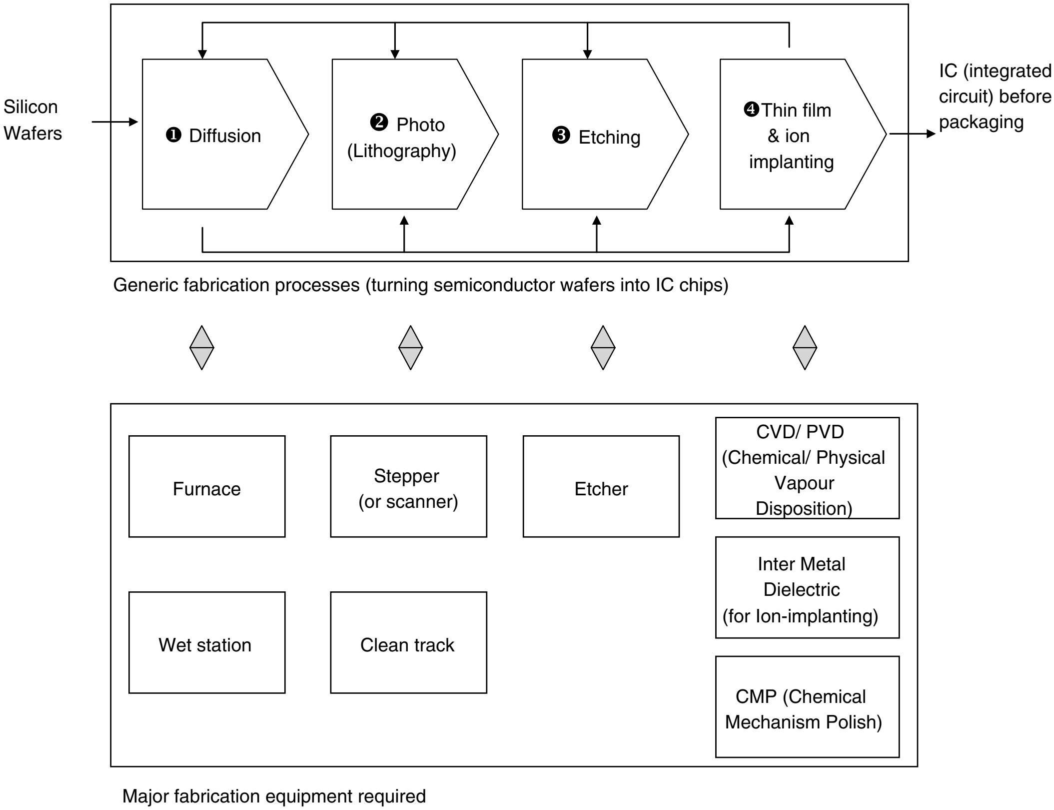

Figure 2. Microchip Fabrication Processes and Machines (based on ChipFab's investigation)

In this fabrication system, problems detected in one machine could be derived from any machine operating in the fabrication process.

In this complex fabrication, field engineers collaborate reciprocally with different expert groups ranging from specialists in electronics, physics, chemistry and mechanics to materials sciences. This is done for two reasons: first, in the technical context, the fabrication process is interactive and has varied degrees of sophistication in product design. Hence, each process requires engineers to hold specialized know-how. Equipment engineers, in contrast, are situated in a linear installation process which requires less fabrication-related knowledge. Second, in the innovative context, field engineers are required to experiment with different analytical techniques and diagnostic methods, requiring them to work with different expert groups. In contrast, the equipment engineers' analytical techniques and diagnostic methods are mainly based on standard maintenance procedures. This requires them to work only with specific expert groups.

Field engineers form ad hoc groups to respond to problems stemming from a variety of situations. Moreover, the rapid innovation in microchip products results in new machines and fabrication processes, rendering troubleshooting unpredictable. Often, this means applying new analytical techniques in order to accomplish repair tasks. Not surprisingly, it takes more than three years working on-site to become a competent field engineer and seven years to become a senior field engineer. The following repair incident describes typical practices performed by field engineers (Table 3). The incident is based on an authentic repair job that has been reconstructed by tracing an actual case of troubleshooting.

Period 1: Standard inspection (Day 1)

Samuel and Ben are engineers who maintain HDP CVD (High Density Plasma — Chemical Vapour Deposition; see module 4, Figure 2) machines in Alpha (a major client of ChipFab). In one case, they had to test-run a mass production of 12-inch wafers. During the Ion-showing procedure (module 4, Figure 2), the CVD machine produced more than 300 particles (like dust) on the wafer; this was considered abnormal because the wafer would be rejected if there were more than 200 particles. Samuel and Ben first checked the machine and used a chemical compound to cleanse the machine chamber. This did not work, so they purged the chamber with cleansing gas. The test result was normal, but the machine still produced particles during the fabrication.

Period 2: Preventive maintenance (Days 2–8)

Samuel and Ben began the preventive maintenance procedure, which involved mechanical inspection, to see whether the problem was caused by worn components. As this inspection was unfruitful, they turned to high-temperature inspection, which involved heating the machine to 662–842°F and purging gases in it. This was intended to ascertain whether the particles were caused by gas under high temperature. Again, the problem was not solved. Accidentally, Samuel found a worn component inside the chamber, called a ‘susceptor’ (containing aluminium), which is used to produce heat for wafers. Thinking that this might be the root cause of the problem, Samuel changed the component. However, the problem still persisted. Ben examined the parts using computer-image analysis (transformation) and found that the susceptor was in good working condition.

Period 3: Composition analysis (Days 9–11)

Samuel and Ben further performed a laboratory test and analysed the chemical compound of the particles. Finding an aluminium reaction, they surmised that it must be a problem caused by another susceptor. Replacing the susceptor, they found that the high-particle problem was eliminated under test production. However, the problem returned soon after the start of mass production. To further investigate the situation, Ben posted the problem on the intra-firm website and requested assistance. Samuel also rang his friends in the Science Park and contacted Simon, a field engineer of ChipFab, for assistance.

Period 4: Improvised troubleshooting (Days 12–19)

Simon organized a series of teleconferencing sessions and invited field engineers from Japan, Korea, Singapore and the USA for support (the social context). Eventually, after three days, a Korean engineer, who reported that

Table 3. The Typical Practice of a Field Engineer

Period	Practice	Issues Observed from the Working Context		
		Technical context	Social context	Innovative context
Period 1: Day 1	The field engineer performs a standard inspection by checking the 'recipe', and by machine cleansing. The particle problem persists.	The engineer follows routine procedures to identify the problem.		
Period 2: Days 2–8	The field engineer inspects the impact of temperature, pressure and electricity on wafer fabrication. The particle problem still persists.	The engineer investigates individual components.		
Period 3: Days 9–11	The field engineer performs a laboratory test to analyse particle composition. A component is replaced, and in the test run the particle problem is eliminated. But when mass fabrication begins, the particle problem reappears.	The engineer examines the fabrication systems, in order to explore the problem occurring in individual machines.	The engineer collaborates with people from the same community of practice (repairing the same machine model).	
Period 4: Days 12–19	The field engineer collaborates with colleagues from different countries. Together, they suspect that the problem might be associated with the chamber lid. But later they find that the chamber lid is irrelevant to the particle problem.	The engineer begins to examine problems along the interactive fabrication process.	The engineer collaborates with members across international boundaries.	
Period 5: Days 20–28	The multidisciplinary team examines the chamber lid structure and particle pattern. The team surmises that the problem could be related to a particular component (backing plate). The particle problem disappears during the test run; but after a few days, the problem reappears.	The taskforce team continues to troubleshoot along the fabrication process and examines machine-to-machine interfaces.	The taskforce team is expanded and more domain experts are involved, in order to increase the chance of identifying the problem.	The product life-cycle is very short. The 'recipe' for supporting different fabrication processes is constantly changing.

Continued

Table 3. The Typical Practice of a Field Engineer (continued)

Period	Practice	Issues Observed from the Working Context		
		Technical context	Social context	Innovative context
Period 6: Days 29–35	Collaborating through many teleconference meetings, the team decides to trace other fabrication processes. It examines those processes where the particle problem does not occur, and narrows down the search to the IMD machine (which involves aluminium fabrication). An inspection reveals no problem.	The team seeks problems along different fabrication processes. In such an interactive system, the cause-effect relationship is not always obvious.	The team has incorporated up to 31 people to examine the problem; this provides boundary-spanning activities.	
Period 7: Days 36–45	One engineer who maintains the IMD machine joins the troubleshooting team. He suggests a comparative analysis of 8-inch and 12-inch IMD machines. The team compares every component and eventually finds that the problem is caused by a new component in the 12-inch IMD that produces intangible chemical compounds.	The team traces the whole fabrication process and finally narrows down its analysis to the IMD machine.	The multidisciplinary team involves different domain experts who specialize in different machines and fabrication processes to complete the maintenance task.	The microchip industry has a rapid pace of innovation. It is difficult to accumulate repair knowledge, as a new machine model is often attached to various new fabrication processes.

he had had a similar experience, suggested employing a particular recipe to test chamber pressure. A pressure test indicated that Chamber D, one of six chamber lids inside the CVD machine, produced an abnormal quantity of particles. Simon, Samuel and Ben invited another nine engineers from Alpha and eight engineers from ChipFab — all of them specialized in dealing with CVD machines — to form a troubleshooting taskforce.

Period 5: Collective troubleshooting (Days 20–28)

The troubleshooting task force inspected the various components of the chamber lids. Since the distribution pattern of particles was similar to the shape of a 'backing plate' (a component of chamber lids that injects ions into a wafer), engineers surmised that this component might be the cause of the high-particle problem. Although the problem disappeared during the test run and mass production, after a few days it recurred, indicating that replacement of the 'backing plate' was clearly not the solution. Having been briefed on the problem, the technical manager of the CVD Department, Steven, asked the team to trace the previous fabrication processes while contacting suppliers to trace component quality.

Period 6: Interactive fabrication processes (Days 29–35)

Since the analysis of particles indicated metallic reaction, the investigation led the team to narrow down the search to the thin-film module (module 4 in Figure 2). In this module, an IMD (Inter Metal Dielectric) machine was used to develop a metallic connector in the microchip. The team examined different machines connecting the fabrication line. Soon, seven more process engineers from Alpha and four field engineers from ChipFab — specialized in different machines — became involved, increasing the number of engineers from different disciplines working reciprocally on the task to 31.

Period 7: Exhaustive analysis of the IMD machine (Days 36–45)

At one meeting, a process engineer expressed his confusion because in his previous experience, this kind of problem had never occurred in the fabrication of 8-inch wafers. This jogged the memory of another engineer, who suggested a comparative analysis of the two IMD machines. The team went through an exhaustive comparison of every single part within the IMD machine used for 8-inch and 12-inch wafer fabrication. Eventually, the team found that this IMD machine was a new model with new components to accommodate the new microchip design and fabrication process. Using the new 'recipe', the components produced intangible chemical compounds when the IMD machine developed metallic connectors in silicon chips during the thin-film process. As the spoiled wafer was processed to the next module and interacted with the CVD under high temperature and pressure, the particles were 'enhanced'. It took the team approximately 45 days to solve this machine dysfunction, which was found to have stemmed from another machine in previous fabrication processes.

Second-Order Analysis: Two Patterns of Knowledge Embeddedness

The second-order analysis compares the practices of the two groups of engineers in three work contexts. In each work context, three major issues are discussed: knowledge transfer, knowledge coordination, and knowledge reuse (Table 4). Discover was rejected by field engineers, not because there were significant knowledge barriers (e.g. a lack of an incentive mechanism), but because field engineers considered the system inapplicable to their maintenance work. The following subsections examine the two distinctive patterns of practice between the equipment engineers and field engineers in three working contexts.

The Technical Context: Linear vs. Interactive Complexity

In the first dimension, we examine the engineers' practices embedded in the technical context. In maintaining a machine, the engineers deal with different degrees of task complexity in the respective technical systems. Equipment engineers conduct repair tasks within an assembly system characterized by 'linear complexity'. In this linear system, the repair task consists of an expected maintenance sequence that is relatively visible, even if it is unplanned (e.g. the Tier 1–3 sequence of machine installation). Equipment engineers perform maintenance work in a step-by-step fashion following directive documents, utilizing Discover as a complementary extension to such documents.

By contrast, field engineers carry out their repair jobs in a technical system that is characterized by 'interactive complexity'. In this interactive system, machine maintenance consists of unfamiliar and unexpected maintenance sequences that may not be immediately comprehensible. Such repair tasks often involve interactive feedback between machines within a particular fabrication formulation. For example, in the particle-high problem, field engineers' practices are embedded in the tightly-coupled fabrication process, where machines interact with each other following a complex, interactive fabrication sequence. Field engineers have to deal not only with the problematic machine, but also with the way it may interact with other machines residing in the entire fabrication system, which typically takes 400 different combinations of the four generic modules (Figure 2). In such a fabrication system, one problem in a single machine could be caused by interacting problems in other machines in the previous modules. It is necessary for field engineers constantly to troubleshoot within machines and between machines (in different fabrication steps), as one field engineer explained:

> 'I can solve problems with a single machine within three days. But problems are often created in previous fabrication processes. Many times, I have to trace back to more than five or six fabrication procedures ... and the analysis is often undetermined.'

In the previous troubleshooting example, Simon (whom we shadowed in this research) concluded:

> 'This is still not the most complex repair task. In other cases, I have had to trace more fabrication steps and deal with more complex problems with wafer materials and

Table 4. Two Patterns of Knowledge Embeddedness

Work Contexts	Pattern 1 The Equipment Engineer	Pattern 2 The Field Engineer	Knowledge Management Issues	Implications for Knowledge Management System Design
Technical Context	Linear complexity — in assembly process	Interactive complexity — in the fabrication process	Knowledge transfer problems: Knowledge is embedded in interactive fabrication processes, in which repair practices are fairly incomprehensible and difficult to articulate through structured documentation. The field engineers can codify only fragmented device knowledge and procedural knowledge.	Document strategic knowledge and provide a comprehensive story to trace the logic of repair. Capture unique strategies developed by senior engineers to tackle the problem.
Social Context	Pooled/sequential mode of collaboration — the repair practice involves three groups of experts	Reciprocal mode of collaboration — the repair practice involves multiple expert communities in a dynamic manner	Knowledge coordination problems: It is not easy for the field engineer to integrate what he knows, as knowledge is often contributed collectively by other experts distributed in the social network.	Document search expertise and pattern of knowledge distribution — of who knows what and where (suppliers, machine-related experts, discipline-related experts, and process experts). Map out the social network and document the troubleshooting stories to show how to seek help from different expert communities in different problem scenarios.
Innovative Context	Stable rate of innovation in machine assembly — the knowledge of installation-related maintenance is relatively continuous	Rapid pace of innovation in the product and fabrication process — the knowledge of fabrication-related troubleshooting is relatively discontinuous	Knowledge reuse problems: In this fast-moving industry, the rate of innovation (e.g. new products and fabrication methods) is rapid. Hence, the repair principle accumulated in maintaining one machine is often not transferable to the next-generation model.	Be careful to document the troubleshooting practices which relate to new machine models, new product designs, and new fabrication processes. Use such information to reflect on maintenance situations where unlearning is required.

machine components. I still have a bag of these unsolved problems ... I am swimming in a sea of complexity. How can I describe all these interconnected problems in the best practice tip? … I mean, how can a fish describe water?'

This gives rise to the problem of knowledge transfer. Working in the linear assembly system, equipment engineers are able to articulate the sequence of repair practice in a Discover tip. However, working in the interactive fabrication system, field engineers can only describe the end-solutions in a 'best-practice' formulation that provides a list of trivial repair tips. Naturally, field engineers find these tips less useful because the contents consist of fragmented device knowledge and procedural knowledge that misses the developmental process of troubleshooting.

The Social Context: A Pooled/Sequential vs. Reciprocal Mode of Collaboration

In the second dimension, the engineers' practices are also embedded in a social context characterized by different modes of human collaboration. Equipment engineers' practices involve a pooled/sequential mode of collaboration. In the pooled mode of collaboration, participants may accomplish work independently; in the sequential mode, participants have to pass on tasks following particular workflows. As long as there is no significant corresponding withdrawal of resources, the others can continue to work without disruption (the pooled mode of collaboration). Equipment engineers pass on their maintenance tasks to other engineers in the three-tier stages (the sequential mode of collaboration). Moreover, to accomplish repair tasks, equipment engineers collaborate with three specific groups of experts (i.e. specialists in mechanics, chemistry and electronics) in specified sequences. The coordination of knowledge is relatively predictable in this social system.

In contrast, to accomplish an evolving repair task, field engineers engage in a reciprocal mode of collaboration within the multiple expert communities. In the reciprocal mode, participants have to work closely with mutual adjustments. They provide each other with assistance in no particular predefined sequence, as problems in one machine could affect the downstream as well as the upstream of fabrication. In fact, for field engineers, the concepts of upstream and downstream are no longer meaningful, as they feed work back and forth to each other during troubleshooting. One engineer described such repair work as a similar situation to that of medical doctors carrying out emergency surgery:

'Writing a tip only gives you a snapshot of the problem. In a typical troubleshooting, I am engrossed in all sorts of machine parameters. I have to talk to a lot of people working around the machines, in order to find out the possible culprits [the root problems]. It is an ER [Emergency Room] situation; and we are like the medical doctors [in relation to the machine]. By the time the job is done, I know that I know everything [about the troubleshooting] but I can hardly write anything about it.'

For field engineers, knowledge is distributed in the social context in which various professional communities are based. One engineer (maintaining PVD machines) explained that most repair work requires assistance from multidisciplinary experts within and outside the company boundary:

> 'The fabrication of microchips involves multidisciplinary knowledge. I cannot possibly know everything about semiconductors, such as knowledge of electronics, physics, chemistry, mechanics, and materials sciences, to name just a few … Besides, to solve a problem, we also need to work reciprocally with experts specialized in different machine models, component suppliers, and fabrication-processes distributed in clients' organizations.'

This gives rise to knowledge coordination problems. When field engineers complete maintenance jobs, it is difficult for them to articulate how they coordinate knowledge gathered from collaborating with multiple, ad hoc expert groups. Effective troubleshooting depends on integrating knowledge through the boundary-spanning expert communities. Even if the practice could be recorded by one engineer, it would be only a snapshot — which is inapplicable for the dynamic repair tasks of field engineers.

The Innovative Context: Stable vs. Rapid Innovation

The semiconductor industry generally follows Moore's law, which states that the number of transistors on an area of silicon doubles every 18 months, and the cost per function of integrated circuits falls by half in about the same time (Hutcheson and Hutcheson 1997). One executive explained that ChipFab was facing two technological trends in microchip fabrication. The first was the fabrication of bigger wafers. The industry was shifting from 8- to 12-inch wafer fabrication, meaning that through almost the same process, more microchips could be produced in a single wafer. The second trend was smaller circuit width. For example, electronic components in these microchips initially measured 0.35 microns but were moving to 0.13 microns (most recently, there has been a move to 90 nano-scale); this meant that one microchip could contain 10 million or more transistors, with a circuitry size 500 times smaller than a strand of human hair. This has resulted in rapid product innovation, inducing fast-changing fabrication know-how. As a result, there is a shorter knowledge life-cycle in repair principles, as these principles are closely linked to the fabrication process. It is difficult for field engineers to accumulate repair tips that are constantly updated, as one engineer explained:

> 'The innovation is changing so fast that the new model of a machine is often incompatible with previous machines. That is not the worst thing; the worst thing is that we have to re-learn everything (repair principles — e.g. how to test particles in a wafer) about the new-generation machine. We are often unable to accumulate what we have learnt from maintaining previous models of machines.'

In this innovative context, field engineers' repair principles (the 'representation' domain) are less repeatable. Documenting such fluid knowledge in the form of Discover tips is considered to be less meaningful for field engineers. Another field engineer elaborated this point:

> 'I don't have the luxury to sit down and write down my best practice tips. Even if I could, the known method would soon become outdated. The Discover archives have no relevance to my present problems. I'm an engineer, not a historian.'

This gives rise to knowledge reuse problems. Although equipment engineers are working in the same industrial context, their focus is more on the installation of individual machines. Their repair principles are relatively stable and continuous because the assembly and subsequent maintenance work are independent of the fabrication system. Even if the design of a fabrication machine may be new, the principle of stand-alone machine maintenance is relatively stable, and is defined by industry standards. Equipment engineers could benefit from the accumulation of knowledge content. However, for field engineers, more new product designs, more efficient fabrication processes, and more powerful machines result in a set of new diagnostic techniques that make little reference to past knowledge. Therefore, field engineers have little to gain from Discover's contents.

Discussion

This study examines the practices of two groups of engineers, practices which are embedded in technical, social and innovative contexts. This embeddedness analysis allows us to understand better the knowledge transfer, knowledge coordination and knowledge reuse problems faced by the two different groups of engineers in their respective work contexts. The findings suggest that equipment engineers employ mainly object-based knowledge, and that Discover is aligned with their practices in maintaining individual machines, collaborating with specific expert communities, and accumulating know-how through structured contents. In stark contrast, field engineers employ practice-based knowledge, situated in a work context, where they need to deal with interactive fabrication processes, multiple boundary-spanning communities-of-practice, and the changing relevance of know-how. The research findings offer important theoretical and practical implications.

Theoretical Implications

The emphasis of current knowledge management research is on problems of knowledge transfer, coordination and reuse (Alavi and Leidner 2001; Sambamurthy and Subramani 2005). Previous analyses have largely examined these problems with regard to knowledge barriers, knowledge distribution, motivation issues and technology acceptance. However, there has been only scant attention to exploration of these problems in relation to the experts' practices and work contexts (cf. Lam 1997; Schultze and Boland 2000; Tyre and von Hippel 1997). This issue is especially important when knowledge transfer is facilitated by information systems (Huber 2001).

To fill this gap, this study examines the problems of knowledge transfer, coordination and reuse through an 'embeddedness' analysis. In examining knowledge transfer problems, the analysis of generic knowledge barriers is insufficient to understand why knowledge is sticky, contextualized and difficult to explicate (Purvis et al. 2001; Szulanski 1996). By examining the way knowledge is embedded in the wider technical context (e.g. maintaining machines within interactive fabrication processes), the findings suggest that knowledge content may be fragmented and no more than a snapshot ('one piece of the jigsaw'), rendering it inapplicable to field engineers' practices. The individual expert is unable to articulate the holistic troubleshooting process.

With regard to knowledge coordination problems, previous studies have stressed issues relating to knowledge location (Hansen et al. 1999), knowledge distribution (Hansen 2002), and knowledge interpretation (Boland and Tenkasi 1995). By examining the way practices are embedded in the social context (e.g. maintaining machines by working with multiple expert groups), the findings add that the experts' boundary-spanning activities also contribute to codification difficulties. Discover's tips are inappropriate to the needs of field engineers because they are unable to capture and integrate collective problem-solving practices embedded in a reciprocal mode of collaboration within multiple, ad hoc work communities.

Regarding knowledge reuse problems, previous studies have analysed motivational issues and different reuse situations (Markus 2001; von Krogh 1998). By examining the way practices are embedded in the innovative context (e.g. maintaining machines within a high-velocity industry), the findings also highlight the need to take account of renewal problems in building knowledge repertoires. The best practice tips are considered irrelevant because the rapid pace of product/process innovation outdates the repair principles so quickly that documenting them is of limited value.

By tracing engineers' practices embedded within their work contexts, this study uncovers new difficulties of knowledge management and system adoption. The failed adoption of knowledge management systems should not be examined solely through issues of technology acceptance. By analysing work practices, this study helps us to see why the same system may generate active adoption in one context, while resulting in failed adoption in another. Furthermore, the case is based on the semiconductor industry, thus extending our understanding of practice-based knowledge transfer to a new context (cf. Barley 1996; Orlikowski 2002; Tyre and von Hippel 1997).

Practical Implications

The findings also offer important practical implications. The embeddedness analysis suggests that a Discover-like system (transferring 'object-based knowledge') is useful for equipment engineers because the encoded device knowledge and procedural knowledge is aligned with the engineers' practices. However, in a work context characterized by interactive complexity, reciprocal collaboration and rapid innovation, field engineers need a new format for Discover to help develop their 'capability-based knowledge'. As discussed, we must note that capability-based knowledge needs to be acquired through learning-by-doing, e.g. through apprenticeship and by participating in communities-of-practice in situ (Brown and Duguid 1991; Lave and Wenger 1991; Orlikowski 2002). The Discover tips can only enhance the engineers' cognitive strategies, in order to strengthen their heuristics and shorten learning curves (Barley 1996). Therefore, our practical solutions are suggested with this limitation in mind.

By considering the three knowledge management problems, we propose three possible solutions to make the Discover-based contents more applicable for field engineers. First, to deal with knowledge transfer problems, the tips should be organized as 'repair stories' documenting 'strategic knowledge' (Gott et al. 1993) — the discovery of the process of troubleshooting — obtained by solving problems in different maintenance situations. The case of CALL (Centre for Army Lessons Learned, US Army) offers a useful point of reference (Thomas et al. 2001) in this respect. Here, battlefield knowledge is captured by interpreting the developmental process of a particular war experience. Instead of asking lieutenants and generals to submit their individual lessons learned in a specific example of warfare, CALL forms a task force consisting of various specialists with expertise ranging from weaponry, linguistics and history to psychology, anthropology, military science, etc. These specialists, using ethnographic methods, gather the army's field experience. Their emphasis is not so much on the structured content of each lesson learned in a particular battle; rather, the specialists focus more on the discovery process of each event — that is, learning how effective learning has been undertaken at critical points of time. CALL has achieved effective utilization through its knowledge systems because it transfers the 'strategic knowledge' considered useful in the field, rather than individual facts and events about warfare. In the spirit of CALL, ChipFab could appoint a group of 'repair story writers' to document how machine maintenance is developed throughout different fabrication processes. Since real-time case documentation is impossible for reasons of confidentiality, a retrospective case tracing using ethnographic methods could be useful. Such stories could provide a 'travel guide' to help engineers 'navigate the labyrinth of semi-conductor fabrication processes', as one chief knowledge officer of a major wafer maker suggested.

Second, to deal with knowledge coordination problems, ChipFab could include a social network map in each repair story. With this map, engineers would be able to understand the knowledge distribution in each problem situation (who-knows-what and where-to-locate-experts). More important, engineers could accumulate experience in managing boundary-spanning sharing activities, and elicit help from different expert groups.

Third, to deal with knowledge reuse problems, ChipFab could include points of unlearning in each repair story. This section should deliberately document any troubleshooting problems stemming from new products, new machines or new fabrication processes (e.g. the new IMD model used for 12-inch fabrication in the example provided). With this 'unlearning' information, engineers would be more sensitive to similar situations where repair problems should be sought by renewing analytical skills.

The findings also suggest that, when a knowledge management system is implemented, companies should not limit their efforts to initiate organizational changes (e.g. by introducing a voluntary change agent in this case), offering more training, and building incentives for better knowledge sharing (e.g. a $500–$1,000 reward for the submission of a tip). Without an appreciation of the problem of embeddedness, the incentives may actually promote counterproductive behaviour. For example, as we learned from our fieldwork, a leading fabrication company promoted a Discover-like system to different departments and offered a similar incentive scheme. However, this only resulted in a 'superficial adoption' of the system. Most engineers submitted tips by cut-and-paste knowledge appropriated from Internet sources. To ensure they could receive the reward, engineers also colluded to produce hyperlinks to each other's tips, and accessed one another's tips to demonstrate a high retrieval rate. This not only wasted the company's resources invested in the system (containing mostly cut-and-paste tips), but also reduced engineers' energy in carrying out repair tasks. Our study suggests that Discover was not rejected due to field engineers' ignorance and fear, or a lack of psychological ownership. Field engineers resisted Discover because it was inapplicable and misaligned with their work practices. An analysis of the problems of embeddedness would help the implementer to gain greater insight into difficulties in technology adoption.

As far as future research work is concerned, we suggest that further research should investigate the way this embeddedness analysis could be applied to the examination of other knowledge management systems adopted in high-velocity industries (e.g. the biotech and software industries). Additionally, researchers could analyse patterns of embeddedness in different work contexts (based in different industries). For example, professional service firms (which employ cognition-based knowledge) may provide a useful contrast to our findings (Hansen et al. 1999). These efforts could enhance our understanding of knowledge management problems associated with technology adoption.

Conclusion

Our research suggests that knowledge management problems and system adoption difficulties must be understood in relation to knowledge attributes (knowledge-as-object, knowledge-as-cognition, and knowledge-as-capability) and people's practices embedded in their work contexts. The analysis of embeddedness reveals three key knowledge-management issues: (1) problem-solving exercises in the technical context: a troubleshooting that stretches over two months in an interactive fabrication process is unlikely to be captured neatly in a structured knowledge repertoire; (2) multiple players (within different communities-of-practice) in the social context: a joint problem-solving process that involves a growing number of experts over time is similarly ill-suited for the representation of fragmented knowledge; and (3) the pace of change in the innovative context: as the troubleshooting case illustrates, field engineers had to search in many places for possible causes. Ultimately, the problem was hidden somewhere in the new machine operating in a new fabrication process. This is because the pace of innovation is very rapid in this high-velocity industry. Hence, the clues upon which the field engineers build may exhaust the most persistent 'if-then-else' coder. This study provides an alternative interpretation of work practices, knowledge management problems and technology adoption challenges. With such an improved approach, we may be able to understand better the interaction between practice and context, and the problems underlying knowledge transfer, coordination and reuse.

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