Journal of Operations Management 28 (2010) 303–315

Contents lists available at ScienceDirect

Journal of Operations Management

journal homepage: www.elsevier.com/locate/jom

Role of explicit and tacit knowledge in Six Sigma projects: An empirical examination of differential project success

Gopesh Anand [a,*], Peter T. Ward [b], Mohan V. Tatikonda [c]

[a] College of Business, University of Illinois at Urbana-Champaign, Champaign, IL 61820, United States
[b] Fisher College of Business, The Ohio State University, Columbus, OH 43210, United States
[c] The Kelley School of Business, Indiana University, Indianapolis, IN 46202, United States

ARTICLE INFO

Article history:
Received 26 November 2007
Received in revised form 5 August 2009
Accepted 23 October 2009
Available online 4 November 2009

Keywords:
Knowledge management
Organizational learning
Process improvement
Six Sigma
Tacit knowledge
Teams

ABSTRACT

This research develops a conceptual model for predicting success of process improvement projects as a result of knowledge-creation practices employed in the projects. The model is empirically examined in the context of Six Sigma black belt projects. New scales are developed to measure explicit- and tacit-knowledge-creation practices in process improvement. Data is gathered via a cross-sectional sample, and the hypotheses are tested using hierarchical regression. Our results support the notion that knowledge-creation practices influence the success of process improvement projects. Specifically, the inclusion of softer, people-oriented practices for capturing tacit knowledge explains a significant amount of variance in project success, as much as the more analytically focused practices that capture explicit knowledge. This research offers practical insights about the influence of practices that project managers use to create new knowledge by capturing explicit and tacit knowledge, and seeks to advance theoretical understanding of process improvement.

1. Introduction

Knowledge management continues to generate practitioner and academic interest (Boone et al., 2008; Edmondson, 2008; Nonaka and von Krogh, 2009). One of the more influential knowledge-management theories is Nonaka's (1991) theory of knowledge creation. Since its inception, this theory has inspired a large body of research (e.g., Arikan, 2009; Cook and Brown, 1999; Spender, 1996). However, application of knowledge-creation theory to tasks carried out by ad-hoc project teams, such as discovering process improvements, though pertinent, has remained largely unexplored (Haas and Hansen, 2007). Moreover, in general, there is a dearth of research looking into differential success rates of process improvement projects, although investigations into success factors for new product development projects have been undertaken (e.g., Gerwin and Barrowman, 2002; Swink and Song, 2007; Tatikonda and Montoya-Weiss, 2001). Thus, this research examines the effectiveness of knowledge-creation practices for success of process improvement projects.

The empirical context of process improvement projects involves some characteristics that warrant a unique perspective to applying knowledge-creation theory to the topic. Process improvement teams are ad-hoc teams put together for the duration of their projects and disbanded after completion of such projects. Typically, work on projects constitutes a fraction of team members' job responsibilities, and accounts for only a portion of their work-times. As a result of these conditions, there are few opportunities for interactions among team members other than project team meetings. Also, team members may not have worked with each other before coming together on a project, and may not formally work together after completion of the project. As such, the social ties among these team members are often not as close as those among team members that work together on portfolios of related projects, as is common in new product development and information technology contexts.

This has implications for the sharing of individual knowledge and its conversion into organizational knowledge (Choo et al., 2007; Siemsen et al., 2009). Thus, the application of knowledge-creation theory in process improvement team projects warrants investigation separate from studies of new product development projects (Boone et al., 2008; Zhang et al., 2004) and information systems projects (Lee and Choi, 2003; Sabherwal et al., 2006), where projects often have longer life-spans and/or more stable team memberships. The study of knowledge creation in process improvement projects also warrants separate inquiry from those conducted at the organizational level of analyses (Anand et al., 2009; Edmondson et al., 2003; Molina et al., 2007), as these studies

* Corresponding author. Tel.: +1 217 244 8051.
E-mail addresses: gopesh@illinois.edu (G. Anand), ward.1@osu.edu (P.T. Ward), tatikond@iu.edu (M.V. Tatikonda).

0272-6963/$ – see front matter © 2009 Elsevier B.V. All rights reserved.
doi:10.1016/j.jom.2009.10.003

do not deal with practices for creating knowledge but focus instead on the topic of a broader environment conducive to knowledge management.

There is a growing prevalence of process improvement initiatives that have the common characteristics of projects lasting for three to nine months, with each project led by a project methodology expert, and involving a diverse team constructed solely for the purpose of the project. Thus, we focus on the practices used by team leaders to extract and integrate knowledge of team members toward achieving project objectives. The topic of this paper is inherently multi-disciplinary because process improvement is central to Operations Management, while knowledge creation in teams, which also involves team dynamics and leadership, is central to Organizational Behavior. This study responds to calls for incorporating human behavioral issues in Operations Management contexts (Bendoly and Hur, 2007; Boudreau et al., 2003; Mantel et al., 2006).

1.1. Relevance of tacit knowledge

The theory of knowledge creation (Nonaka, 1991) is based primarily on Polanyi's (1966) categorization of knowledge as explicit and tacit. It prescribes the capture of both explicit and tacit types of knowledge, making it available to the organization in order to generate competitive capabilities. Explicit knowledge is codified knowledge articulated in words, figures, and numbers. It is objective, and relatively easy to share in the form of specifications, standard operating procedures, and data. Tacit knowledge is knowledge that has not been codified and is relatively difficult-to-codify. It is subjective and based in individual experiences.

Nonaka and Takeuchi (1995) point out that Western managers were more likely to overlook tacit knowledge than their Japanese counterparts, who were experts at capturing it. Particularly in the context of process improvement, the tendency to focus exclusively on explicit knowledge is exacerbated by the fact that most projects have objectives related to exploiting and controlling existing process capabilities (March, 1991; Schroeder et al., 2008). The tendency for leaders of such projects to concentrate on explicit knowledge that is easier to capture, while getting blindsided by tacit knowledge that may be relevant, makes it important for practice and academia to examine the missed opportunities that may result from ignoring tacit knowledge.

1.2. Empirical context of Six Sigma projects

The Six Sigma process improvement initiative originated in 1986 from Motorola's drive toward reducing defects by minimizing variation in processes, which in turn required explicit measurement of solid metrics (Kumar and Gupta, 1993). Applications of the Six Sigma project execution methodology have since expanded to include more explorative objectives, such as increasing customer satisfaction, or developing closer supplier relationships, and the use of softer practices, such as brainstorming and "five-why" analyses to capture tacit knowledge of project team members (Hoerl, 2001). The question that remains unanswered is whether the use of tacit-knowledge-capturing practices provides a higher degree of project success.

Thus, our research is motivated by two main issues: (1) the application of knowledge creation to explain differences in success levels achieved by process improvement projects; and (2) the potential benefits of practices to capture the more-often ignored, and more difficult to include, tacit knowledge. Although the setting for our empirical investigation is Six Sigma projects, the results of our study are applicable to other process improvement initiatives, such as total quality management (Mukherjee et al., 1998) and lean management (Shah and Ward, 2007). Broadly, the domain of this research is participative team projects for process improvement under the guidance of leaders who are trained in project execution practices.

We begin by relating knowledge creation to Six Sigma process improvement projects in Section 2. In Section 3, we develop our conceptual arguments, and present hypotheses that relate practices for capturing explicit and tacit knowledge to Six Sigma project success. Section 4 describes the development of our survey instrument and the empirical methodology used to test our hypotheses. We present the results of our analyses in Section 5, followed by a discussion of the implications of these results for theory and practice in Section 6. Section 7 concludes the paper by addressing limitations and directions for future research.

2. Knowledge creation and Six Sigma

The knowledge-based view of business strategy supports the notion that knowledge can be a valuable resource for competitive advantage; see, for example, Argote et al. (2003) and Kogut and Zander (1992). By creating new knowledge about processes, and increasing their productivity, process improvements contribute to the competitive positions of organizations (Shah and Ward, 2003; Zu et al., 2008). The underlying principle for process improvement projects is looking beyond reactive corrections of processes to root causes for problems and to opportunities for enhancements. Thus, knowledge creation provides an appropriate lens through which we can study process improvement projects.

2.1. Explicit and tacit knowledge types

Nonaka's framework (1991, 1994) provides a rationale for the use of knowledge-creation practices to generate group knowledge by engaging individual team members in process improvement projects. The framework depicts the process of knowledge creation as cycles of conversions between two types of knowledge—explicit, and tacit (see Fig. 1). It is worthwhile to note that this classification of knowledge as either explicit or tacit is one of two prominent classifications in the knowledge-management literature (Table 1

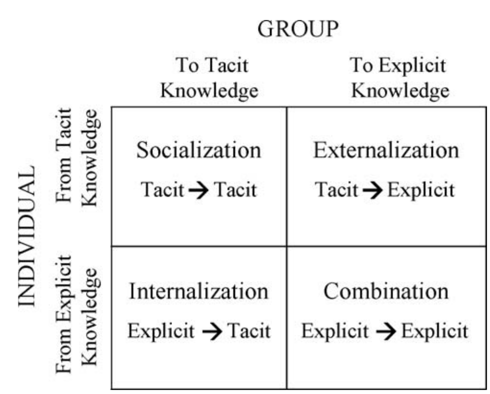

Fig. 1. Nonaka's (1991, 1994) framework of knowledge-creation mechanisms.

Table 1
Selected classifications of knowledge-creation mechanisms.

Author(s)	Year	Knowledge-creation mechanisms
Argyris	1977	Single & double loop learning
Nonaka	1991	Combination, internalization, socialization & externalization
Kogut and Zander	1992	Knowing-what & knowing-how
Kim	1993	Operational & conceptual learning
Spender	1996	Capturing individual and organizational knowledge
Nahapiet and Ghoshal	1998	Acquiring intellectual & social capital

provides a brief overview of different classifications of knowledge-creation efforts). The other established classification is based on whether knowledge addresses the questions of "know-what" (dealing with facts, concepts, and generalizations) or "know-how" (dealing with skills, procedures, and processes) (Kogut and Zander, 1992). Know-what knowledge is described as being similar to a "list of ingredients," and know-how knowledge is compared to a "recipe" (Kogut and Zander, 1992). While a recipe (know-how) includes explicit instructions, it also has tacit elements that cannot be expressed completely in the form of instructions. Given that the domain of our research is process improvement projects, which deal mainly with know-how types of knowledge, we adopt the explicit–tacit classification in this study following Edmondson et al. (2003). We focus on practices used by team leaders to capture explicit and tacit knowledge of team members, and create new know-how knowledge for process improvement.

Explicit knowledge is codified and documented, and its transfer can take place in impersonal ways—for instance, through written instructions and diagrams. Tacit knowledge is knowledge that is difficult to articulate, especially in terms of cause–effect relationships. It is context-specific, and is transferred mainly through social interactions (Polanyi, 1966). Language is an excellent example of tacit knowledge: native speakers of a language are often unable to articulate the grammatical and syntactic rules governing it. Tacit knowledge contributes to the "stickiness" of information required for problem-solving, making it difficult for others to gather, transfer, and utilize (von Hippel, 1994). The difficult-to-codify nature of tacit knowledge contributes to difficult-to-imitate capabilities that may provide competitive advantage to the organization (Barney, 1995; Nahapiet and Ghoshal, 1998). Success of process improvement projects depends on the capture of both explicit and tacit types of knowledge.

2.2. Six Sigma projects

Process improvement projects involve the use of tools and techniques—project execution practices—to harness the knowledge of team members for specific objectives. The Six Sigma initiative contains one such organizational design, involving tools and techniques used to discover and execute process improvements with contributions of individuals (Schroeder et al., 2008). Six Sigma methodology experts, commonly known as "black belts," lead project teams that consist of employees across functional lines, and are connected to the affected process. Some team members routinely work on or manage the targeted process (e.g., an insurance sales agent or supervisor), while others work to support the process (e.g., an information technology expert who provides support to the insurance claims process). Unique project teams are put together for each of the projects, and disbanded after these projects are completed, handing off resulting improvement-actions to process owners—people who routinely operate the processes.

Although each project has different objectives and specific tools employed, overall these projects follow a standardized, structured five-phase project management approach known as "DMAIC" for Define, Measure, Analyze, Improve and Control phases (Schroeder et al., 2008). Project leaders are trained in the use of practices for collecting, combining, and synthesizing the knowledge of team members for use in process improvements (Hoerl, 2001). For example, as part of conducting projects, these leaders may be called upon to design simulations and conduct multivariate statistical analyses, as well as to lead focus groups and brainstorming sessions. Thus, in Six Sigma projects, a variety of practices may be used to capture explicit and tacit knowledge of team members for achieving specific project goals. Fig. 2 provides examples of such knowledge-capturing practices mapped onto mechanisms of Nonaka's (1991) knowledge-creation framework.

	To Tacit Knowledge	To Explicit Knowledge
From Tacit Knowledge	Socialization • Brainstorming • Nominal group technique • "Five why" analysis • Discovery phase for surveys	Externalization • Work breakdown structure • Fishbone diagram • Value stream map • Failure modes and effects analysis
From Explicit Knowledge	Internalization • Error-proofing • Control charts in the control phase • Training for frontline operators • Job rotation	Combination • Design of experiments • Multiple regression • Simulation • Quality function deployment (QFD)

Fig. 2. Six Sigma practices, classified by knowledge-creation mechanisms.

We examine the reasons for differences in success levels of Six Sigma process improvement projects. Six Sigma initiatives generally include projects with a broad range of specific objectives, such as yield improvement, cycle-time reduction, inventory reduction, streamlining supplier relationships, and improving customer satisfaction. Moreover, organizations may have differing benchmarks of success for their Six Sigma projects as a result of diverging levels of maturity in the deployment of their initiatives (Shenhar et al., 1997). Thus, we use the term "project success" to depict the level to which desired results are achieved. This definition is applicable across different types of projects, and covers the domain of project success for organizations in varying stages of Six Sigma deployment. The generality of this definition is appropriate for addressing the question of differential levels of project success achieved from the use of different knowledge-capturing practices within the same organizational context. We use the term "practices" to refer to tools and techniques used in the execution of Six Sigma projects, and develop our hypotheses based on Nonaka's (1991) categorization of four knowledge-creation mechanisms, two of which focus on capturing explicit knowledge, and two on capturing tacit knowledge.

3. Conceptual development

The topic of knowledge creation through process improvement projects has previously been addressed in the context of total quality management initiatives by Mukherjee et al. (1998). Focusing on technological knowledge, their study finds operational and conceptual forms of learning to be significant predictors of project success. Operational learning involves superficially learning how to run a process, and how to react to certain changes. Conceptual learning involves gaining deeper knowledge of cause–effect relationships. While Mukherjee et al.'s (1998) treatment of these variables focused on explicit-knowledge contexts, we incorporate the role of tacit knowledge. Thus, our research builds upon the research by Mukherjee et al. (1998), and evaluates the argument that capturing tacit knowledge in addition to explicit-knowledge results in higher levels of project success.

Becerra-Fernandez and Sabherwal (2001) studied the effects of Nonaka's (1991) knowledge-creation mechanisms on individual satisfaction with knowledge availability for day-to-day tasks within sub-units of the Kennedy Space Center. Results showed that some contingent task characteristics of the sub-units affected the relationship between knowledge-creation mechanisms and individual satisfaction. Our study makes a leap from individual satisfaction with knowledge availability for day-to-day tasks to achievement of success in team projects.

In another related study, the learn-what and learn-why classification of knowledge creation was used to research adoption of best practices in neo-natal intensive care units in hospitals (Tucker et al., 2007). While results of that study supported the effects of learn-how adoption practices on success of best practice implementation, learn-what practices were found to have no effect. As described earlier, the learn-how or know-how categorization of knowledge includes explicit and tacit dimensions. We focus on the explicit–tacit distinction, and develop hypotheses related to the value of capturing the two types of knowledge in process improvement projects.

3.1. Capturing explicit knowledge

Following Nonaka's (1991) framework, explicit knowledge can be captured either by sharing such knowledge through *combination* (explicit → explicit) practices or by making it tacit through *internalization* (explicit → tacit) practices (see Figs. 1 and 2). Combination (explicit → explicit) practices for knowledge creation make team members aware of explicit relationships between process elements through measurement of metrics and analysis of data (Zhang et al., 2004). These practices combine elements of explicit knowledge from different sources, reconfiguring and systematizing them to yield new explicit knowledge for the group (Constant et al., 1996). On the other hand, internalization (explicit → tacit) practices translate explicit knowledge into tacit knowledge so that it is commonly understood by the team and used to improve how work is being done (Choo, 1998; Grant, 1996).

In the context of Six Sigma projects, combination (explicit → explicit) practices are focused on making explicit knowledge easily accessible so that existing repositories of knowledge are reused (Snee and Hoerl, 2003). These practices include use of project report databases with search capabilities, such as Siemens' knowledge-sharing system described by Voelpel et al. (2005). Combination (explicit → explicit) practices are also focused on making sense of explicit knowledge to make it specifically useful for the process improvement project, e.g., through the use of software to compute correlations and through controlled experiments conducted to assess cause–effect relationships (Breyfogle, 2003).

Internalization (explicit → tacit) practices, used to capture explicit knowledge, converting it into tacit knowledge, include measures taken to adopt and understand best practices from other areas and projects (Tucker et al., 2007). They also include practices such as using control charts and error-proofing (*poka yoke*) procedures, which may indicate a need for tacit on-the-job corrections. For example, an operator may rely on the explicit information provided by control charts to make small adjustments to a manufacturing process, or, based on the unique needs of a customer, a bank teller may make adjustments to a standard operating procedure. Alternatively, explicit measurements that indicate errors may generate the need for team meetings to exchange tacit knowledge by brainstorming ideas about what may be wrong, why it went wrong, and how it can be corrected (Hoerl, 2001). In addition, learning-by-doing activities, such as on-the-job training, that are used to implement the results of projects also come under the category of internalization (explicit → tacit) practices (Becerra-Fernandez and Sabherwal, 2001).

Six Sigma project teams often deal with cross-functional and cross-divisional issues that warrant the use of integrative knowledge practices. In addition, the teams consist of members from diverse backgrounds who come together only for the duration of the project and, even while involved in a project, work only part-time on the project. Using combination (explicit → explicit) practices, project team leaders can help their teams sift through explicit data, drawing explicit insights about the targeted processes. In addition, internalization (explicit → tacit) practices make it possible for the explicit knowledge that is harnessed to be comprehended and absorbed by team members and people working on the processes. Such recombination of explicit knowledge and its conversion into tacit knowledge is critical for the creation of team knowledge about the working of the processes being targeted for improvement. Thus, our first set of hypotheses (H1) cover the importance of capturing explicit knowledge for the success of Six Sigma projects (see Fig. 3).

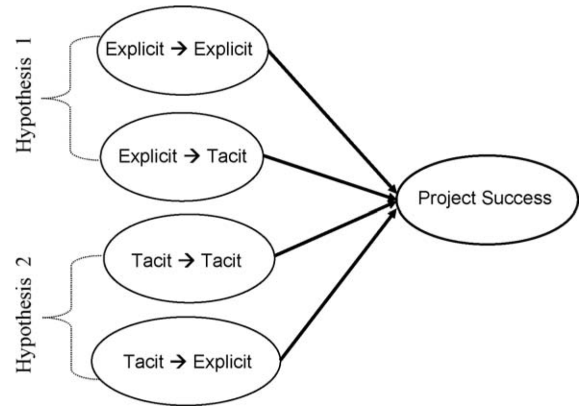

Fig. 3. Proposed conceptual model and hypotheses: Knowledge-creation practices as predictors of project success.

H1. The following knowledge-creation practices for capturing explicit knowledge contribute significantly and positively to Six Sigma project success:

a. combination (explicit → explicit knowledge), and
b. internalization (explicit → tacit knowledge).

3.2. Capturing tacit knowledge

According to Nonaka's framework (1991), *socialization* (tacit → tacit) practices are used to share tacit knowledge, and *externalization* (tacit → explicit) practices convert tacit knowledge into explicit knowledge. Socialization (tacit → tacit) practices combine individuals' tacit knowledge and create common understanding among group members about processes being investigated (Fiol, 1994; Weick and Roberts, 1993). The group-level tacit knowledge that is the outcome of such practices is not concrete enough to be expressed in comprehensible written or pictorial forms. On the other hand, externalization (tacit → explicit) practices enable the explicit expression of tacit ideas in the form of language and visual schemata. These practices convert tacit knowledge (held by individuals and the group) into explicit forms, such as written descriptions, objective numbers, or pictures and diagrams that facilitate group discussion and analysis (Bohn, 1994; Hansen et al., 1999).

Socialization (tacit → tacit) practices enable team members to incorporate each others' perspectives while coming up with ideas for the possible causes of defects being targeted, as well as ways to correct them. These practices enable individuals to express to each other their ideas in light of their experience; in some ways, they bring to the group individual insights about the problem at hand that others might not have even considered relevant had they remained in isolation. The verbalization of ideas is subject to immediate absorption and response by others. Socialization (tacit → tacit) practices are time-consuming, but they are richer in information and more effective because they ensure that the idea-generation of team members is not hindered in any way by communication barriers. There is nothing lost in translation into language or pictures, and any clarifications needed may be immediately obtained.

Externalization (tacit → explicit) practices enable individuals to express, summarize, and view explicitly the knowledge they have created jointly through the exchange and synthesis of tacit knowledge, thus creating common understanding. Further, externalization (tacit → explicit) practices assign explicit measurements to subjective performance attributes, thus facilitating assessment, comparison, and scientific experimentation. Expressing tacit knowledge, i.e., making it explicit through externalization practices, can aid the analysis of such knowledge before it is established that such knowledge should be used to improve a process (Raelin, 1997). While socialization practices generally require physical proximity and joint action, externalization practices can support communities of practice that transcend distances (Constant et al., 1996; Voelpel et al., 2005).

In the context of Six Sigma, socialization can be achieved through the inclusion of individuals in project teams from across functional, hierarchical, and even organizational boundaries (e.g., suppliers and customers), and by their attendance at team meetings. An illustration of the value of direct customer interactions is provided by international specialty chemicals company Buckman Laboratories (Zack, 2003), which entered into knowledge-sharing agreements with customers, undertaking projects to reduce their materials consumption. Buckman was able to leverage tacit knowledge, about how a few customers used their product as raw material, to service the whole customer segment. Further, when setting up their knowledge-management system, Buckman Laboratories recognized the importance of tacit knowledge and included opportunities for socialization (group conversations and one-to-one interactions) among their own employees as part of the system (Zack, 2003). Specific socialization (tacit → tacit) practices that Six Sigma project leaders can use include such idea-generation and meeting-facilitation methods as brainstorming and nominal group technique (Breyfogle, 2003).

In Six Sigma projects, externalization (tacit → explicit) practices aid the conversion of difficult-to-codify tacit knowledge into explicit knowledge by providing templates (Jensen and Szulanski, 2007), such as cause-and-effect diagrams and failure modes and effects analysis charts (Breyfogle, 2003). Such templates serve as a common and convenient language for team members, facilitating communication and analysis, and resulting in knowledge that helps to achieve project goals. Other examples of such templates in the Six Sigma tool kit include value stream maps, affinity diagrams and project tollgate reports. Externalization (tacit → explicit) practices also include actions that motivate employees to express their ideas, and train them to express such ideas in explicit form (Field and Sinha, 2005; Siemsen et al., 2008; Tucker, 2007). Practices include providing incentives for suggestions, and providing end-of-shift time to note errors and ideas for improvement.

Socialization and externalization (tacit → tacit, and tacit → explicit) practices are designed to capture the more-difficult-to-capture tacit knowledge from team members that may be crucial for the success of process improvement projects. The capture of such knowledge in Six Sigma projects can provide insights that result in higher levels of process improvements than could be achieved solely through explicit-knowledge-capturing practices. When Six Sigma projects originated at Motorola, their main thrust was the capture of explicit knowledge; project leaders now recognize the critical need to focus their attention on capturing tacit knowledge of team members in order to take advantage of the tremendous knowledge base of their team and, thereby, maximize the return that they can realize from the investments that such projects represent. Thus, our second set of hypotheses (H2) state that the integration of tacit knowledge through socialization (tacit → tacit knowledge) and externalization (tacit → explicit knowledge) practices adds value over and above that created by concentrating solely on the utilization of explicit knowledge.

H2. The following knowledge-creation practices for capturing tacit knowledge contribute significantly and positively to Six Sigma project success over and above the effects of practices that capture explicit knowledge:

a. socialization (tacit → tacit knowledge), and
b. externalization (tacit → explicit knowledge).

4. Methods

We test the hypothesized linkages between knowledge-creation practices and Six Sigma project success using data collected from U.S. companies deploying Six Sigma initiatives. The unit of analysis is a Six Sigma "black belt" project completed within the last three years; respondents providing the data are "black belts" in their capacity as project leaders. Black belts are in a good position to provide information about the knowledge-creation practices used in the execution of their projects. They are trained in the use of Six Sigma tools and techniques and, as project leaders, select practices for capturing individual knowledge through their projects.

4.1. Data

Data for the study were collected between January and September 2006 from black belts at five different companies via surveys administered over the Internet. These companies were promised anonymity in exchange for their participation. The survey consisted of objective questions on the start and end dates of projects, number of team members, project leaders' Six Sigma experience levels, and targeted and achieved project goals. Perceptual questions were used to evaluate constructs, such as the extent to which practices under each of the four knowledge-creation mechanisms were used, and the success achieved by the projects.

A total of 271 black belts were contacted, which resulted in 101 responses. Three responses were deleted because of missing values, resulting in a usable sample of 98 projects and an overall response rate of 36%. Projects in our sample deal with a variety of process improvement objectives, such as cost reduction, revenue generation, inventory control, first pass yield, call response time, billing accuracy, and generation of valid schedules. Demographic data for the black belts contacted was not available to enable direct tests for non-response bias. However, the response rate varied considerably across the five companies, and ranged from 23 to 77%. We checked, subsequently, to see if responses on knowledge creation and project success varied by company with the idea of comparing the higher response rate companies with the lower response rate companies. Using analysis of variance (ANOVA) tests, no significant differences were found. Overall, these results provided some evidence against non-response bias. A description of the five companies in our sample, and information on response rates are provided in Table 2. Brief company profiles are presented in Table 3.

4.2. Scale development

Researchers have constructed scales to measure the use of knowledge-creation mechanisms proposed by Nonaka (1994). However, there are inherent differences between knowledge creation for new product and process development, for which most of the existing scales were created (Johnson and Johnston,

Table 2
Sample characteristics.

Company[a]	Industry	Location	Revenue[b] ($ billions)	Usable responses	Response rate
1	Industrial services	Ohio	3	30	77%
2	High-tech industrial products	Ohio	5	15	23%
3	High-tech office equipment & services	New York	15	16	40%
4	Financial services	Kentucky	11	26	25%
5	High-tech industrial products	Indiana	3	11	44%

[a] See also company profiles presented in Table 3, with corresponding reference numbers.
[b] Annual sales figures for 2005.

2004; Zhang et al., 2004), and that for process improvement, which is the focus here. Similarly, several knowledge-creation scales were created for organization-level analyses (Johnson and Johnston, 2004; Lee and Choi, 2003), and are therefore not completely suitable for our research, which focuses on the team project level of analysis. Scales constructed by Becerra-Fernandez and Sabherwal (2001) focus on ongoing work (as opposed to specific-objective finite-period projects) within sub-units at the Kennedy Space Center. Moreover, their level of analysis is the individual, and the main focus of their study is individual satisfaction with the knowledge-creation process, thus making the scale unsuitable for our purpose. As we did not find any previous instances of knowledge-creation scales used for process improvement projects, we developed new scales for our study.

Our scales are designed to evaluate the extent to which Six Sigma practices, categorized based on Nonaka's (1991) knowledge-creation mechanisms, are used in each project. While developing these scales we took steps to ensure the content validity and face validity of our scales (Ahire and Devaraj, 2001; Flynn et al., 1990). First, we formulated scales based on our study of Six Sigma and quality management literature (e.g., Kumar and Gupta, 1993; Linderman et al., 2004), Nonaka's (1991) descriptions of knowledge-creation mechanisms, and related scales developed by previous researchers (e.g., Becerra-Fernandez and Sabherwal, 2001; Lee and Choi, 2003). This resulted in an initial list of 18 scale items divided among four knowledge-creation categories. Second, in order to ensure that the domain of the construct was sufficiently being captured by the scale items (Carmines and Zeller, 1991), we presented these scales to Six Sigma practitioners, and academic researchers in process improvement and knowledge management. We refined the wordings of scale items based on their feedback.

Finally, we conducted a *q*-sort exercise (Moore and Benbasat, 1991) among graduate business students to assess whether, based on the wording of the scale items, the scales were evaluating the respective constructs. The exercise involved presenting definitions for the four knowledge-creation constructs along with the set of 18 items in jumbled order (Roth et al., 2007). Respondents were asked to sort the items by constructs. This exercise resulted in the elimination of one item as it did not appear to be a clear indicator of any one knowledge-creation mechanism. The 17 items that remained measure the extent to which mechanisms were used, based on a five-point scale ranging from "not at all" to "to an extremely large extent." Scale items are listed in Appendix A.

Individual scale principal component analyses (PCA) resulted in dropping one item from each of three knowledge-creation scales—combination, internalization, and socialization (COM1, INT3, and SOC1)—and two items from externalization (EXT3 and EXT4). These items were dropped based on commonly used guidelines of 0.50 for loadings (Hair et al., 1998). Further, exploratory factor analysis (EFA) of the 12 remaining items through the means of maximum likelihood estimation with Varimax rotation revealed that it was not possible to identify four distinct constructs for knowledge-creation mechanisms. Instead, two factors were identified, accounting for 40% of the total variance. Combination (explicit → explicit knowledge) and internalization (explicit → tacit knowledge) scale items loaded on one factor. This factor represented mechanisms that capture explicit knowledge. The second factor represented tacit-knowledge-capturing mechanisms, with both socialization (tacit → tacit knowledge) and externalization (tacit → explicit knowledge) items loading on it.

Thus, it appears that in our sample, the two types of knowledge-creation mechanisms that capture explicit knowledge form one

Table 3
Company profiles.

Company	Description
1	This company is a leader in the United States in its main line of business—providing supplies and maintenance for physical facilities of all kinds such as restaurants, factories, hospitals, and office buildings. With over 30,000 employees, and more than 400 warehouses, the company services facilities for 700,000 diversified business customers across the U.S. Through Six Sigma projects completed in 2005, the company claimed to have reduced back orders by 75% and increased customer satisfaction by 40%.
2	For over a century, this company has been manufacturing high technology equipment and components for industrial markets, such as mining, rail, oil and gas, aerospace, and automobiles. With operations in 27 countries, it leads the world in sales of some of its products. The company uses Six Sigma projects as part of a broader initiative targeting productivity and safety. This initiative enabled the company to achieve a 9% annual growth in sales per associate and a 25% reduction in lost-time accidents during 2001-5.
3	This company has been manufacturing, selling, leasing, and servicing office equipment for over 100 years. In 2005, it was operating in more than 160 countries, with 55,000 employees. Through indigenous development of innovative technology, the company introduces new products quite regularly, which makes quality control and improvement all the more critical and challenging. Initiatives such as Six Sigma are used by the company to cut costs and improve output from manufacturing and transactional processes.
4	As an international provider of financial services and investment resources to individual customers, this company employed more than 37,000 people, and managed more than a trillion dollars of financial assets in 2005. It was then, and continues to be today, one of the leading providers of retirement planning services in the U.S. Six Sigma projects were credited with annualized savings of over 6 million dollars for the company in 2005, averaging $250,000 per project.
5	This company is a leading manufacturer of power generation equipment for diverse industries. In 2005, it employed more than 30,000 people in 50 countries, with more than 5000 employees in the U.S. After-sales service accounts for over one-third of the company's revenues. Service processes and manufacturing processes, are targets for improvement through the company's Six Sigma initiative.

factor; we call this factor *technically oriented practices*. The second factor, which combines the two types of knowledge-creation mechanisms that capture tacit knowledge, is labeled *socially oriented practices*. On the basis of the EFA results, we estimated a confirmatory factor analysis (CFA) model with six items each mapped onto the two identified factors: technically, and socially, oriented practices. The fit of this model was good, with its normed χ^2 (i.e., χ^2/df) value of 1.32 and root mean square error of approximation (RMSEA) value of 0.05 falling below the respective recommended maximum values of 3 and 0.08 for acceptable fit. The standardized root mean square residual (SRMR) of 0.07 for the model was within the recommended maximum of 0.08. Further, values of the non-normed fit index (NNFI) of 0.96, the comparative fit index (CFI) of 0.97, and the incremental fit index (IFI) of 0.97, were above the commonly used cutoff value of $\geq$0.90 (Hu and Bentler, 1999).

All the measured items loaded significantly on their factors, representing underlying latent constructs ($p \leq 0.001$), providing evidence of convergent validity (loadings listed in Table 4). Following Fornell and Larcker (1981), the variances extracted by the two latent variables in the CFA were found to be greater than the squared correlation between the two variables, providing support for the existence of two separate constructs. As a supplementary test for divergent validity, we estimated an additional CFA model with the correlation between the two knowledge-creation constructs fixed at one. The fit of this model was considerably worse, with a statistically significant difference between the χ^2 values of the two models, leading to the rejection of the hypothesis that the two latent variables are perfectly correlated (Bagozzi and Phillips, 1982). Further, the 99% confidence interval for correlation between the two knowledge-creation variables did not include the maximum coefficient value of 1.00 (Anderson and Gerbing, 1988; Bagozzi, 1980), providing support for the notion that the two latent variables for technically and socially oriented knowledge-creation practices are not the same construct.

After assessing the content and construct validities of the two knowledge-creation scales, we proceeded to compute their reliabilities. The Cronbach's alpha score for the scale for technically oriented practices was 0.82, and that for the socially oriented practices scale was 0.76. Both these scores are above the common rule of thumb of 0.70. The corrected-item total correlation (CITC) scores for each of the 12 scale items were also above the recommended cutoff of 0.40, providing further evidence of the reliability of these scales.

Project success is measured using an index created by averaging the scores from three single-item scales (shown in Appendix A) representing different dimensions of performance (Jugdev and Müller, 2005; Tatikonda, 2008). The first item measures the extent to which performance of the process targeted by the project improved, as compared to its performance before the project. Improvements resulting from a project may be achieved in one or more areas of process performance, such as cost reduction, cycle-time reduction, or sales increase. Thus, the first item in the project success index is intended to generalize across different performance improvement objectives for targeted processes. The second and third items in the project success index focus on benefits realized by the organization as a result of the project (Shenhar et al., 2002).

Table 4
Scales for knowledge-creation practices: Standardized factor loadings from CFA.

Factors	Items[a]	Loadings
Technically oriented	COM2	0.66
	COM3	0.69
	COM4	0.70
	INT1	0.53
	INT2	0.60
	INT4	0.60
Socially oriented	SOC2	0.51
	SOC3	0.69
	SOC4	0.53
	EXT1	0.63
	EXT2	0.62
	EXT5	0.54

Cross-loadings fixed to 0.
[a] Scale items listed in Appendix A.

These dimensions evaluate (1) the immediate benefits realized, and (2) the long-term benefits expected, as a result of the project. While projects focusing on "profit and loss statement" related end-goals (such as increasing sales, and decreasing defects) are judged primarily by immediate benefits, those focusing on "balance sheet" goals (such as reducing inventory, and rationalizing supplier-payment-terms) are evaluated mainly by their expected long-term benefits. The second and third items of the project success index also allow for different aspirations of companies for organizational benefits from their process improvement projects, based on the levels of maturity in their Six Sigma deployment (Shenhar et al., 1997). Overall, as a composite of three dimensions, the project success index is a formative indicator, combining observed variables that need not co-vary (Bollen and Lennox, 1991). The index is intended to account for possible tradeoffs among its performance dimensions (Stock and Tatikonda, 2008; Swink et al., 2006).

We also solicited objective measures of project performance (e.g., dollar savings and cycle-time reduction). Most respondents were reluctant to provide this information. However, for 36 of the 98 cases in our sample, we did get objective information, usable for validating the data collected by means of our three-item index of project success. This objective information was in the form of project-targets and -achievements, and referred to the main goals of projects. Data on these "target" and "achieved" figures were expressed in terms of dollars, units of inventory, error rates, or cycle times. In order to make this data amenable to statistical analysis, we transformed it using a four-point coding scheme. The extent to which the target of each project is achieved is coded as 0 for no achievement to 50% achievement, 1 for greater than 50% but less than 100% achievement, 2 for 100% achievement, and 3 for exceeding target. Similar coding schemes have been used by previous researchers to codify project metrics that are expressed in different units of measurement (see, for example, Haas, 2006; Mukherjee et al., 1998). The significant correlation (Spearman's $\rho = 0.50$; $p < 0.01$; $n = 36$) between this process performance measure and the three-item index of project success provides evidence of the validity of the index. The project success index is used as a dependent variable for the rest of our analysis.

Because data on knowledge creation and Six Sigma project success were collected from a single respondent per project, we conducted Harman's one-factor test to detect the presence of mono-method bias (Podsakoff and Organ, 1986); we carried out an EFA without specifying the number of factors on the twelve items for knowledge-creation practices, and three items for project success. The resulting un-rotated solution had three factors with eigen-values greater than one (variance extracted: 12, 21, and 12%) providing assurance that any mono-method bias that exists is not likely to be problematic.

In gauging the effects of knowledge-creation practices on the success of process improvement projects, we controlled for variables outside of our hypothesized model that are known to influence project success. A variable based on a five-point scale with the end points "Did not affect at all" and "Affected to an extremely large extent" was used to account for the extent to which events external to the project affected the progress of the project. We also controlled for size of the project team, duration of the project, and the number of years of Six Sigma experience of the project leader (Ethiraj et al., 2005). While team size, project duration, and external events account for complexity of projects (Dailey, 1978), project leader experience controls for the effect of team leader characteristics on project success (Sarin and McDermott, 2003). Finally, as our data were collected from five different companies, we created four dummy variables for our regression analysis to account for differences in organizational infrastructures of the five Six Sigma initiatives.

5. Analyses and results

We used hierarchical regression to analyze our model for which we computed latent construct scores for the two multi-item knowledge-creation scales as averages of items for each scale. A correlation matrix that includes means and standard deviations for all the variables used in the regression analysis is presented in Table 5. The two knowledge-creation constructs are significantly correlated with project success, and with each other, with coefficients ranging from 0.18 to 0.42. The high correlation between the knowledge-creation variables raised concerns of potential multicollinearity issues, so we assessed variance inflation factor (VIF) scores as part of subsequent regression analyses. The highest VIF score for any independent variable term was 1.5, well below the 10.0 threshold, hence suggesting that multicollinearity does not pose a problem for interpreting the regression results.

5.1. Regression estimation

We have proposed that knowledge-creation practices for capturing explicit knowledge, combination (explicit → explicit knowledge) and internalization (explicit → tacit knowledge), have a direct and positive impact on Six Sigma project success, as outlined in H1. For this hypothesis to be supported, the technically oriented knowledge-creation practices must explain significant variance in Six Sigma project success. The second hypothesis, that tacit-knowledge-capturing practices contribute to Six Sigma project success, is supported if we find that significant incremental variance in Six Sigma project success is explained by socialization and externalization (tacit → tacit and tacit → explicit knowledge), after accounting for variance explained by the explicit-knowledge-capturing practices (i.e., combination and internalization: explicit → explicit and explicit → tacit knowledge).

Results of the regression analysis are presented in Table 6. With project success as the dependent variable, in the first step we entered all of the control variables. Team size, project leader experience, and project duration were log-transformed before entering, as these variables had highly skewed distributions. The other variables entered in the first step were external events affecting the project and dummy variables identifying companies in which the projects were executed. We determined the R^2 and the F statistic for the complete regression model in the second step (Table 6, column 2), and the coefficient for technically oriented practices in the second and third steps (Table 6, columns 2 and 3) to test the first hypothesis. We used the change in R^2 and the F statistic for the change between steps 2 and 3, combined with the coefficient for socially oriented practices (Table 6, column 3) to test the second hypothesis.

5.2. Regression results

In the first step of the analysis (Table 6, column 1), we find that predictors for team size, project leader experience, and project duration do not explain a significant amount of variance in the dependent variable, Six Sigma project success (b = 0.14, *ns;*

Table 5
Descriptive statistics and correlation matrix of variables.

	Mean	Standard deviation	1	2	3	4	5	6	7	8	9	10
1. Project success	4.301	0.692										
2. Log (team size)	1.693	0.393	0.114 (91)									
3. Log (leader experience)	−0.027	0.881	0.041 (97)	−0.078 (90)								
4. Log (duration)	5.522	0.630	−0.047 (83)	0.125 (76)	**−0.255**** (83)							
5. External events	3.133	1.190	**−0.180*** (98)	0.114 (91)	−0.053 (97)	**0.361***** (83)						
6. Company dummy 1	0.153	0.362	0.048 (98)	−0.031 (91)	−0.146 (97)	**0.201*** (83)	−0.024 (98)					
7. Company dummy 2	0.163	0.372	−0.003 (98)	**0.177*** (91)	−0.027 (97)	0.015 (83)	0.044 (98)	N.A.				
8. Company dummy 3	0.265	0.444	−0.126 (98)	**−0.197*** (91)	−0.118 (97)	−0.016 (83)	0.011 (98)	N.A.	N.A.			
9. Company dummy 4	0.112	0.317	−0.046 (98)	−0.044 (91)	0.105 (97)	0.060 (83)	−0.040 (98)	N.A.	N.A.	N.A.		
10. Technically oriented practices	3.565	0.837	**0.284***** (98)	**0.177*** (91)	**0.195*** (97)	−0.035 (83)	0.029 (98)	−0.102 (98)	0.083 (98)	−0.056 (98)	−0.060 (98)	
11. Socially oriented practices	3.647	0.679	**0.181*** (98)	**0.251**** (91)	0.153 (97)	0.000 (83)	**0.180*** (98)	**−0.190*** (98)	**0.208**** (98)	0.132 (98)	−0.053 (98)	**0.420***** (98)

Figures in parentheses indicate sample size for each pair. Values in bold indicate statistically significant correlations.
* $p \le 0.10$.
** $p \le 0.05$.
*** $p \le 0.01$.

Table 6
Results of regression predicting Six Sigma project success (dependent variable) based on knowledge-creation practices.

Predictors:	Step 1	Step 2	Step 3
Control variables			
Log (team size)	0.14	0.07	0.02
Log (leader experience)	−0.02	−0.06	−0.08
Log (project duration)	0.02	0.01	0.02
External events	−0.19	−0.16	−0.21*
Company 1	−0.02	−0.05	−0.03
Company 2	−0.11	−0.12	−0.17
Company 3	−0.25*	−0.24*	−0.31**
Company 4	−0.08	−0.05	−0.05
Knowledge-creation practices			
Technically oriented (capturing explicit knowledge)		0.33***	0.24*
Socially oriented (capturing tacit knowledge)			0.25*
F for the step	1.02	8.38***	3.47*
F for the regression	0.97	1.89*	2.11**
R^2	0.10	0.21	0.25
Adjusted R^2	0.00	0.10	0.13

n = 76. Regression coefficients are standardized betas.
* $p \leq 0.10$.
** $p \leq 0.05$.
*** $p \leq 0.01$.

b = −0.02, *ns*; and b = 0.02, *ns*, for log-team size, log-project leader experience, and log-project duration, respectively). The effect of external events is also not significant (b = −0.19, *ns*). Projects from company three appear to show somewhat poorer performance (b = −0.25, $p \leq 0.10$). The eight control variables together explain 10% of the variance in project success, and the overall regression model is not significant (F = 0.97, *ns*).

The addition of technically oriented knowledge-creation practices as a predictor in the second step (Table 6, column 2) explains a significant amount of additional variance (change in R^2 = 0.11, F for the step = 8.38, $p \leq 0.01$). The F statistic for the regression model is marginally significant, and the R^2 value is 21%, indicating the variance in the dependent variable explained by the nine independent variables (Table 6, column 2; F = 1.89, $p \leq 0.10$). The independent variable of interest, technically oriented knowledge-creation practices, is positively and significantly associated with Six Sigma project success (b = 0.33, $p \leq 0.01$).

In the third step of the equation (Table 6, column 3), the addition of socially oriented knowledge-creation practices explains marginally significant additional variance in Six Sigma project success (change in R^2 = 0.04, F for the step = 3.47, $p \leq 0.10$). The variable for socially oriented knowledge-creation practices added in this step has a marginally significant positive coefficient (b = 0.25, $p \leq 0.10$), and the effect of technically oriented knowledge-creation practices is also marginally significant (b = 0.24, $p \leq 0.10$). The drop in the coefficient for technically oriented knowledge-creation practices from 0.33 to 0.24 is attributed to the high correlation (0.42; $p \leq 0.01$) of this variable with socially oriented knowledge-creation practices. The negative coefficient for the variable measuring the effect of external events is marginally significant (b = −0.21, $p \leq 0.10$); here also, projects from company three have significantly poorer success levels (b = −0.31, $p \leq 0.05$). The overall R^2 is 25% (F = 2.11, $p \leq 0.05$); adjusted for number of parameters estimated, the R^2 is 13%.

Thus, from the results shown in column 2 of Table 6, and the coefficients for technically oriented practices in column 3 of Table 6, we can see that H1 is supported, given the limitation of the two-factor solution for the knowledge-creation mechanism variables. A significant amount of variance (11%) in Six Sigma project success is explained by technically oriented knowledge-creation practices in step 2 of the regression. H2, regarding the incremental effect of tacit-knowledge-utilizing socially oriented practices, is also supported. The addition of the socially oriented practices variable to the regression equation explains a marginally significant amount of incremental variance (4%) in project success, and the coefficient for socially oriented practices is marginally significant.

6. Discussion

The aim of this research has been to examine the role of different categories of knowledge-creation practices in the success of process improvement projects. Using the empirical setting of Six Sigma projects, we have found that success levels of process improvement projects are significantly related to the use of (1) practices that utilize the *explicit* knowledge of team members converting such knowledge into either explicit or tacit workable knowledge, and (2) practices that utilize the *tacit* knowledge of team members, converting such knowledge into tacit or explicit knowledge applied toward process improvement. Thus, both technically and socially oriented knowledge-creation practices are important for the success of process improvement projects. Thus, project team leaders should be trained in, and encouraged to make use of, both technically and socially oriented knowledge-creation practices in the execution of their projects, and especially to seek out and incorporate non-obvious, frequently overlooked, more-difficult-to-capture tacit knowledge. This is especially so because socially oriented practices enable project leaders to make up for the lack of close ties between team members, inherent to the nature of project teams, and that are otherwise considered critical for capturing tacit knowledge.

6.1. Theoretical implications

Our research adds to the body of work on the use of tacit knowledge for process improvements. Existing research points to the requirement of strong interpersonal ties for the capture of tacit knowledge, and that of weak ties for the utilization of explicit knowledge (Granovetter, 1973). Our research examines the capture of both explicit and tacit types of knowledge when interpersonal ties among knowledge-players are not strong. Project teams are made up of members who represent diverse functions; these members may even belong to different organizations and be located far from each other. Moreover, the tenure of these teams is finite—three to nine months in the case of most Six Sigma projects—and work on these projects usually constitutes only a part of team members' job responsibilities. These circumstances preclude many opportunities for team members to form strong social ties, which are considered essential for the capture of tacit knowledge. Our results address this situation by adding the dimension of knowledge-capturing practices to the connection between tacit knowledge and its utilization. Simply stated, we show that even in the absence of strong social ties, team leaders can make use of knowledge-creation practices to induce the sharing of tacit knowledge within the domain of a project, thus harnessing such knowledge for the benefit of the organization.

Our statistical analyses did not distinguish between practices that simply share tacit knowledge among team members and those that share tacit knowledge by converting it into explicit knowledge. However, our discussions with executives from respondent companies revealed that there may be several long-term benefits in addition to immediate project-objective benefits of practices for converting tacit knowledge captured into explicit knowledge. The immediate project-objective benefits of converting tacit knowledge into explicit come from the enhanced reflection on knowledge by team members made possible by the codification of tacit knowledge, using practices such as value stream mapping, affinity diagrams, and failure modes and effects analysis (FMEA) reports. In addition, benefits that continue beyond the duration of the project accrue from practices such as codification of tacit knowledge into a repository of best practices that can be shared across the organization.

Our research also has implications for research on leadership, as our results support expanding the scope of responsibilities for project team leaders related to capturing tacit knowledge while leading diverse and ad-hoc teams. In addition to capably putting together a cohesive team and motivating members of the team to work well together, these leaders must be proficient in techniques for capturing tacit knowledge of team members. By employing the right practices in the execution of projects, team leaders can overcome the difficulties faced in engaging a disparate set of participants in the sharing of knowledge.

6.2. Managerial implications

Our first result, regarding the importance of practices for capturing explicit knowledge, supports the adage, "In God we trust, all else bring data" (Shaver, 2007), quoted to us by one of our respondents. It is well established that the use of hard data and analytical tools to synthesize explicit knowledge into meaningful relationships is beneficial for process improvement (Davenport, 2006). Support for our first hypothesis therefore underscores the criticality of techniques, such as correlation-based data analysis, and of standard operating procedures, which utilize explicit knowledge. Further, this result highlights the importance of training employees in the use of statistical techniques, as advocated by Deming (1983).

While explicit knowledge is incorporated in process improvement through analytical procedures, the conversion of explicit knowledge into tacit knowledge takes place through apprenticeships and job rotations. Support for our first hypothesis also provides evidence of the utility of such practices. Management executives frequently lament that process improvements implemented as a result of projects often fall by the wayside with the passage of time. Our result points to the significance of using techniques, such as work break-down structures and control charts, so that employees can observe the functioning of their own processes and generate discussions, perhaps leading to ideas for additional improvement cycles.

While practices that make use of explicit knowledge operationalize or diffuse knowledge, it is the practices for capturing tacit knowledge that generate knowledge that is truly "new" (Wilkstrőm and Normann, 1994). In most industries the ability to use explicit knowledge for process improvement has become a "qualifier." Most continuous improvement deployments—total quality management, lean production, or Six Sigma—capture explicit knowledge at a minimum. On the other hand, the ability to capture tacit knowledge continues to hold the potential for discovering "winner" process improvements that provide sustainable competitive advantages (Meyer, 1998). Specific examples of efforts to capture tacit knowledge for improving processes are provided by engineers for Matsushita Electric Company's bread-making machine, who apprenticed under a hotel's head baker (Nonaka and Takeuchi, 1995), and by Nissan's engineers, who hobnobbed with pickup truck owners in Texas in order to discover possible enhancements for their "Titan" trucks (Kerwin, 2003). The challenge of tacit knowledge is that while its capture can be critical for the benefit of an organization, such knowledge is not conducive to tapping without concerted and focused efforts (McMahon et al., 2004).

The tendency of project leaders to ignore tacit knowledge that is potentially useful but difficult to obtain was described to us, through an analogous folk narrative, by an executive in one of our respondent companies. The story involves a man searching for a valuable ring that he has dropped. The man is focusing his search in an area considerably distant from where he has dropped the ring. When asked why, the man explains that while it is dark and difficult to see in the area where he has dropped it, it is brighter and easier to see in the area in which he is conducting his search. The executive who related this story equated the attitude of the man in the story to that of project leaders who focus exclusively on knowledge that is codified and relatively easily accessible, at the cost of knowledge that is tacit, requiring hard work to be extracted and even harder work to be codified. The executive observed that while the importance of analyzing available data and testing hypotheses based on such data has gained prevalence with the spread of process improvement frameworks, it is still a challenge to get project leaders to take a step back from available data, explore new areas in which information may be relevant, and then make attempts to capture that knowledge. Realizing this inclination of project leaders, the company has now included extensive training for their black belts in the use of practices for capturing tacit knowledge.

When we shared the results of our research with companies in our sample, one executive observed that by "instigating" the emergence of tacit knowledge from team members, team leaders can direct members into uncharted solution spaces in search of remedies for process problems. This executive advocates the use of tacit-knowledge-capturing practices in the early stages of projects because he believes it can help better formulate the process problems. Quoting Albert Einstein, he pointed out that the formulation of a problem is more vital than its solution because it requires creative imagination, while the solution may result from applying known analytical tools. Thus, he believes, project leaders should pay special attention to capturing tacit knowledge of team members in the early stages of projects.

Another executive added a cautionary note against overstating our results regarding capture of tacit knowledge. She pointed out the possibility of team leaders focusing too much time and effort in the search and utilization of tacit knowledge. In her view, timeliness of a solution is as important as its contribution in optimizing process performance. Thus, she added, project leaders should be adept at balancing tacit knowledge-capturing activities with applying knowledge to get timely results. She advocates the use of deadlines for different stages of projects (that the company calls "tollgate due dates") as a safeguard against team leaders focusing too long on the gathering of tacit knowledge.

While tacit knowledge is difficult to harvest, it is also difficult for competitors to duplicate; it can, therefore, provide a competitive advantage that is sustainable until knowledge spreads to competitors. Thus, an organization that can successfully gather and translate the tacit knowledge that resides with its employees, suppliers, and customers into workable and valuable knowledge for process improvement, can build competitive advantage through better-designed processes. The results of the test of our second hypothesis provide support for this very notion, in that they highlight the role that concerted efforts to utilize tacit knowledge (resulting in both tacit and explicit process knowledge) have, in ensuring the success of process improvement projects.

7. Conclusions

Our results should be considered in light of certain limitations. The sample size of 98 projects from five companies prevents us from making stronger claims about the generalizability of the results. Future studies replicating our approach, but employing larger samples, are appropriate. Our scales for knowledge-creation practices did not discriminate between two ways of capturing tacit knowledge and two ways of capturing explicit knowledge as proposed by Nonaka (1994), and our two-factor solution extracted only 40% of the variance in the scale items. Further research is needed to (1) examine if there is, or is not, a finer grained classification of knowledge-creation practices applicable to process improvement projects, and (2) create measures for evaluating the extent to which practices in each category are used in projects. The single informant approach is not ideal. We controlled for external events, team size, and project duration, all aspects of project complexity. Still, future research can study other aspects of project complexity and other moderators which could influence relationships between knowledge-creation practices and project success. Although we verified that the VIF scores in our final regression model were within the maximum acceptable threshold, the high correlation between the two knowledge-creation variables may have affected some of our statistical results. The standard errors for each of the two predictors were not materially inflated, but the coefficient for technically oriented knowledge-creation practices did decline, from 0.33 ($p \leq 0.01$) to 0.24 ($p \leq 0.10$), when socially oriented knowledge-creation practices were entered into the regression.

We studied knowledge-creation practices at the project/team level, but practices at the organizational level, such as job rotation practices, the existence of common meeting facilities, and cultural differences of team members and functions, may also affect the success of projects. Still, it is noteworthy that the independent variables in our study did explain 25% of variance in project success. This study did account for project leader experience, but did not delve into detailed demographic characteristics of team members. Future research should consider team experience and other team characteristics. Finally, more specific multi-item measures of each facet of project performance can also be developed.

Our main finding is that practices used in team projects to extract team-member knowledge can be quite valuable for process improvement project success. This contributes to theoretical understanding in Operations Management and Organizational Behavior disciplines. Exploration of additional nuances of relationships between knowledge-creation approaches and process improvements requires further research. Examination of the cost–benefit implications of using different knowledge-creation approaches represents an opportunity for future researchers. Future investigation should better understand the state of evolution, or maturity, of a firm's Six Sigma initiative and the resultant impact on knowledge-creation practice selection and effectiveness. In addition, the scales we created for capturing explicit and tacit knowledge represent a contribution, and can be used to address questions on the types of projects for which it would be more beneficial to focus on one type of knowledge capture over another. Our approach shows that process improvement in general, and Six Sigma in particular, benefit from perspective and analysis at the project level of observation. The insights from this study on the role of knowledge creation in process improvement provide practical guidance for Six Sigma project leaders and other managers of process improvement projects and initiatives, especially in regards to the importance of capturing tacit knowledge.

Acknowledgements

We are thankful to Joseph Mahoney, two anonymous reviewers, and an anonymous Associate Editor for their helpful suggestions at various stages of this manuscript. Support provided for this research by the Center for Operational Excellence at The Ohio State University is acknowledged. We greatly appreciate the contributions of the five companies whose participation made this research possible.

Appendix A. Scale items

A.1. Knowledge-creation mechanisms

Extent to which the following practices were used in your project
Five-point scale ranging from 1 = Not at all, to 5 = To an extremely large extent

Combination
Using formal reports from past projects for analyses in current project (COM1)
Numerical data analysis (COM2)
Formally codifying objective project results into standard operating procedures (COM3)
Systematically recording objective findings and results for future reference (COM4)

Internalization
Using diagrams and models to initiate discussions during the project (INT1)
Using codified reports to initiate discussions about project performance (INT2)
Implementing documented changes using on-the-job training (INT3)
Using codified reports to generate discussions after implementation of results (INT4)

Socialization
Discussions among people working directly on the process (SOC1)
Discussions among members of the project team (SOC2)
Discussions among team members and customers of the process (SOC3)
Discussions among team members and suppliers of the process (SOC4)

Externalization
Formalizing implied project objectives by preparing business case document (EXT1)
Formally and systematically listing implied customer requirements (EXT2)
Linking tacit customer requirements to specified process characteristics (EXT3)
Recording improvement ideas in a database (EXT4)
Converting subjective customer requirements to objective requirements (EXT5)

Note: Italicized items were deleted based on results of scale validity analyses.

A.2. Project success

How much process improvement was realized as a result of the execution of the project?

No improvement	Slight improvement	Moderate improvement	A lot of improvement	Great deal of improvement

Did/Will this project provide immediate benefits?

Definitely no	Probably no	Maybe	Probably yes	Definitely yes

Did/Will this project provide long-term benefits?

Definitely no	Probably no	Maybe	Probably yes	Definitely yes

References

Ahire, S.L., Devaraj, S., 2001. An empirical comparison of statistical construct validation approaches. IEEE Transactions on Engineering Management 48 (3), 319–329.
Anand, G., Ward, P.T., Tatikonda, M.V., Schilling, D.A., 2009. Dynamic capabilities through continuous improvement infrastructure. Journal of Operations Management 27 (6), 444–461.
Anderson, J.C., Gerbing, D.W., 1988. Structural equation modeling in practice: a review and recommended two-step approach. Psychological Bulletin 103 (3), 411–423.
Argote, L., McEvily, B., Reagans, R., 2003. Managing knowledge in organizations: an integrative framework and review of emerging themes. Management Science 49 (4), 571–582.
Argyris, C., 1977. Double loop learning in organizations. Harvard Business Review 55 (5), 115–125.
Arikan, A.T., 2009. Interfirm knowledge exchanges and the knowledge creation capability of clusters. Academy of Management Review 34 (4), 658–676.
Bagozzi, R.P., 1980. Causal Methods in Marketing. John Wiley and Sons, New York, NY.
Bagozzi, R.P., Phillips, L.W., 1982. Representing and testing organizational theories: a holistic construal. Administrative Science Quarterly 27 (3), 459–489.
Barney, J.B., 1995. Looking inside for competitive advantage. Academy of Management Executive 9 (4), 49–61.
Becerra-Fernandez, I., Sabherwal, R., 2001. Organization knowledge management: a contingency perspective. Journal of Management Information Systems 18 (1), 23–55.
Bendoly, E., Hur, D., 2007. Bipolarity in reactions to operational constraints: OM bugs under an OB lens. Journal of Operations Management 25 (1), 1–13.
Bohn, R.E., 1994. Measuring and managing technological knowledge. Sloan Management Review 36 (1), 61–73.

Bollen, K., Lennox, R., 1991. Conventional wisdom on measurement: a structural equation perspective. Psychological Bulletin 110 (2), 305–314.
Boone, T., Ganeshan, R., Hicks, R.L., 2008. Learning and knowledge depreciation in professional services. Management Science 54 (7), 1231–1236.
Boudreau, J., Hopp, W., McClain, J.O., Thomas, L.J., 2003. On the interface between operations and human resources management. Manufacturing & Service Operations Management 5 (3), 179–202.
Breyfogle, F.W., 2003. Implementing Six Sigma. Wiley, Hoboken, NJ.
Carmines, E.G., Zeller, R.A., 1991. Reliability and Validity Assessment. Sage Publications, Newbury Park, NJ.
Choo, A.S., Linderman, K.W., Schroeder, R.G., 2007. Method and psychological effects on learning behaviors and knowledge creation in quality improvement projects. Management Science 53 (3), 437–450.
Choo, C.W., 1998. The Knowing Organization: How Organizations Use Information to Construct Meaning, Create Knowledge and Make Decisions. Oxford University Press, New York.
Constant, D., Sproull, L., Kiesler, S., 1996. The kindness of strangers: the usefulness of electronic weak ties for technical advice. Organization Science 7 (2), 119–135.
Cook, S.D.N., Brown, J.S., 1999. Bridging epistemologies: the generative dance between organizational knowledge and organizational knowing. Organization Science 10 (4), 381–400.
Dailey, R.C., 1978. The role of team and task characteristics in R&D team collaborative problem solving and productivity. Management Science 24 (15), 1579–1588.
Davenport, T.H., 2006. Competing on analytics. Harvard Business Review 84 (1), 98–107.
Deming, W.E., 1983. The New Economics for Industry, Government, Education. Center for Advanced Engineering Study, Massachusetts Institute of Technology, Cambridge, MA.
Edmondson, A.C., 2008. The competitive imperative of learning. Harvard Business Review 86 (7/8), 60–67.
Edmondson, A.C., Winslow, A.B., Bohmer, R.M.J., Pisano, G.P., 2003. Learning how and learning what: effects of tacit and codified knowledge on performance improvement following technology adoption. Decision Sciences 34 (2), 197–223.
Ethiraj, S.K., Kale, P., Krishnan, M.S., Singh, J.V., 2005. Where do capabilities come from and how do they matter? A study in the software services industry. Strategic Management Journal 26 (1), 25–45.
Field, J.M., Sinha, K.K., 2005. Applying process knowledge for yield variation reduction: a longitudinal field study. Decision Sciences 36 (1), 159–186.
Fiol, C.M., 1994. Consensus, diversity, and learning in organizations. Organization Science 5 (3), 403–420.
Flynn, B.B., Sakakibara, S., Schroeder, R.G., Bates, K.A., Flynn, E.J., 1990. Empirical research methods in operations management. Journal of Operations Management 9 (2), 250–284.
Fornell, C., Larcker, D.F., 1981. Evaluating structural equation models with unobservable variables and measurement error. Journal of Marketing Research 18 (1), 39–50.
Gerwin, D., Barrowman, N.J., 2002. An evaluation of research in integrated product development. Management Science 48 (7), 938–953.
Granovetter, M.S., 1973. The strength of weak ties. American Journal of Sociology 78 (6), 1360–1380.
Grant, R.M., 1996. Toward a knowledge-based theory of the firm. Strategic Management Journal 17 (Winter Special Issue), 109–122.
Haas, M.R., 2006. Knowledge gathering, team capabilities, and project performance in challenging work environments. Management Science 52 (8), 1170–1184.
Haas, M.R., Hansen, M.T., 2007. Different knowledge, different benefits: toward a productivity perspective on knowledge sharing in organizations. Strategic Management Journal 28 (11), 1133–1153.
Hair, J., Anderson, R.E., Tatham, R.L., Black, W.C., 1998. Multivariate Data Analysis, 5th edition. Prentice Hall, Upper Saddle River, NJ.
Hansen, M.T., Nohria, N., Tierney, T., 1999. What's your strategy for managing knowledge? Harvard Business Review 77 (2), 106–116.
Hoerl, R.W., 2001. Six Sigma black belts: what do they need to know? Journal of Quality Technology 33 (4), 391–406.
Hu, L., Bentler, P.M., 1999. Cutoff criteria for fit indexes in covariance structure analysis: conventional criteria versus new alternatives. Structural Equation Modeling 6 (1), 1–55.
Jensen, R.J., Szulanski, G., 2007. Template use and the effectiveness of knowledge transfer. Management Science 53 (11), 1716–1730.
Johnson, W.H.A., Johnston, D.A., 2004. Organizational knowledge creating processes and the performance of university–industry collaborative R&D projects. International Journal of Technology Management 27 (1), 93–114.
Jugdev, K., Müller, R., 2005. A retrospective look at our evolving understanding of project success. Project Management Journal 36 (4), 19–31.
Kerwin, K., 2003. It's big. It's brawny. It's Japanese. Business Week 3854 (October), 54.
Kim, D.H., 1993. The link between individual and organizational learning. Sloan Management Review 35 (1), 37–50.
Kogut, B., Zander, U., 1992. Knowledge of the firm, combinative capabilities, and the replication of technology. Organization Science 3 (3), 383–397.
Kumar, S., Gupta, Y.P., 1993. Statistical process control at Motorola's Austin assembly plant. Interfaces 23 (2), 84–92.
Lee, H., Choi, B., 2003. Knowledge management enablers, processes, and organizational performance: an integrative view and empirical examination. Journal of Management Information Systems 20 (1), 179–228.
Linderman, K., Schroeder, R.G., Zaheer, S., Liedtke, C., Choo, A.S., 2004. Integrating quality management practices with knowledge creation processes. Journal of Operations Management 22 (6), 589–607.
Mantel, S.P., Tatikonda, M.V., Liao, Y., 2006. A behavioral study of supply manager decision-making: Factors influencing make versus buy evaluation. Journal of Operations Management 24 (6), 822–838.
March, J.G., 1991. Exploration and exploitation in organizational learning. Organization Science 2 (1), 71–87.
McMahon, C., Lowe, A., Culley, S., 2004. Knowledge management in engineering design: personalization and codification. Journal of Engineering Design 15 (4), 307–325.
Meyer, C., 1998. Relentless Growth: How Silicon Valley Innovation Strategies can Work in Your Business. The Free Press, New York, NY.
Molina, L.M., Lloréns-Montes, J., Ruiz-Moreno, A., 2007. Relationship between quality management practices and knowledge transfer. Journal of Operations Management 25 (3), 682–701.
Moore, G.C., Benbasat, I., 1991. Development of an instrument to measure the perceptions of adopting an information technology innovation. Information Systems Research 2 (2), 192–222.
Mukherjee, A.S., Lapre, M.A., Van Wassenhove, L.N., 1998. Knowledge driven quality improvement. Management Science 44 (11), S35–S49.
Nahapiet, J., Ghoshal, S., 1998. Social capital, intellectual capital, and the organizational advantage. Academy of Management Review 23 (2), 242–266.
Nonaka, I., 1991. The knowledge-creating company. Harvard Business Review 69 (6), 96–104.
Nonaka, I., 1994. A dynamic theory of organizational knowledge creation. Organization Science 5 (1), 14–37.
Nonaka, I., Takeuchi, H., 1995. The Knowledge-creating Company: How Japanese Companies Create the Dynamics of Innovation. Oxford University Press, New York, NY.
Nonaka, I., von Krogh, G., 2009. Tacit knowledge and knowledge conversion: Controversy and advancement in organizational knowledge creation theory. Organization Science 20 (3), 635–652.
Podsakoff, P.M., Organ, D.W., 1986. Self-reports in organizational research: problems and prospects. Journal of Management 12 (4), 531–544.
Polanyi, M., 1966. The Tacit Dimension. Doubleday, Garden City, NY.
Raelin, J.A., 1997. A model of work-based learning. Organization Science 8 (6), 563–578.
Roth, A., Schroeder, R., Huang, X., Kristal, M., 2007. Handbook of Metrics for Research in Operations Management. Sage, Thousand Oaks, CA.
Sabherwal, R., Jeyaraj, A., Chowa, C., 2006. Information system success: individual and organizational determinants. Management Science 52 (12), 1849–1864.
Sarin, S., McDermott, C., 2003. The effect of team leader characteristics on learning, knowledge application, and performance of cross-functional new product development teams. Decision Sciences 34 (4), 707–739.
Schroeder, R.G., Linderman, K., Liedtke, C., Choo, A.S., 2008. Six Sigma: definition and underlying theory. Journal of Operations Management 26 (4), 536–554.
Shah, R., Ward, P.T., 2003. Lean manufacturing: context, practice bundles, and performance. Journal of Operations Management 21 (2), 129–149.
Shah, R., Ward, P.T., 2007. Defining and developing measures of lean production. Journal of Operations Management 25 (4), 785–805.
Shaver, K., 2007. The Social Psychology of Entrepreneurial Behavior: All Others Bring Data. Springer, New York, NY.
Shenhar, A.J., Levy, O., Dvir, D., 1997. Mapping the dimensions of project success. Project Management Journal 28 (2), 5–13.
Shenhar, A.J., Tishler, A., Dvir, D., Lipovetsky, S., Lechler, T., 2002. Refining the search for project success factors: a multivariate, typological approach. R&D Management 32 (2), 111–126.
Siemsen, E., Roth, A., Balasubramanian, S., 2008. How motivation, opportunity, and ability drive knowledge sharing: the constraining-factor model. Journal of Operations Management 26 (3), 426–445.
Siemsen, E, Roth, A.V., Balasubramanian, S., Anand, G., 2009. The influence of psychological safety and confidence in knowledge on employee knowledge sharing. Manufacturing and Service Operations Management 11 (3), 429–447.
Snee, R.D., Hoerl, R.W., 2003. Leading Six Sigma: A Step-by-step Guide Based on Experience with GE and Other Six Sigma Companies. Financial Times Prentice Hall, Upper Saddle River, NJ.
Spender, J.C., 1996. Making knowledge the basis of a dynamic theory of the firm. Strategic Management Journal 17 (SI), 45–62.
Stock, G.N., Tatikonda, M.V., 2008. The joint influence of technology uncertainty and interorganizational interaction on external technology integration success. Journal of Operations Management 26 (1), 65–80.
Swink, M., Song, M., 2007. Effects of marketing-manufacturing integration on new product development time and competitive advantage. Journal of Operations Management 25 (1), 203–217.
Swink, M., Talluri, S., Pandejpong, T., 2006. Faster, better, cheaper: a study of NPD project efficiency and performance tradeoffs. Journal of Operations Management 24 (5), 542–562.
Tatikonda, M.V., 2008. Product development performance measurement. In: Loch, C.H., Kavadias, S. (Eds.), Handbook of New Product Development Management. Butterworth-Heinemann, Oxford, U.K., pp. 199–216.
Tatikonda, M.V, Montoya-Weiss, M.M., 2001. Integrating operations and marketing perspectives of product innovation: the influence of organizational process factors and capabilities on development performance. Management Science 47 (1), 151–172.

Tucker, A.L., 2007. An empirical study of system improvement by frontline employees in hospital units. Manufacturing and Service Operations Management 9 (4), 492–505.

Tucker, A.L., Nembhard, I.M., Edmondson, A.C., 2007. Implementing new practices: an empirical study of organizational learning in hospital intensive care units. Management Science 53 (6), 894–907.

Voelpel, S.C., Dous, M., Davenport, T.H., 2005. Five steps to creating a global knowledge-sharing system: Siemens' ShareNet. Academy of Management Executive 19 (2), 9–23.

von Hippel, E., 1994. "Sticky information" and the locus of problem solving: implications for innovation. Management Science 40 (4), 429–439.

Weick, K.E., Roberts, K.H., 1993. Collective mind in organizations: heedful interrelating on flight decks. Administrative Science Quarterly 38 (3), 357–381.

Wilkström, S., Normann, R., 1994. Knowledge and Value: A New Perspective on Corporate Transformation. Routledge, New York, NY.

Zhang, Q., Lim, J., Cao, M., 2004. Learning and knowledge creation in product development: a LISREL analysis. International Journal of Product Development 1 (1), 107–129.

Zack, M.H., 2003. Rethinking the knowledge-based organization. Sloan Management Review 44 (4), 67–71.

Zu, X., Fredendall, L.D., Douglas, T.J., 2008. The evolving theory of quality management: the role of Six Sigma. Journal of Operations Management 26 (5), 630–650.