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ENGINEERING PROBLEM SOLVING AND SUSTAINED LEARNING: A MIXED METHODS STUDY TO EXPLORE THE DYNAMICS OF ENGINEERING KNOWLEDGE CREATION

by

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DISSERTATION

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DEDICATION

To Steve

"Thousands of candles can be lit from a single candle, and the life of the candle will not be shortened. Happiness never decreases by being shared."

>>> Buddha <<<

To My Parents

“No day in which you learn something is a complete loss.”

>>> David Eddings <<<

To Hanna, Destiny, Walther, Brownie, and Riley

“The world is extremely interesting to a joyful soul.”

>>> Alexandra Stoddard <<<

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This dissertation is the culmination of work that began in early 2008, with the inception of a new program, the Global Executive Track (GET) in the Industrial & Systems Engineering (ISE) Department. As the program took off, so did my journey as I was in the first cohort. Looking back, I realize that this journey has been long enough to see two Presidential Elections, the tsunami disaster and subsequent Fukushima accident in Japan, and many other tumultuous events around the world. It has been an interesting process of self-discovery, with a test of resilience thrown in at times. During this time, a great number of people helped me sustain my “aircraft” of hope, aspiration, and knowledge. Now that the flight has begun its descent, it is time to pay tribute to those who played key roles in my academic voyage.

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In preparation for landing, I send my heartfelt thanks to all of these individuals. My intellectual debts are truly huge, enough to fill the airfield that is now in plain view.

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CHAPTER 1: INTRODUCTION

Today's business environment is anything but certain, simple, or static. Sustaining a viable enterprise in such a high-turbulence market is a major challenge for all organizations. Innovation—be it incremental or novel—must continue. Enticing products must be developed and introduced seamlessly to maintain market position. Manufacturing capabilities must be maintained. Supply chains and logistics must resist disruption. Post-sale maintenance and service must deliver that which is promised. Corporate policies and processes must keep a vigilant watch over the firm's financial, infrastructural, and technological resources. In other words, products or services must be sustained once engendered, and this effort touches all areas of business operations. Failures to perceive a game-changer in any of these areas can bring adverse consequences as demonstrated time and again in our history by many notable examples. As Rastogi (2000) discusses, well-known cases include, but are not limited to,

- U.S. auto manufacturers' losing a large market share to the new entrants from Japan
- Sears' failing to adapt to changing landscape of retailing exemplified by Wal-Mart's new business model
- Compaq's missing the opportunity to adopt the just-in-time assemble-to-order process, which Dell exploited to huge success

More recently, Blockbuster Inc. and Borders Group Inc., once very successful enterprises, went into bankruptcy. Blockbuster's success was founded on its computerized inventory tracking system that optimized its movie selection, from classics to newest releases, available at its family-friendly stores (Gandel, 2010). Eventually, rivals such as

Netflix and Redbox overtook the market by enabling even easier access, often at much lower costs, to films through on-line streaming, delivery by mail, and pick-up at vending kiosks (Gandel, 2010; Lee, 2011). Similarly, Borders continued expansion of its brick-and-mortar stores and invested heavily in CDs and DVDs just when the industry was going on-line and digital. By the time the company went on the defensive, Amazon had captured a large market share of the on-line bookstore and released its first Kindle; Barnes and Nobles released its Nook e-reader; and iTunes had firmly taken hold of music market ("Why Borders failed and Barnes & Noble hasn't: 4 theories," 2011). Failure to fully embrace the impact of media digitization (Lee, 2011) is not limited to Borders' and Blockbuster's cases. The record industry is dwindling for very similar reasons despite increasing listenership to recorded music (Hiatt & Serpick, 2007). Analysts attribute the industry's decline to its inability to adapt to a variety of new ways consumers now interact with music, coupled with its failure to effectively address on-line piracy issues earlier when illegal file-sharing was rampant (Hiatt & Serpick, 2007). Sustaining operation is indeed a multi-dimensional affair that requires attention to all aspects of one's business.

Operational sustainability has an intimate link to knowledge management and learning. Innovation is sustained by leveraging the organization's accumulated knowledge to prompt new ideas and possibilities (Bartel & Garud, 2009). Entrepreneurial firms grow by engaging themselves in “experimental behavior” to induce experiential learning and understand what works and what does not (Fuller, Warrent, & Argyle, 2007). Suppliers are retained because of, among key sourcing factors, their know-how (Ulaga & Eggert, 2006). Organizational capabilities that sustain competitive advantage in dynamically evolving markets are tied to the firm's ability to integrate its knowledge bases into appropriate operational contexts (Grant, 1996; Rastogi, 2000). Simply put, in today's increasingly complex and rapidly changing environment, effective knowledge capture and translation into practice is critical for sustaining an organization.

Engineering has a major influence on operational sustainability through its contribution to product lifecycle management. Engineers leverage their technical knowledge bases to translate customer expectations into product specifications; to design and manufacture products to these specifications; and to perform post-launch maintenance and services. Essentially, engineering involvement in each phase of the product lifecycle—from concept to launch to field operation—is about managing and addressing product requirements. Learning comes out from each phase, and it is via seamless feedback of lessons learned into the existing product requirements and future product management routines that engineers enhance the quality and reliability of their products (Boersma, Loke, Petkova, Sander, & Brombacher, 2004; den Ouden, Yuan, Sonnemans, & Brombacher, 2006; Magniez, Brombacher, & Schouten, 2009).

Engineering lessons learned are derived from new knowledge gained from technical problem solving. Problem solving as a mechanism for creating knowledge is addressed in organizational learning and related literature. Cori and Storto's (2000) causal model, for example, treats behavioral aspects of technical problem solving as mediators influencing the quality of knowledge generation. Similarly, McEvily and Marcus (2005) hypothesize a fully mediated relationship between organizational factors and development of new capabilities by firm-supplier "joint problem solving." Engineering, essentially, is about problem solving. Engineers are "hired, retained, and rewarded for solving problems" (Jonassen, Strobel, & Lee, 2006, p. 139). Despite the intimate link between engineering and problem solving, however, the literature is lean in bridging the understanding of engineering problem solving processes to knowledge creation. Engineers solve problems every day, but **how** their solutions become part of sustained organizational learning is underexplored in engineering and management research.

Literature addressing business sustainability issues highlights two key aspects of organizational mechanisms that are relevant in sustaining competitiveness. One is flexibility and routinization aspects of processes and a careful interplay between the two. These dialectical dimensions of “coherence and pliability” (Bartel & Garud, 2009) or the “tension between […] pattern-breaking and recurrent practices” (Fuller et al., 2007, p. 11) promote dialogs for new ideas, essential for innovation (Bartel & Garud, 2009). The second aspect is tapping into tacit knowledge possessed by individuals in the organization. Integration of such knowledge is described as key to developing new capabilities and thereby maintaining competitive advantage (Grant, 1996). While behavioral and cognitive aspects of organizational mechanisms are well established in the organizational learning literature as having profound effects on knowledge creation, the engineering literature is relatively silent about them.

Engineering literature—and practice—is saturated with outcome-based, prescriptive routines that approach problem solving by emphasizing explicit forms of knowledge. Both routines and explicit knowledge are undoubtedly required for effective engineering operations. Structured routines bring coherence to people with diverse knowledge and connect them to a larger context in which they share goals and purposes (Bartel & Garud, 2009), thereby attaining efficiency through endorsing commonized practice (Fuller et al., 2007). Explicit knowledge takes the form of product designs, specifications, and other artifacts of engineering and signifies outcomes of engineering processes that codified existing knowledge for easy and rapid transfer across organization (Edmondson, Winslow, Bohmer, & Pisano, 2003). For example, the Design for Reliability (DFR) and Design for Six Sigma (DFSS) methodologies facilitate pre-emptive design optimization during the front end of product lifecycle to avoid future failures (Goh, 2002; Sarakakis, Gerokostopoulos, & Mettas, 2011). On the production floor (i.e., the back end of product lifecycle) manufacturers pursue defect reduction with such initiatives as Quality Circles, Kaizen (= continuous improvement), Zero Defects, and Poka Yoke (= mistake proofing)—introduced in American manufacturing since the 1980s in response to the challenges from international competition, especially from the Japanese (Raisinghani, Ette, Pierce, Cannon, & Prathima, 2005). Six Sigma, a widely popular methodology pioneered by Motorola, deftly integrates traditional process and statistical tools to improve processes (Linderman, Schroeder, Zaheer, & Choo, 2003; Raisinghani et al., 2005; Schroeder, Linderman, Liedtke, & Choo, 2008). In a yet broader scope, the ISO 9000 series quality standards—from which the U.S. automotive industry developed its own QS 9000 system that has since then evolved to become the TS 16949 standard—provide a set of quality system criteria necessary for firms to compete effectively (Franceschini, Galetto, & Cecconi, 2006).

Supporting these frameworks are well-established analytical tools that induce knowledge. Myriad tools exist in engineering to support structured problem solving endeavors. Failure Modes and Effects Analysis (FMEA) and Fault Tree Analysis (FTA), major tools for risk assessment, aid safety analysis by applying inductive (FMEA) and deductive (FTA) logics (US Nuclear Regulatory Commission, 1981). Life data analysis and physics-of-failure approaches in the framework of reliability engineering enable modeling of product failure patterns (Lewis, 1996). Designed experiments (often referred to as “DOE” in industry jargon) assist in establishing design parameters that optimize product performance (Barker, 2005). Cause-and-effects diagramming (Ishikawa, 1982) helps identify possible causes for a specific problem and continues to serve as an indispensable tool for structured problem solving, especially on the shop floor. Taken together, these methodologies facilitate the production and codification of useful product knowledge in both qualitative and quantitative forms.

Engineering problem solving, however, is not just about following prescribed steps and operating various tools to capture knowledge. Within each routine, there exist instances in which highly situated human cognition is more critical than consistency of action for reliable performance (Ndubisi, 2011). Further, technical know-how that drives engineering problem solving is tacit in nature and “raises […] interesting and complex issues regarding its transfer both within and between organizations” (Grant, 1996, p. 377). Seeing engineering problem solving from a perspective of consistency-flexibility interplay that leverages practical knowledge culminating in solutions, then, leads to several interesting questions. How do engineers go about defining a problem, which is the first step of any structured problem solving routine? How do they assign meaning to the problem, given the fact that real-world problems tend to be “ill-structured” (Jonassen et al., 2006)? How do engineers make sense of customer feedback from the field given that such information is noted for being incomplete and ambiguous (Wu & Meeker, 2002)? Setting parameters for reliability modeling (e.g., Weibull beta, Lewis, 1996) is as much art as science and requires a great deal of prior knowledge about the failure pattern (Abernethy, 2004; Nicholls & Lein, 2009). How do engineers go about pulling existing product knowledge, much of which is likely to be deeply embedded in local contexts, so they can make inferences about appropriateness of chosen design parameters? Likewise, for a designed experiment, identification and selection of experimental variables often require amassing knowledge from boundary-spanning areas of expertise. How do engineers balance diverse perspectives while accounting for resource constraints (Barker, 2005)? At the completion of a problem solving routine, such as the five-step DMAIC process prescribed by Six Sigma (Goh, 2002), how do engineers make sense of the outcomes? While past research has enriched the understanding of engineering problem solving from the "what" perspective, it has yet to offer in-depth analyses and answer to these "how" questions.

The gaps of the **how** of engineering problem solving in extant literature call for an alternate perspective that complements the existing orientation that emphasizes structural control and visible outcomes. Historically, engineering system / operations research frameworks treated human cognition as if it were perfectly rational (Gino & Pisano, 2007; Loch & Wu, 2007) on one end; as error-prone thereby requiring minimization on the other (Ndubisi, 2011). Altogether, they "invoked oversimplified models of motivation, learning, creativity, and other such aspects of human behavior that are vital to the success of management policies in practice" (Chopra, Lovejoy, & Yano, 2004, p. 13). Incorporation of elements that more realistically represent such human factors, therefore, will further enrich traditional models (Chopra et al., 2004). In this light, studies that address the behavioral and cognitive sides of engineering problem solving will be a useful addition to the research landscape.

The purpose of this dissertation research is to study engineering problem solving from experiential and cognitive perspectives and illuminate pathways to effective and efficient achievements of goals and outcomes. The core focus of the study is to explore how the dynamics of engineering knowledge that is embedded in local contexts can be leveraged to find solutions and achieve (or not achieve) sustained learning. Empirical studies have already established links between organizational antecedents and technical performance outcomes. Cumulative experience impacts product reliability (e.g., Ramdas & Randall, 2008). Organizational learning influences product quality (e.g., Levin, 2000). A socio-technical system that integrates learning-driven management philosophy and technical practices, exemplified by Toyota's lean manufacturing concept (Womack, Jones, & Roos, 1990), enhances operational sustainability. By framing engineering problem solving from both experiential and cognitive perspectives, and by focusing on tacit knowledge, this study expects to uncover the dynamics of how these links are formed and actually play out in practice. As Levin (2000) suggests, a more qualitative exploration into "the *how* of organizational learning curves[…] to probe more deeply inside the 'black box' of organizational learning" (p. 645) is a fruitful area of research.

This research is implemented as a two-stage inquiry process and addresses the following four questions:

1. How do engineers perceive problem solving prompted by product-related problems?
2. How is knowledge created through problem solving routines?
3. What conditions promote or inhibit problem solving and sustained organizational learning?

4. To what extent can the findings about engineering problem solving, knowledge creation, and organizational learning be generalized across engineering communities?

Due to the nature of the inquiry, which is both exploratory and confirmatory, the study uses both qualitative and quantitative research methods to leverage the distinct methodological strengths of each to answer these four questions (Creswell & Plano Clark, 2007). In the first stage, which addresses the first three questions, a qualitative investigation is conducted to explore the dynamics of engineering problem solving, discover key aspects of knowledge creation, and generate hypotheses to theorize how engineering knowledge obtained through problem solving is transformed into sustained organizational learning. The findings from the first stage are subsequently followed up with a confirmatory study using quantitative methods to test the hypotheses and answer the fourth question. By combining the inductive and deductive analyses that a mixed-methods approach enables (Johnson & Onwuegbuzie, 2004), the research framework intends to provide full coverage of the issues in question.

The unit of analysis throughout the two stages is "engineers" as the study focus is the "emic"[1] perspective of engineering problem solving. The study adapts Schein's (1996, p. 14) definition of "engineer" and "engineering culture" and broadly defines engineers as "designers of products and systems that have utility, elegance, permanence, efficiency, safety, and aesthetic appeal." In the first stage of the study, strict application of this definition limits engineers to those who are **directly** engaged in the design, application, or

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[1] The term "emic" was coined by a linguist, Kenneth Pike. It was later adopted by anthropology. An "emic" perspective (as opposed to its counterpart "etic") emphasizes the subjective meanings shared by the "natives" of a social group (e.g., engineering) and attempts to shed light on their "culturally specific model of experience" (Seymour-Smith, 1986, p. 92).

manufacture of a product. This definition is relaxed in the second stage to include those in engineering professions that play key technical support roles to the architecture or design of products, for example, quality, reliability, and field service engineers. Finally, the research framework adopts Lloria's (2007) perspective that knowledge creation is a direct outcome of organizational learning, despite the treatment in some of the literature of these two constructs as separate research streams. Knowledge is almost akin to "a stock" that is created through "a flow" of learning (Lloria, 2007, p. 675). Extending this viewpoint, in this study, organizational learning and knowledge creation are defined as having taken place when engineering problem solving, the learning flow, results in **system changes**.

The goal of this research is to develop a model for understanding and effectively managing the dynamics of engineering problem solving. The research framework draws heavily from Nonaka's knowledge-creation theory (Nonaka, 1994; Nonaka & Takeuchi, 1995; Nonaka, Toyama, & Konno, 2000), while building on the research stream of organizational learning (Fiol & Lyles, 1985; Huber, 1991; Levitt & March, 1988) and related concepts such as organized sensemaking (Weick, 1979, 1988; Weick, Sutcliffe, & Obstfeld, 2005) and absorptive capacity (Cohen & Levinthal, 1990; Eisenhardt & Martin, 2000). The outcomes of the study are expected to make a contribution in three major ways:

1. The research will help fill the gap in engineering management literature by providing a complementary perspective to engineering problem solving and exploring the little addressed link between organizational learning and engineering.

2. The results from this study are expected to further enrich the research landscape of organizational learning by offering empirical evidence of engineering knowledge creation dynamics.
3. For practitioners, the new perspective being developed from this research effort should contribute to enhancement of such areas as product development, warranty management, and operational sustainability in general.

Additionally, this study, to the best of our knowledge, will be the first to quantitatively model and test the concept of *ba*—an empirically underexplored yet critical ingredient of knowledge creation (Nonaka, von Krogh, & Voelpel, 2006). Within the framework of Nonaka's knowledge-creation theory, previous studies focused predominantly on Japanese and South Korean cultural settings and, more recently, on European firms (Schulze & Hoegl, 2006). Schulze and Hoegl's (2006) study on 33 European (German, Austrian, and Swiss) firms found no support for some researchers' "doubts about the transferability [of Nonaka's concept] from an Asian setting to European and North American contexts" (p. 225). Following their lead, this research will further the knowledge about the applicability of Nonaka's theory in non-Asian cultural contexts, which is an additional benefit of this study.

Past engineering problem solving research has offered a wealth of knowledge about structural control and its measurable outcomes. By exploring the cognitive aspects of engineering problem solving, the underlying process that creates knowledge and sustains organizational learning for competitive advantage is better understood. This enhanced understanding will contribute to building a more complete epistemology of engineering practices, particularly as they pertain to engineering problem solving.

CHAPTER 2: THEORETICAL FOUNDATION

Chapter 1 has illuminated the need for exploring the cognitive and experiential aspects of engineering problem solving and how they link to knowledge creation. Engineers solve problems every day, but the process through which the solutions become sustained learning is not well understood. Chapter 1, in closing, posed four basic questions:

1. How do engineers perceive problem solving prompted by product-related problems?
2. How is knowledge created through problem solving routines?
3. What conditions promote or inhibit problem solving and sustained organizational learning?
4. To what extent can the findings about engineering problem solving, knowledge creation, and organizational learning be generalized across engineering communities?

The goal of this chapter is to establish a theoretical foundation for addressing these questions, upon which to develop investigation strategies. The literature review in this chapter draws heavily from streams of extant research in organizational learning and systems theory, with particular focus on problem solving and failure management, to develop an initial conceptual framework for viewing engineering problem solving (EPS) as a knowledge-creation vehicle. The existing body of EPS literature that probes deeply into the lived lives of engineers is scarce and tends to be concentrated in engineering educational research (see, for example, Atman et al., 2007; Jonassen, Strobel, & Lee, 2006; Trevelyan, 2007; Williams & Figueiredo, 2010, 2011). In particular, the roles of organizational routines and tacit knowledge in enabling sustained learning in engineering contexts are little addressed.

In facilitating the literature review, engineering knowledge creation is viewed as a subset of general organizational learning that is facilitated in specific contextual settings. The remainder of this chapter is organized as follows. First, it establishes a link between problem solving and knowledge creation, as well as identifies key factors that enable this link. Secondly, the literature review explores the influence of organizational contexts on the EPS process and outcomes. Finally, the discussion zooms into the role of mental models in realizing sustained learning. The chapter concludes by establishing an initial view of EPS, as a set of exploratory and structured routines carried out in a dynamic socio-technical system.

Problem Solving as a Path to Knowledge Creation

The path to knowledge creation and sustained learning from problem solving is *double-loop learning* (Argyris, 1976) because that is the only way to make system changes. The discussions that follow first establish the role of double-loop learning in problem solving and demonstrate that it is not possible without a successful root cause analysis. Further, because of the nature of knowledge, especially its tacitness and sociality, effectiveness of a root cause analysis becomes very dependent on the protocols used as the discussions will illustrate.

Problem, problem solving, learning, and knowledge. Problem solving as a mechanism for learning is well recognized in the literature (Corti & Storto, 2000; Hedberg, 1981; Tucker & Edmondson, 2003; Tucker, Edmondson, & Spear, 2002). Learning tends to be triggered by problems, so problem solving is a dominant form of learning in many situations (Hedberg, 1981). Since engineering is really about solving problems (Jonassen et al., 2006), ample opportunities should be available for learning. The question is **how** the knowledge created from EPS becomes **sustained** organizational learning.

Organizational learning literature defines “problem” as the gap between the existing state and the desired state (Corti & Storto, 2000; Tucker et al., 2002), and “problem-solving” as a set of rational activities to reduce or eliminate this gap (Corti & Storto, 2000). If a car operates with a higher than expected noise level, then there clearly is a gap between the expected and observed performances. The implication, from the perspective of problem solving, is that how the "desired" state is defined will set the course for the problem investigation. Since "problem-solving framing naturally fosters identification of new interpretations of the situation" (Corti & Storto, 2000, p. 251), this framing will influence problem-solving outcomes. Improvements made over time in everyday products—from the reliability of passenger cars to the speed of computers—are all cumulative results of technical problem solving that set the goal to a higher state of product performance. In so doing, the interpretations of expected driving and computing have forever changed. No longer does anyone expect to carry spare automotive parts and tools on a casual holiday outing; nor do personal computer users think of processor speed in lower than GHz terms.

Huber (1991, p. 89) proposes that “an organization learns if any of its units acquires knowledge that it recognizes as potentially useful to the organization.” Organizational learning is about "a process of improving organizational action through better knowledge and understanding" (Tucker et al., 2002, p. 124). Further, organizational learning has taken place when system changes—such as changes in product, work designs, or routines—occur in response to new knowledge or insights that can improve the organization's performance (Dodgson, 1993; Tucker & Edmondson, 2003). Product features, blueprints, specifications, and design approaches are all engineering artifacts that reflect past system changes, which themselves are likely to have been prompted by previous EPS. Even though system changes can occur as a result of problem solving, however, the link between the two is not necessarily automatic. Not all problem-solving endeavors immediately—or ever—result in system changes. As often seen in the management of warranty claims, customer complaints, and in the worst case, recalls, there is a time lag (Hora, Bapuji, & Roth, 2011). Sometimes there is a considerable time span between a problem solving event and the eventual changes in the product, especially in a fast-paced industry such as consumers electronics (Magniez, Brombacher, & Schouten, 2009).

Organizational learning is about amalgamation of people's knowledge. The only way for an organization to "learn" is for its members to learn, specifically through the action of individuals who create ways in which organizational transformation can be facilitated (Dodgson, 1993; Senge, 2006). Learning produces knowledge, and a constructionist view of knowledge associates knowledge development with social interactions within the organization and thereby also associates knowledge with the cognitive characters of individuals (Corti & Storto, 2000). This view implies that the collective learning starts with individuals' tacit knowledge, and the manner in which these knowledge holders socialize greatly influences collective knowledge output. Because tacit knowledge is embodied in each individual and does not easily transfer to others (Edmondson, Winslow, Bohmer, & Pisano, 2003; Nonaka, 1994; Nonaka & Takeuchi, 1995), it will need to be transformed into a more portable form so it can be elevated to an organizational level. Tacit knowledge is closely tied to procedural knowledge or know-how; explicit knowledge, on the other hand, is often referred to as know-what or declarative knowledge (Edmondson et al., 2003; Nonaka, 1994). Engineers use both theories and practical know-how to design, test, and manufacture products. Thus, both types of knowledge—explicit and tacit—have close affinity with engineering.

Knowledge is transformable. Individual cognitive development is facilitated by processing of declarative knowledge into one's procedural knowledge (Anderson, 1993), and declarative knowledge was once upon a time someone's tacit knowledge that was later codified (Edmondson et al., 2003). Indeed, Nonaka (1994) argues that knowledge transformation can be bi-directional, capable of not only changing its state from one to the other but can also amplify by combining multiple knowledge sets of the same type. In other words, in his concept, knowledge can morph from tacit to explicit and vice versa, as well as from tacit / explicit to amplified tacit / explicit.

Double-loop learning. Problems trigger problem solving, but not all problem-solving endeavors result in learning. Double-loop learning (Argyris, 1976) links problem solving to organizational learning. Double-loop learning is a result of second-order problem solving immediately following first-order problem solving and is by definition required to effect fundamental system changes (Tucker & Edmondson, 2003). While first-order problem solving “fixes” the problem, the resulting learning—single-loop learning—does not question the organization’s fundamental norms and assumptions to look for better ways of doing things as does double-loop learning. If a car buyer’s complaint about an ill-functioning audio unit is resolved by merely replacing the unit without further investigation, no new knowledge is gained other than the fact that a complaint was received and a replacement was made. Yet, if the product developer seeks to understand why the unit did not work as intended, new insights about the audio unit's susceptibility to conditions affecting its design parameters can be gained.

Double-loop learning is possible only through a successful root cause analysis (Tucker & Edmondson, 2003). Originally developed in psychology and systems engineering, a root cause analysis seeks underlying causes by going beyond an analysis of symptomatic issues (Wu, Lipshutz, & Pronovost, 2008). A "root cause" is a condition, the elimination of which would have precluded the problem from occurring in the first place (Handley, 2000; Smith, 1998). Using the analogy of fire, without oxygen and fuel (underlying causes), sparks (direct cause) would not cause a fire. It is only through a successful root cause analysis to get down to the "bottom of it" to produce relevant knowledge needed for system improvements to "destroy existing premises and establish new ones" (Nonaka & Takeuchi, 1995). Therefore, knowledge creation is intimately tied to double-loop learning (Nonaka, 1994; Nonaka & Takeuchi, 1995), which root cause analyses support.

Structured problem solving methods used widely in engineering practice are designed to engender root cause analysis. Be they Five-Why's, Kepner-Tregoe, Six Sigma, or any other, all are intent on getting to the root of the problem and make systemic changes to prevent problem recurrence (Handley, 2000; MacDuffie, 1997; Smith, 1998). Structured problem-solving approaches are typically designed as multi-step investigation routines. While the actual number of steps varies among different methods, a structured problem-solving methodology normally begins with a problem definition and ends with a routinization of new solutions (MacDuffie, 1997). Particularly important here is the first step, which sets the tone for the remainder of problem-solving journey. Problem definition does not take place in a vacuum but rather is a reality that is "perceived by organizational actors in light of established routines" (MacDuffie, 1997, p. 481). How the problem is framed—for example, major versus minor, design-related versus process-related—will determine what and how much information to seek to understand the problem, the amount of effort exerted on analyzing the data, and how to go about selecting and implementing a solution.

Framing will also affect routinization of the new solution. Routinization is a result of successful double-loop learning. In order for double-loop learning to occur, the relevant knowledge generated during the root cause analysis, some (if not, most) of which is tacit, must eventually be translated into organization-wide routines. Routinization is achieved via codification of the learning and knowledge gained—that is to say, making the individual and group-level knowledge explicit—so the organizational members outside that group are able to adopt it. In engineering, for example, development of new design guidelines and specifications enables the deployment of codified knowledge. Because framing influences formation of attitudes and opinions (Chong & Druckman, 2007), the quality of tacit knowledge affected by framing effects permeates all the way into the quality of chosen solutions and their implementation effectiveness.

Justification. Cognitively speaking, problem solving can also be seen as an attempt to deal with uncertainty or ambiguity by trying to resolve or reduce this state (Corti & Storto, 2000). For example, an engineering problem, when first reported, may be as vague as "the car makes a lot of noise." The problem can be caused by any number of factors in the drivetrain, chassis, or anywhere else. Through iterative diagnostics, more insight is gained that infuses clarity into the picture. Thus, problem solving proceeds as actors' cognitive perspectives move progressively from fuzzy to less fuzzy—and eventually to "completely understood" if the root cause analysis is successful. A successful root cause analysis should take engineers "through a subtle game going from the creation of highly uncertain and ambiguous situations to the reduction of these” (Corti & Storto, 2000, p. 253). At the end of a successful double-loop learning routine, a new set of standards is created, through which "contradictions are resolved and concepts become transferable” (Nonaka, 1994, p. 21)—hence, a successful routinization.

A problem-solving environment does not transition from fuzzy to clear without a conversion mechanism. Bits and pieces of data initially available must be churned into a cohesive set of facts as the root cause investigation progresses. Learning, after all, is about human action (Senge, 2006). This aspect of learning lends itself to a subjective and context-specific nature of knowledge, which is consistent with a constructionist view (Corti & Storto, 2000). The subjective nature of knowledge points to a need for its validation. In other words, in order for knowledge to become an institutional-level logic set, it needs to be gauged and polished against a set of “standards” or “justification mechanisms” as Nonaka (1994) and Nonaka and Takeuchi (1995) conceptualize. As already touched upon, the quality of a root cause analysis depends on how causality is ascribed in light of what is deemed abnormal versus normal (Smith, 1998), that is to say, *framing*. MacDuffie (1997) cites, from his case study of three automotive plants, an example in which problem solvers operate with a preconceived notion (which is developed through iterations of past problem-solving experience) that design-related changes are nearly impossible to implement due to organizational constraints. Having learned that the “normal” problem-solving framework is to stay within the boundary of product features that can be controlled without involving design engineering, the root cause investigation team attempts to assign causality to only the aspects that can be worked out directly between the plant and its suppliers—eliminating opportunities for potential design improvements. Causality, thus, can largely be a mental construction and is influenced greatly by the organizational justification logic provided. Somewhat akin to the control logic for an embedded (i.e., microprocessor-based) system, it is this justification mechanism that first elevates the outcome of a first-order problem solving to a cause worthy of further investigation in the second-order problem solving; facilitates cause assignment that "makes sense" to the entire problem-solving team; and provides algorithms necessary to work each bit of data to transform the system status from less coherent to more coherent, culminating in a clear set of executable directions.

Organizational Contexts

If an EPS effort is to culminate in learning, stewardship must be provided to help transition the actors' cognitive perspectives from fuzzy to clear and to raise the group knowledge from local to a higher level. Contextual factors greatly influence problem solving and resulting knowledge and learning. The discussions that follow explore organizational contexts and their effects on EPS. The EPS environment viewed from a system perspective provides a powerful explanation for factors that inhibit or promote learning.

EPS environment as a socio-technical system. The quality of organizational knowledge creation depends heavily on the social interactions that take place within a cultural milieu (Corti & Storto, 2000; Dodgson, 1993; Nonaka, 1994; Nonaka & Takeuchi, 1995; Simon, 1991). EPS may very well be viewed as an exercise that plays out in a socio-technical system. Every non-conformance is ultimately traced to system design, as evidenced by many documented failures of quality / process improvement initiatives. Organizational initiatives, such as Lean, fail to take root unless implemented with concerted effort to appropriately alter the organization's culture, which a socio-technical system engenders (Carroll, Rudolph, & Hatakenaka, 2002; Senge, 2006). Lean operations **emerge** from a purposefully constructed system architecture (Liker & Morgan, 2006; Womack, Jones, & Roos, 1990). Likewise, as Leveson (2011) argues from a product safety management perspective, safety is an emergent property of a socio-technical system. Similarly, quality does not just happen; quality management is effective only so far as the system enables it (Crosby, 1979; Deming, 1982). Learning from EPS, then, is also an emergent property of the socio-technical system in which the problem-solving activities occur.

Following Leveson's (2011) application of system controls theory to a human socio-technical structure, an EPS environment may be conceptualized as a controller that **dynamically** controls a problem-solving process using a set of algorithms. Further, from the perspective of safety management, Leveson (2011) draws attention to three insightful characteristics of a dynamic system: It (1) has interacting components; (2) can change over time (often referred to as "asynchronous evolution"); and (3) requires feedback to maintain a desired state, for example, gauging how successfully the intended functions are being performed. Implications of the first point are that a well-functioning system is one in which all parts are operating together in a seamless manner. Leveson (2011) argues that accidents or failures are often a result of dysfunctional interactions among the system components. The success of the Toyota Production System—hailed as the founder and master of Lean—is attributed to a well-orchestrated system of reciprocal obligation among workers, management, and suppliers who support each other for a collective cause (Liker & Morgan, 2006; Womack et al., 1990). In EPS situations, inter-dependencies of system components have implications in the way information is shared among all stakeholders. EPS is typically a cross-functional endeavor as the product complexity of this day and age surpasses the technical expertise possessed by any one engineer. More often than not, the problem itself is a complex system of various hardware and software sub-systems and components. Information sharing among subject-matter experts helps pinpoint areas of interactions among these components. The key, then, is to facilitate healthy interactions among team members and stakeholders who may not, at first, necessarily share the same technical views. Effective information sharing in a root cause analysis context should create new opportunities for people to communicate with each other, as well as constructively challenge each other to rethink their assumptions (Carroll et al., 2002).

A dynamically-operating system can change its state in a fraction of a second, as well as evolve over time. Socio-technical systems in the context of single- and double-loop learning can exhibit similar behaviors. Just as any system control loop includes time lags between the receipt of input and generation of output, there is a time lag before single-loop learning has a chance to advance to double-loop learning. If this time lag is too great, first-order problem solving will be less likely to develop into second-order problem solving because valuable information gained from the single-loop learning has been lost. As Tucker and Edmondson (2003) and Tucker et al. (2002) demonstrate in their case study of a healthcare unit, a socio-technical system that encourages “problem-solving behaviors that focus solely on remedying or overcoming immediate obstacles preclude organizational learning…[partly] because valuable data that can be used to justify and inform removal effects are lost” (Tucker et al., 2002, p. 123).

In addition to the input-to-output conversion time span, in a closed-loop control system there is also the time lag that is associated with the system’s feedback on the generated output. At every iteration of problem investigation that ends with first-order problem solving, that is, without proceeding to second-order problem solving, the extent to which the feedback is delayed has a profound effect on the future state of the system. If the delay is excessive or near infinity—in other words, feedback never comes or comes only after the problem occurrence frequency has reached a major crisis level—the system is effectively endorsing the short-term effectiveness of first-order problem-solving behaviors. Such feedback diminishes the motivation for second-order problem-solving efforts. Over time, with multiple iterations of such lost opportunities for second-order problem, the system eventually evolves into a stable state in which repeated short-term fixes become a normal way of life. If engineers continuously "explain away" or "write off" problems with no further action, lack of engineering system response to question such behaviors has effectively established the premises of single-loop learning that are now ingrained in the organizational culture. Such a system may be "stressful, but basically in balance…[leading to] worker burnout…[which] further decreases the chance of effortful engagement in second-order problem solving" (Tucker & Edmondson, 2003, p. 66).

Structural controls and exploration. Viewing EPS environment from a system perspective sheds light on the dynamics of the double-loop learning process and how the socio-technical system itself can dynamically adapt through behaviors of the controller. The controller, in this case, is the one that controls the problem solving process and environment, to which the system feeds back response signals prompted by the process outcomes. The controller is a critical component of a system. Akin to the electronic control unit in a piece of complex machinery, organizational routines fulfill the process control function in a socio-technical system. Organizational routines are "forms, rules, procedures, conventions, strategies, and technologies" but also include more intrinsic factors such as "the structure of beliefs, frameworks, paradigms, codes, [and] cultures" (Levitt & March, 1988, p. 320). In the context of EPS, routines are analogous to algorithms that purposefully process data and convert them into executable instructions to run the problem solving process.

EPS routines are essentially knowledge-transfer mechanisms that leverage tacit knowledge embedded in local engineering contexts. Tacit knowledge by its nature is idiosyncratic because it is held by individuals coming from varied backgrounds (Nonaka, Toyama, & Konno, 2000; Nonaka, von Krogh, & Voelpel, 2006). The heterogeneity of tacit knowledge makeup makes its transfer far more susceptible to coordination mechanisms than knowledge already explicitly written on paper or expressed in a hardware form. The choice, sequence, and combination of routines introduced at the right time maximize effectiveness and efficiency of tacit knowledge transfer. For example, an experienced engineer may immediately seek cross sectioning and metallurgical analysis in an attempt to find a root cause of a failed microelectronic component. A less experienced engineer, on the other hand, may first have to learn about such techniques as scanning electron microscopy and energy dispersive spectroscopy. Depending on the knowledge level of the EPS team, the investigation may begin with a hypothesis grounded in previously experienced failure incidents or an open-ended brainstorming session to find a clue on where to begin. If the level of expertise or analysis capability required for problem solving is not available in-house, the engineer may have to coordinate with his purchasing department to outsource the needed service. All of these factors change the nature of dialog and logistics in EPS, which the organizational routines can help or inhibit. In other words, an EPS process, having a high tacit knowledge content, can be a very path-dependent affair (Edmondson et al., 2003).

Some routines are oriented more towards exploration of new ideas than exploitation of existing premises (Bartel & Garud, 2009; March, 1991) and vice versa. Consequently, matching tasks with appropriate execution routines based on the task characteristics is a logical thing to do—since some tasks are more effectively executed by explorative routines than narrowly prescribed set of directions. In some contexts, the nature of business is such that both types of routines can exist side by side in an organization. Hwang and Christensen (2008) argue, for example, that the existing healthcare system is a mixture of both the explorative and routine elements. They call the former "solution shops" which are characterized with high ambiguity and uncertainty and rely exclusively on the highly-situated human cognition of physicians. The latter are "value-adding processes" that is more repetitive in nature such as routine diagnostics performed by nurses and billing specialists. For EPS, how the routines are applied at various phases of root cause analysis may be critical. Edmondson et al. (2003) argue for contingent thinking that matches knowledge contents of tasks to appropriate routines. They argue that an effort to adopt practices based on codified knowledge may benefit from a straight transfer by copying existing best practices. Practices that have a high tacit knowledge content, on the other hand, may be more appropriately implemented in an improvisational, learn-by-doing environment. Following their logic, then, it makes more sense to enact an environment that fosters a forward-looking, explorative outlook in early phases of EPS when engineers must confront ambiguity. As the root cause investigation moves toward completion, the routines should exercise control to standardize and deploy across the organization the new solutions that the investigation has discovered.

Routines can be structurally induced. For example, Schroeder, Linderman, Liedtke, and Choo (2008) discuss Six Sigma as one of the methodologies that facilitate structural controls and structural exploration simultaneously through systematically executed routines. Structural exploration is conducive to early phases of EPS when the level of ambiguity is high. Purposefully designed training routines, such as those used by Six Sigma, can not only facilitate acquisition of technical problem solving skills but also provide a forum for socialization and learning the basic values underlying the process improvements (Schroeder et al., 2008). Schroeder et al. (2008) argue that Six Sigma training institutes a “common language” and enhances boundary-spanning communication as a result, which greatly facilitates opportunity exploration. Similarly, MacDuffie’s (1997, pp. 495-497) shop-floor case study reports that Honda’s “actual place, actual situation” dialog policy implemented through “spontaneous meetings” (coined “Y-gaya” at Honda) is likely to “yield a common language and a common understanding of what standards should be applied to deciding what will or won’t be defined as a problem” in the problem definition phase. At the same time the exploration of improvement opportunities is pursued, Six Sigma’s five-step DMAIC (= define-measure-analyze-improve-control) meta-routine coupled with periodic toll gate reviews to assess progress acts as a form of structural and behavioral control to ensure consistency in approach (Schroeder et al., 2008). In EPS, any structured problem-solving methodology, such as 8D and Five Why’s, has the capability of doing the same.

Transition from structural exploration to structural controls as the root cause analysis nears its end may be induced by routines such as experimentation and pre-/post-data comparison to confirm efficacy of the chosen solution (MacDuffie, 1997). Such transition routines ready the system for complete standardization. The basic principles of statistical process control and Kaizen dictate that the system must first be stabilized and standardized before the next rounds of continuous improvement can begin (Deming, 1982; Liker & Morgan, 2006; MacDuffie, 1997). In this light, Liker and Morgan (2006) and MacDuffie (1997) argue, structural controls that foster a mental vision that the end of this problem-solving journey may be the start of a next one should help keep the performance frontier open. Structural exploration and control, thus, can be induced. Both are needed and both need to be introduced at appropriate times as the EPS effort is underway, thereby achieving both adaptability and efficiency.

Deliberate creation of contexts. Structural exploration seeks to evoke innovative ideas while structural controls target consistency. In this vein, Liker and Morgan (2006) demonstrate how the Lean / Toyota Production System (TPS) principles—which are now widely deployed in manufacturing areas across industries—may be applied to the product development process (PDP). Their idea of a "lean PDP" is expressed in terms of a four-step process that begins with establishment of customer values—followed by exploration of various solutions—and ends with a standardization of activities (Liker & Morgan, 2006). From the perspective of context-induced routines, these four steps are very much analogous to structural exploration eventually transitioning into a routinized operation. Organizational contexts that prompt different routines can be—and probably should be—deliberately created, especially in EPS effort because a swift resolution of the problem is usually desired.

Effective problem-solving contexts, indeed, can and should be created through a deliberate effort. As chronicled in MacDuffie's (1997) case study of three automotive manufacturing plants, problems are "fuzzy" in their definition when first discovered. If the plant's "quality systems force problems into one category or another…the benefits of rich, ambiguous data will be lost and the search for solutions may be misdirected" (MacDuffie, 1997, p. 498). In an EPS context, if the problem solvers know from the start that a particular categorization of the problem can lead to a potential solution that management would not approve until the next model change, they might try to steer the root cause analysis to assign causality to other product features that are less difficult to convince management to be potential solutions. MacDuffie (1997) notes the powerful effects that the system imposes upon problem framing by contrasting two scenarios observed in his case study. One is a plant operation routine at an American automotive manufacturer that requires, at the start of a problem investigation, charging costs for resolving the problem to specific parties; the other is a practice at a Honda manufacturing facility, whose "accounting system is deliberately designed to minimize the time spent figuring out who's to blame" (MacDuffie, 1997, p. 488). Openness in the information exchange resulting from the system feedback to endorse "Five Why's"—rather than "Five Who's"—in the latter case is dramatic. Such is the power of system feedback.

A system eventually becomes what its feedback mechanism instructs it to be (Leveson, 2011), as discussed earlier on how too much success in first-order problem solving in a context that does not support double-loop learning further amplifies single-loop culture (Tucker et al., 2002). Once again using the system controls analogy, contexts can serve as a feedback mechanism to encourage or discourage particular routines. For example, Jidoka, which is one of the building blocks of the TPS (Liker & Morgan, 2006), provides a mechanism for assemblers to call for help if a problem is detected in the assembly line. The mechanism is the Andon system, another signature item of TPS, which uses lights and sounds to announce detection of a process deviation (Liker & Morgan, 2006). When an operator activates the Andon, help arrives—"not in the next few hours but in the next few seconds" (Liker & Morgan, 2006, p. 7). The immediacy of attention to the help request then feeds back a signal to the "controller" (i.e., the operators) assuring the legitimacy of Andon action and restoring the system state to that which TPS continuously strives to maintain.

Feedback, in the context of knowledge construction, is essentially a justification mechanism to align quality of knowledge with the organization's vision (Nonaka, 1994). The physical presence of managers participating in the dialog about problems, right at the spot where they were discovered—demonstrated by the Gemba-Genjitsu policy practiced by Honda and Toyota (Liker & Morgan, 2006; MacDuffie, 1997)—helps build common language and definition of the issue at hand. Such active and direct management participation encourages boundary crossing, assures psychological safety, and thus promotes structural exploration (Tucker & Edmondson, 2003). Likewise, deliberate attempts to foster creative tension, i.e., a positive tension between constancy and change, also enhance structural exploration (Fiol & Lyles, 1985; Senge, 2006; Womack et al., 1990). Effective use of EPS goals, such as that which is demonstrated by Six Sigma's goal-focused approach, can influence the members' perceptions about their "performance frontier" (Linderman, Schroeder, Zaheer, & Choo, 2003).

Role of Mental Models

Equating the EPS socio-technical environment with a "system" has illuminated system feedback as a justification mechanism for the EPS action. In system controls, proper feedback provided at the right time keeps the controller healthy. In a microprocessor-based, embedded system, it is the health of this microprocessor that is central to ensuring correct operations of the controller. Further delving into the system analogy, one could say that the role of microprocessor equates to that of mental models, shared by people on the problem-solving team. A system without an effective feedback loop drives people to substandard alternatives by adversely influencing their mental models.

Bounded rationality. Humans can be rational only to the extent that their surrounding environment allows them to be (Leveson, 2011; Senge, 2006), which is a bounded-rationality problem (Simon, 1991). The theory of bounded rationality—which is "about the limits upon the ability of human beings to adapt optimally, or even satisfactorily, to complex environments" (Simon, 1991, p. 132)—helps explain how organizational factors can affect the state of the mental model held by each EPS player. An organization learns only through its people, and their learning will go so far as "their ability to interpret complex reality" (Dodgson, 1993, p. 384). One of the extensions of bounded rationality, which is particularly relevant in EPS contexts, is that people rarely attempt to go beyond the perceived system boundaries so "the learning process is generally conservative and sustains existing structures of belief" (Dodgson, 1993, p. 385). For a double-loop learning process to occur, therefore, problem solving must be framed in such a manner as to help the members overcome their own mental boundaries. If contextual factors are overly restrictive—for example, forcing the problem into pre-set categories or restricting the repertoire of corrective actions from the beginning—will further inhibit the problem solvers' mental frontiers and in turn cause their investigation scope to atrophy (MacDuffie, 1997). A reduction of the problem-solving frontier will undoubtedly affect quality of learning.

EPS is normally instigated by a performance failure. While mistakes and errors are opportune triggers for problem solving and thereby setting a launch pad for learning (Scott & Vessey, 2000; Tjosvold, Yu, & Hui, 2004)—more so than the experience of success

(Baumard & Starbuck, 2005)—impediments exist that can inhibit learning from failure. Potential barriers to learning are embedded in both the technical and social systems and will need to be addressed through measures such as information systems, systematic reviews, training, availability of needed expertise, and deliberate postulation of "failure as opportunity" to ensure psychological safety (Mark D. Cannon & Edmondson, 2005). Managerial behaviors that dismiss "small" failures result in reinforcing existing premises and over time give consistent patterns to these failure incidents (Baumard & Starbuck, 2005). Eventually, these patterns will settle into a "normal state of affairs" now firmly ingrained in the organizational members' mental models. Similarly, a punitive or controlling response to errors—such as "shoot the messenger"—would reinforce mental barriers to the open flow of information and discourage participation in double-loop learning (Carroll et al., 2002; Leveson, 2011). Hence, in order to effectively learn from failure, deliberate—not haphazard—attempts should be made to preclude undesired psychological interference. Effective and speedy completion of EPS requires opportunity framing to assure freedom to define the problem, not unduly constrained by costs, politics, or other organizational factors. Such freedom actively steers information processing and keeps the momentum going toward problem resolution (Mark D. Cannon & Edmondson, 2001; Mark D. Cannon & Edmondson, 2005; Carroll et al., 2002).

Intuition-reason balance. Bounded rationality in double-loop learning, through which a problem must be transformed into a new solution that triggers system changes, has a profound effect on the state of mental models. A mental model is concerned with the interplay between intuition and reason, which must be properly balanced to achieve the model's maximum potential (Senge, 2006). In EPS contexts, then, if the socio-technical system is such that it places too much emphasis on highly situated human cognition—without providing a mechanism to systematically and routinely address problem solving issues—the mental model will never reach an optimal intuition-reason balance.

An account of single-order problem solving in a healthcare unit chronicled by Tucker and Edmondson (2003) demonstrates how a system that emphasizes individual vigilance and personal accountability without providing support structures goes into a perpetual cycle of reactive behaviors (Carroll et al., 2002; Senge, 2006; Tucker & Edmondson, 2003). Over time, mental models operating in such a system eventually “collapse”—leading to the high personnel turnover chronicled in the case study (Tucker & Edmondson, 2003). Learning, hence, cannot be expected from a system that continuously employs “symptomatic solutions as if they are fundamental solutions, [as] the search for fundamental solutions stops and shifting the burden sets in” (Senge, 2006, p. 110).

Borrowing Leveson’s (2011) system analogy, akin to a microprocessor in a controller, problem solvers’ mental models dynamically seek intuition-reason balance through constant justification provided by the system’s feedback loop to counteract changes in the environment. Weick and Sutcliffe's (2007) “high reliability organization (HRO)” concept, for example, offers a practical strategy for developing resilience against crisis situations. They identify five characteristics that HROs appear to have in common: *pre-occupation with failure*, *reluctance to simplify*, *sensitivity to operations*, *commitment to resilience*, and *deference to expertise*. Put together, these five principles form a deliberate strategy of organizational *mindfulness* to promote properly-situated human cognition and keep organizational members’ mental models robust. In the context of EPS, therefore, properly administered structural controls and exploration routines discussed earlier should also play a role in maintaining a healthy mental model.

Intention as a system boundary. The impact of bounded rationality is that people rarely question their own conclusion-drawing processes (Carroll et al., 2002); that our mental models are often systematically flawed, missing critical feedback, misjudging time delays (Senge, 2006); and that people essentially will not do what does not make sense to them (Leveson, 2011; Senge, 2006). Further, as the system dynamically changes its state, what made sense at one time may not any longer—the reason that, according to Leveson (2011), "instructions and written procedures are almost never followed exactly as operators try to become more efficient and productive and to deal with time pressures" (p. 41). Similarly, as Smith (1998) demonstrates in his example of shop-floor problem solving, parts coming out of the American factory's final run each day were of substantially lower quality than its Japanese counterpart because American workers, in a hurry to get home, did not cool furnaces as slowly as they should. Understanding of human behavior in different contextual settings led to this root cause that is deeply tied to bounded rationality.

Leveson (2011) argues, from a safety management point of view, that better learning is achieved by framing accidents not as events stemming from operator errors but as a "sense-making" events. She advocates that we change "our emphasis in analyzing the role of humans in accidents from what they did wrong to **why it made sense** [emphasis added] for them to act the way they did" (Leveson, 2011, p. 39). Leveson (2011) argues that causes of an accident ultimately point, not to the operators or faulty components, but to a lack of properly administered system constraints that gave rise to faulty behaviors. What is meant by "constraints" is a set of explicitly stated value criteria that provide a yardstick for judging legitimacy of one’s action (Leveson, 2011). Depending on the nature of the system, the constraints may be a set of engineering requirements or a safety mission statement such as “Water quality must not be compromised” (Leveson, 2011, p. 86). Enforcement of system constraints, Leveson (2011) argues, along with the system feedback administered appropriately at appropriate times, help limit the type of undesirable changes from occurring in the system while allowing maximum flexibility and improvement.

Leveson’s (2011) concept of system constraints is very analogous to Nonaka’s (1994) and Nonaka and Takeuchi’s (1995) concept of “intention.” Intention is an organizational vision that sparks knowledge creation and serves as judgment criteria for the type of knowledge to be developed. Similarly, Deming (1982) advocates that quality starts—and can only start—with the organization’s intention and constancy of purpose expressed by senior management. Placing these concepts in an EPS context, it can be envisioned that an effective EPS environment would have problem-solving goals explicitly expressed by a high authority. These goals then set the system boundaries that will provide a frame of reference for problem resolution and sustained learning.

Initial View of Engineering Problem Solving

Engineering problem solving (EPS) is, hence, conceptualized as an epistemic journey to conquer ambiguity by dynamically converting tacit knowledge into explicit knowledge. The goal of this journey is double-loop learning, that is to say, system changes. Further, situating EPS as a set of routines that dynamically take place in a socio-technical system lends itself to a system controls analogy. Analogous to an engineered embedded control system, the EPS environment can be characterized with problem-solving goals and vision, akin to system constraints, which provide the initial trigger needed to put the first-order problem solving onto the launch pad for the second-order problem solving; and with structurally induced control and exploration routines that serve as the control logic that operates the problem-solving activities. Furthermore, similar to a closed loop control system, these routines are adjusted by input from a higher authority—for example, management—serving as a sensor that feeds back data to communicate the system state. The amount, quality, and timing of this sensor feedback will intimately affect the information processing power of the EPS team, very akin to that of a microprocessor.

In conclusion, a socio-technical system that properly bounds EPS contexts with appropriate constraints and feedback that adjusts with time is likely to promote streamlined root cause analysis, knowledge creation, and thereby sustained learning. Such a system provides effective justification mechanism throughout the EPS journey and by so doing facilitates properly balanced cognitive state to keep the problem solvers’ mental models healthy.

CHAPTER 3: METHODOLOGICAL APPROACH

This dissertation research is implemented as a two-stage investigation that follows the "exploratory sequential" research design within mixed methods approaches (Creswell & Plano Clark, 2007). In this design, the focus is exploratory. The investigation begins with a qualitative study, which is then followed by the second study that collects and analyzes quantitative data to confirm or further explain the qualitative findings. The quantitative phase, thus, builds on the preceding qualitative phase by connecting the two sets of data obtained sequentially (Creswell & Plano Clark, 2007). Themes resulting from the qualitative data are to be analyzed to form a theoretical model, which is to be subsequently tested in the quantitative study. The expectation of this approach is that the qualitative findings and their analysis and interpretations provide a general understanding of the phenomena of interest; that once relevant variables are identified, the quantitative study can help measure their significance and relationships (Creswell & Plano Clark, 2007).

The remainder of this chapter discusses the strategy for implementing the exploratory sequential protocol in detail. It does so by first providing a justification for using a mixed methods approach, the exploratory sequential design in particular. Subsequently, planned designs and methods for executing the qualitative and quantitative studies are presented. Note that the scope of this chapter stays within the **strategic** aspects of implementing the two studies. Methodological specifics such as interview protocol (qualitative study only), hypotheses (quantitative study only), and data analysis tools and procedures will be discussed in detail in conjunction with the study findings in the subsequent two chapters.

Rationale for Mixed Methods

The central premise of a mixed methods research approach is that quantitative and qualitative methods in combination can provide a better understanding of the phenomenon under study (Creswell & Plano Clark, 2007; Johnson & Onwuegbuzie, 2004). In a qualitative study, people's voices are directly heard. Qualitative data are rich in nuances and subtle cues, which are directly observable. Findings from a qualitative study help researchers understand the contexts in which actors express their views. Such richness of data content cannot be delivered by a quantitative research design. While lacking contextual richness, however, quantitative study findings are far-reaching. A quantitative study can encompass a wide audience efficiently, which is difficult to achieve with a qualitative investigation. In other words, a quantitative methodology is much more suited if the focus of the investigation is to study the generalizability of hypothesized trends. Thus, a qualitative investigation can work to reveal important variables in the phenomenon of interest, which may be evaluated quantitatively to ascertain their relevance and applicability to wider audiences (Creswell & Plano Clark, 2007; Johnson & Onwuegbuzie, 2004). Simply stated, the two methods put together are more likely to offer comprehensive evidence and answers to the research questions that neither method alone can effectively address.

As discussed in the first chapter, there are four questions that guide this research. They are re-stated below:

1. How do engineers perceive problem solving prompted by product-related problems?
2. How is knowledge created through problem solving routines?

3. What conditions promote or inhibit problem solving and sustained organizational learning?
4. To what extent can the findings about engineering problem solving, knowledge creation, and organizational learning be generalized across engineering communities?

The first three questions are about “how” and “what”—rather than “how many” or “how much”—and so are qualitative in nature. The experiential aspects of engineering problem solving (EPS), in the eyes of engineers as the chief actors, constitute unknown entities which is best approached using field work with an inductive orientation (Koro-Ljungberg & Douglas, 2008; Strauss & Corbin, 1998). The need to extract intricate details from the actors’ responses without prior knowledge naturally points to a qualitative approach (Ercikan & Roth, 2006; Koro-Ljungberg & Douglas, 2008; Strauss & Corbin, 1998). The fourth and last question, on the other hand, logically lends itself to quantitative analysis methods—once the important variables that answer the first three questions become known.

This research has as its aim to develop a model of EPS and resulting knowledge creation. The inquiry is exploratory in nature because, as Creswell and Plano Clark (2007) suggest,

- The variables are unknown
- No guiding framework or theory exists

In such a case, the exploratory sequential design is ideal because it seeks to “explore a phenomenon in depth and then measure its prevalence” (Creswell & Plano Clark, 2007, p. 75). Hence, a two-phase sequence strategy to first identify important variables and to later generalize the findings across a large group is warranted.

Shown below is a process flow diagram that depicts the study procedures, adapted from Creswell and Plano Clark (2007):

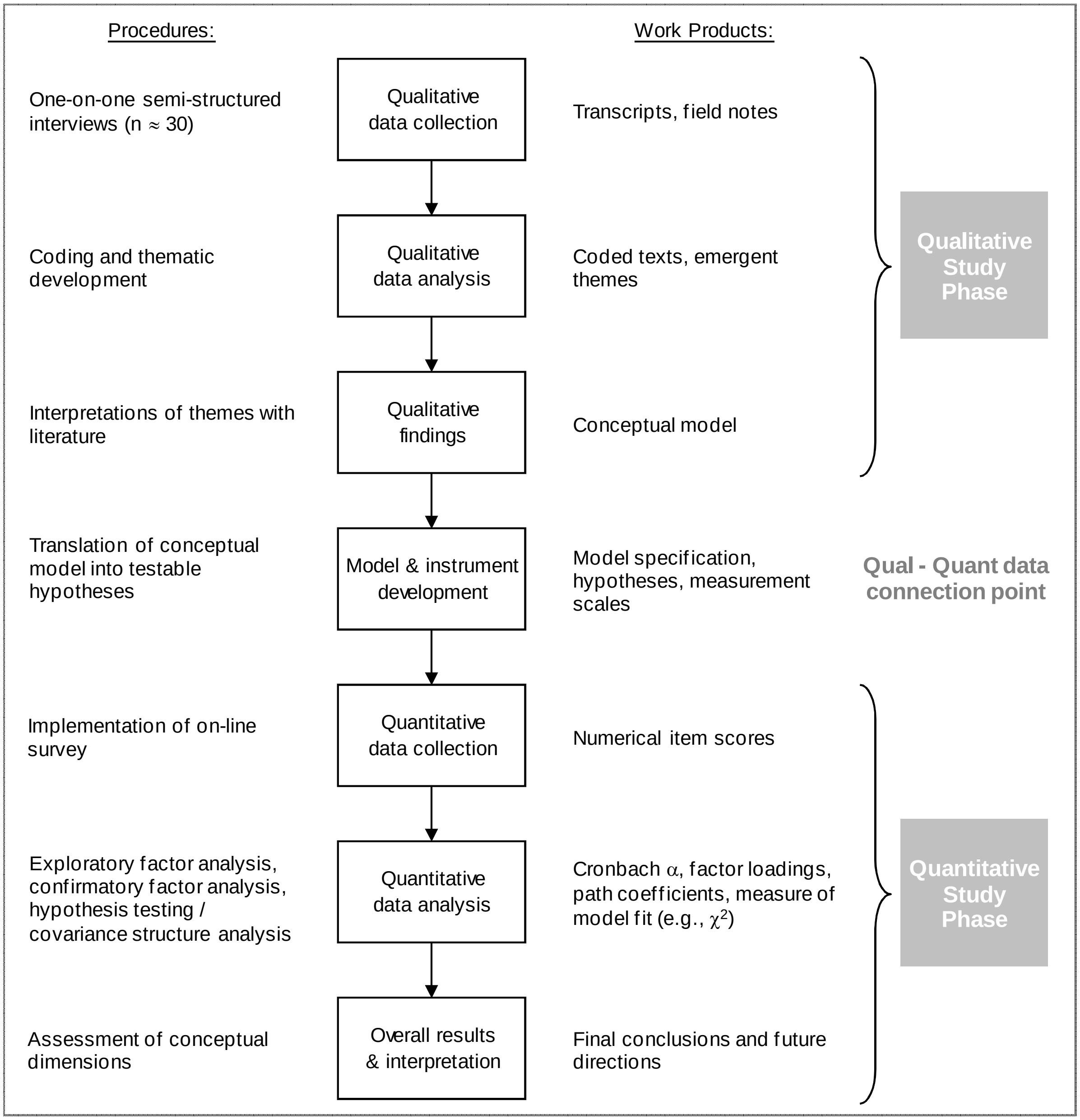

Figure 1. Process flow diagram for the proposed two-phase sequence study design. Adapted from *Designing and Conducting Mixed Methods Research* (p. 53) by J. W. Creswell and V. L. Plano Clark, 2007, Thousand Oaks, CA: Sage Publications. Copyright 2007 by Sage Publications, Inc.

As shown in Figure 1, an instrument to measure the variables identified based on the participants' qualitative responses is to be developed during the intermediary stage that transitions the research from the first phase to the second. The design and methods for each study phase—qualitative then quantitative—are presented next.

Qualitative Study

The design and methods for the qualitative study follow a grounded theory approach. Grounded theory is well-suited to this investigation phase, which attempts to uncover complex processes in potentially intricate contexts (Corbin & Strauss, 1990; Strauss & Corbin, 1998; Suddaby, 2006; Vandenbosch, Saatcioglu, & Fay, 2006) of EPS. Grounded theory aims to develop a theory and makes "knowledge claims about how individuals interpret reality" (Suddaby, 2006, p. 634). The major goal of this study phase is to develop a conceptual model of EPS dynamics, which grounded theory is expected to facilitate.

Sampling procedures. "Product engineers" who have product-related problem-solving experiences are expected to constitute the sample for this study. Potential respondents are to be recruited from the author's personal networks, and the recruitment effort is to be augmented with snow-balling techniques to reach desired sample size and composition. For the purpose of this study, "product engineers" are "designers of products and systems that have utility" as Schein (1996, p. 14) defines. Exercising a strict interpretation of this definition, the sourced respondents are to be U.S.-based technical professionals who take ownership in designing, applying, integrating, or manufacturing products. A "product" may be a physical entity, software, or an information technology (IT) architecture. "Product-related problem" can include any problematic issue that pertains to design, application, testing, manufacturing, servicing, or field usage of the product.

Grounded theory, by its design, does not dictate sample size and composition *a priori*. Instead, the approach relies on "theoretical sampling," which is a process of sampling responses to generate comparisons between them until no new data appears (Corbin & Strauss, 1990; Douglas, 2003; Suddaby, 2006). Theoretical sampling is closely tied to grounded theory's central tenet, "method of constant comparison" (Corbin & Strauss, 1990; Douglas, 2003). The method of constant comparison principle denotes an iterative process of continually interacting with the data, gradually advancing from coding to conceptual categories and eventually to theory development (Corbin & Strauss, 1990; Douglas, 2003; Suddaby, 2006). As new insights unfold during the data analysis, the sample may require adjustments. Sample recruitment is expected to continue until the data analysis demonstrates that conceptual saturation has long since been reached.

Permissions needed. Permission to conduct the qualitative study has been granted by Wayne State University's institutional review board (IRB) through IRB's Expedited Review process. Details of this IRB filing are available under HIC #088509B3E and Protocol #0908007458. Included in the IRB filing is information on how the respondents' anonymity and confidentiality are to be assured.

Data collection and recording. Data collection is to be accomplished by means of personal interviews, either face-to-face or by telephone, conducted by the author. Each interviewee is to be asked to narrate "stories" from his or her past product-related problem solving experience. With each interviewee's approval, the author plans to digitally record the interview and subsequently to have the recording transcribed. Should a respondent choose not to grant permission for audio-recording, the author is prepared to develop a transcript based on her notes taken during the interview. This transcript is to be subsequently reviewed and approved by the interviewee for accuracy. The interview is to be administered in a semi-structured format using a pre-fabricated interview protocol, which may require adjustments based on the new insights that in-process findings reveal.

Data analysis. Qualitative data analysis normally starts with coding text segments, proceeds to theme formation, and eventually arrives at broad generalization by inter-relating the emergent themes (Creswell & Plano Clark, 2007). In grounded theory, data analysis is concurrent with data collection (Corbin & Strauss, 1990). Thus, the data analysis is to begin immediately after the first interview. The entire procedure works to synergize “emic” and “etic” approaches. While an emic outlook is an insider’s view of the culture under study, the etic perspective seeks generalized cultural principles as an outsider to that culture (Morris, Leung, Ames, & Lickel, 1999). The emic approach pursues “tribal knowledge” that is deeply situated in a bounded milieu (Ybema, Yanow, Wels, & Kamsteeg, 2009). The etic investigation, on the other hand, is concerned about discerning the “differences across cultures in terms of a general, external standard” (Morris et al., 1999, p. 781). The data analysis in grounded theory, as such, works in such a way as to “combine emic understanding with etic analysis” (Ybema et al., 2009, p. 11) and proceeds in three steps.

The first step is “open coding” (Corbin & Strauss, 1990; Douglas, 2003; Walker & Myrick, 2006). Open coding is a rigorous process of reading each transcript line-by-line and identifying “codable moments”—which are words, phrases, sentences, or paragraphs of potential significance (Corbin & Strauss, 1990; Douglas, 2003; Walker & Myrick, 2006). These textual segments are categorized and assigned labels. These categories are not selected *a priori* but are rather allowed to emerge directly from the data, that is, the engineers' voices. Thus, the open-coding phase has a heavy emic leaning to attain "thick description" (Morris et al., 1999) to maximize the gain of initial data exploration.

The second step is "axial coding" (Corbin & Strauss, 1990; Douglas, 2003; Walker & Myrick, 2006). The activity in this phase involves clustering the open codes around specific points or conceptual "axes" (Corbin & Strauss, 1990; Douglas, 2003; Walker & Myrick, 2006). Here, the process starts to interact with the etic domain. The purpose of axial coding is to understand categories in relation to other categories and subcategories—specifically, contexts and cause-effect relationships recounted in problem solving narratives that may hint relationships among the assigned code labels. In other words, the researcher continues to strive for increased familiarity with the data, but also starts to incorporate an etic stance at the same time. She starts to distance herself in an attempt to see "new things more clearly [while] sustaining an inquisitive stance" (Ybema et al., 2009, p. 11) as a cultural insider. In axial coding, she also consults the literature to facilitate identification of patterns and distinctions in the data. At the end of the second step, iterative grouping / re-grouping of codes is expected to result in a reduced number of label categories.

The third and final step is "selective coding" (Corbin & Strauss, 1990; Douglas, 2003; Walker & Myrick, 2006) where an active interplay between emic and etic insights occurs to abstract general findings from the lived lives (Morris et al., 1999; Ybema et al., 2009) of product engineers. Selective coding further analyzes code clusters for their potential relationships. Literature continues to aid this process, as do research memos and journals to be kept in tracking the analysis (Corbin & Strauss, 1990; Douglas, 2003). Through the iterative process of "zooming in and zooming out" (Ybema et al., 2009), the selective coding process further collapses the code clusters, until key findings emerge at which point the analysis has reached a conceptual saturation.

Quantitative Study

Some scholars argue that an emic approach works well in exploratory research, whereas etic orientation can effectively generate criteria for evaluating hypotheses (Morris et al., 1999). In this light, the quantitative study can serve to provide refinements to the findings discovered by the cultural insiders (Morris et al., 1999). Quantitative research hypotheses are to be formulated after the qualitative study phase is completed. The quantitative research design and methods described here rely on the general quantitative procedures provided by Creswell and Plano Clark (2007). The outcomes of the qualitative investigation are to determine the further specifics of the quantitative study design.

Development of measurement instrument. Prior to starting the quantitative study, a measurement instrument needs to be developed to gauge the importance of and relationships among the variables in the hypothesized model. As much as possible, the items in the instrument are adopted from existing scales that have established acceptable levels of reliability and validity. Scale development is to follow well-recognized guidelines, such as those provided by DeVellis (2003) and Hair and his colleagues (2010).

Sampling procedures. The unit of analysis continues to be the same as that in the qualitative study, that is, product engineers. U.S.-based engineering / technical professionals are to comprise the quantitative research sample. The same definitions as those used in the qualitative study for “engineer,” “product,” and “product-related problem solving” apply except that consideration for expanding the definition of “product engineer” is made. Whereas a strict adherence to the earlier definition of engineer (Schein, 1996) can limit respondent categories to design or manufacturing engineers, engineering professions also encompass product support roles such as quality / reliability / safety / field service engineers. Including them in the quantitative study is likely to be beneficial for testing the boundaries of model applicability, as well as for ease of meeting the sample size requirement.

Once again, the same recruitment strategies used for the qualitative study are to be deployed. Solicitation sent to the qualifying individuals in the author's personal networks, coupled with snow-balling techniques, is expected to be a primary means for recruiting respondents. Sufficient time is to be allotted to collect a minimum of 200 responses.

Permission needed. Permission to conduct the quantitative study has been granted by Wayne State University's IRB with an Exemption status. Further information of this IRB filing is available under HIC #108711B3X and Protocol #1110010264. The IRB filing contains details of the strategy to assure the respondents' anonymity and confidentiality, such as absence of identifier in the measurement instrument that ties any respondent to his / her answers unless he or she voluntarily provides contact information for the purpose of receiving summary survey results.

Data collection and recording. Data collection is to be accomplished by a self-administered, on-line survey that asks questions about the respondent's experience in product-related problem investigation and resolution. The on-line survey is to be set up using the services of a provider selected among Wayne State University's approved sources. Prior to deployment, the questionnaire is to be thoroughly pre-tested then pilot-tested using a convenience sample. Results from these tests are to be used only for debugging purposes and should not be included in the study. The real survey, once deployed, are to be kept open for an adequate length of time to collect a desired sample size.

Data analysis. The model of engineering problem solving and knowledge creation dynamics resulting from the qualitative investigation is to be studied using correlational analysis techniques. Possible methodological choices in this analysis strategy are multiple regression analysis, path analysis, and either component-based or covariance-based structural equation modeling (SEM) with measurement analyses. Subject to the final sample size attained, the preferable approach is that of SEM. Several unique features distinguish SEM from other covariance structure analysis techniques. For example, SEM allows estimation of **simultaneous** impact of observed variables on one another without implementing artificial measures such as blocking (Clayton & Pett, 2008). Additionally, should the hypothesized research model posit mediation, SEM can more robustly analyze mediation structures than can conventional regression analysis (Iacobucci, Saldanha, & Deng, 2007).

Concluding Remarks

Mixed methods research approaches are “often the best way to address the complex research questions” allowing researchers “to measure trends, prevalences, and outcomes” while examining “meaning, context, and process” (Creswell & Plano Clark, 2007, p. 175). Further, organizational phenomena involve both the emic and etic logics (Morris et al., 1999). This two-phase investigation first capitalizes on the power of qualitative-inductive approach to generate a theory of EPS dynamics. Through the iterative immersion in and distancing from the data, the complementary nature of emic and etic approaches are expected to facilitate theory generation. At the end of the process, the etic functional logic is expected to link engineering cultural practices to hypothesized antecedent factors (Morris et al., 1999). Once the model and accompanying hypotheses are developed, the quantitative-deductive methodology can confirm the extent to which they hold across a wider engineering audience.

CHAPTER 4: QUALITATIVE STUDY

This chapter presents the qualitative study conducted based on the methodological approach discussed in Chapter 3. The results of the investigation have, to date, been published through three venues (see Itabashi-Campbell, Gluesing, & Perelli, 2011, 2012; Itabashi-Campbell, Perelli, & Gluesing, 2011). The aim of this chapter is to discuss the insights gained from this qualitative inquiry and set the ground for the next and final phase of the research, the quantitative investigation.

The chapter has three major parts. The first part provides the methodological details of the field work and data analysis—namely, sample, data collection, and data analysis. In the second part, discussion zooms in on the key findings that emerged from the data analysis. In the third and final part, these findings are vigorously interpreted. Aided by the extant literature, the discussion infuses meaning into the phenomena observed, leading to a conceptual model of engineering problem solving (EPS) dynamics. The chapter concludes with a set of propositions derived from this model, thus transitioning the study to the quantitative investigation.

Methods

As already discussed in Chapter 3, the central tenet of grounded theory is a “method of constant comparison,” pairing and comparing cases for similarities and differences until patterns in the observations become coherent. In a grounded theory approach, data sampling, collection, and analysis proceed concurrently and in an interactive manner. Rather than proceeding in a sequential fashion that characterizes quantitative methods, these activities constantly feed into each other, influencing the next course of action as the investigation progresses. The entire process is fluid and integrative, rather than linear and driven by steps set *a priori* as it would be in a quantitative study. Robustness of analysis in a grounded theory protocol is controlled, not through statistical procedures, but by two procedural attributes. One is the use of multiple sources or indicators to identify rising themes so, as the sections that follow will demonstrate, "Each case is analogous to an experiment, and multiple cases are analogous to multiple experiments" (Eisenhardt, 1989b, p. 542). The other aspect is the use of literature in conjunction with data analysis, which is "particularly crucial in theory-building research because the findings often rest on a very limited number of cases" (Eisenhardt, 1989b, p. 545). Thus, construct validity is established through building evidence and internal validity through tying the emergent theory to existing literature.

The data collection proceeded from August 2009 through August 2010. Data analysis, which started concurrently with data collection, continued through December 2010 and was guided by both Dr. Sheri Perelli and Dr. Julia Gluesing.

Sample. In grounded theory, a research sample is determined by theoretical sampling strategy. Theoretical sampling chooses samples, not based on statistical justification, but for theoretical reasons to replicate, expand, or confirm the emergent themes (Eisenhardt, 1989b). As such, research subjects were initially recruited utilizing the author's personal and professional networks. As data collection and analysis proceeded, the sample composition was continuously assessed while adding new recruits. A snowball technique to source new interviewees nominated by earlier respondents generated additional subjects. Recruiting efforts continued until no new thematic insights could be gained from the data, that is to say, theoretical saturation.

Thirty-one product engineers[2] having from three to over 30 years of experience with an average of 17 comprised the final sample. Recruitment criteria followed Schein's (1996) definition of "engineers"—that is, "designers of products and systems that have utility" (Schein, 1996, p. 14)—to seek “product engineers having ownership of design, application, integration, or manufacture of physical goods, software, or information technology (IT) architecture.” Meeting these requirements, the respondents were typically “product,” “applications,” “systems,” “software,” or “manufacturing” engineers and managers. They were also “information services” or “information technology” specialists and managers. They were, on the other hand, **not** “quality,” “reliability,” or “field service” engineers (or managers) since these professionals do not typically play a primary role in regards to designing or manufacturing a product. Additionally, a two-year minimum work experience that included team-based problem solving was specified as participant criteria. Table 1 below summarizes the respondents’ basic demographic characteristics.

Table 1

Basic Demographic Characteristics

Years of experience:	2+ but less than 5	5+ but less than 10	10+ but less than 15	15+ but less than 20	20+
Men	2	1	6	8	10
Women	0	0	1	2	1

Twenty-seven men and four women with varying industry backgrounds participated in the study. The small number of female respondents corresponds well with national statistics on women in the engineering professions (Bureau of Labor Statistics, 2009). As the

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[2] There were originally 32 interviewees. Narratives provided by one of the interviewees, however, were out of scope and had to be dropped from analysis.

data in Table 1 demonstrate, a majority of the participants were in their mid- to late-career stages.

All but one of the respondents held bachelor's degrees, 16 had earned master's degrees, and two were PhD's. Many had multiple industry, as well as product, experiences. In terms of the nature of product ownership, 24 had been engaged in design / application / system integration of physical goods, three in manufacturing, and the remaining four in IT architecture / infrastructure development. Using the Industry Classification Benchmark (ICB)[3] scheme developed by FTSE as a guide, the respondents' current industry associations were classified into eight categories[4] as follows:

- Automotive & Parts (16 respondents)
- Aerospace & Defense (3 respondents)
- Software & Computer Services (3 respondents)
- Other (one respondent each in Alternative Energy, Chemicals, Construction & Materials, Financial Services, and Household Goods & Home Construction)

Twenty-seven respondents were currently employed full time. The remaining four had either recently retired or were temporarily out of the workforce. Finally, the majority of the recruits were U.S.-born (22 respondents) with the rest representing five countries of origin: Three from India, two each from Canada and China, and one each from Japan and Lebanon.

Data collection. The primary method of data collection was semi-structured interviews that lasted from 40 to 90 minutes with an average of 50 minutes. The author

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[3] Available at http://www.icbenchmark.com/ICBDocs/ICB_%20Product_Spec_Nov2011.pdf

[4] Used ICB's "sector" level classification, for example, "automotive & parts" is classified under sector code 3350.

conducted all of these interviews between August 2009 and August 2010, either face-to-face or by telephone. A total of 31 interviews[5]— face-to-face (14) and by telephone (17)— constituted the first wave of data collection. Subsequently, a follow-up interview had to be conducted on three interviewees to clarify a few points that surfaced during their earlier interviews. These additional interviews were done by telephone. All interviewees granted permission to digitally record their interviews, and a transcript was produced from each recording. An interview protocol, developed in advance but adjusted as the research continued, guided the interview process. On-going adjustments of the interview protocol are not only acceptable but are necessary in a theory-building qualitative study in order to effectively probe potential themes as they surface (Eisenhardt, 1989). Appendix A presents the final interview protocol.

Each interview began by asking the respondent's personal and professional background including education, motivation for becoming an engineer / technical specialist, past and current roles in engineering, and other information such as hobbies that the interviewee cared to volunteer. Following this introductory dialog, each interviewee was asked to recount an example of product-related problem solving that, **from his or her perspective**, was "very successful" and then to narrate a second, "less effective" case. It was made very clear to each interviewee that he or she was free to define what constituted "effective" or "successful" problem solving. All of the 31 engineers were able to provide a "successful" story each. All but two were also able to come up with a "less successful" example, resulting in 29 samples. The interviewees who had been able to recite both the successful and less successful examples were then asked to compare and contrast the two

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[5] The number excludes one interview that was dropped from analysis due to the out-of-scope nature of narrated account.

cases. The strategy of contrasting polar opposite cases to inform the emergent themes (Eisenhardt, 1989) helped to understand “what is” and “what is not” a “successful” problem-solving scenario. Probes were used to elicit rich elaboration.

Finally, the interviewee was asked to comment, in generalities, on what he or she thought might be the best ways to capture and share knowledge that engineers create every day. This final part of the interview prompted further reactions and insights from the product engineers that chronicled real-world experiences outside the specific problem solving cases that they had narrated earlier. They brought up examples of ways in which engineering knowledge could effectively be captured and disseminated in an organizational context, including “things gone right” and “things gone wrong” observed in their respective work experiences. These additional stories not only confirmed the findings but enhanced the understanding of their inter-relationships, helping to facilitate the development of a new model of engineering knowledge creation dynamics. The interview concluded with administration of a short survey to collect demographic data.

Data analysis. Data analysis began with the first interview and continued non-stop throughout data collection and beyond. Each audio recording, as well as its transcript, was subjected to several rounds of review prior to a formal analysis. Thereafter, every transcript was open coded. All coding work, starting with open coding and ending with selective coding, was performed manually. Memos and journals were kept throughout the study to track analysis.

As already touched upon in Chapter 3, the purpose of open coding is to identify and document “codable moments” that potentially contain significant meaning underlying the observed phenomena. Following the protocol of grounded theory, the analysis proceeded with a conscientious effort to “avoid thinking about specific relationships between variables and theories as much as possible, especially at the outset of the process” (Eisenhardt, 1989b, p. 536). A total of 2,675 textual fragments were identified from the 31 interviews, containing 31 “successful” and 29 “less successful” problem solving narratives, and were subsequently categorized under 189 labels. Just as the definition of “successful” versus “less successful” problem-solving effort was left up to each interviewee, no pre-set classification scheme was used for label assignment. Rather, code clusters and labels were allowed to emerge from the data. Thus, multiple indicators from multiple sources were generated, from which to search for patterns and build evidence.

Subsequent to open coding, the “method of constant comparison” goes into full swing with the axial and selective coding procedures that follow. In axial coding, the second analytic phase, interview narratives were actively paired and compared in an attempt to better understand the relationships among the code clusters. Effort was made to determine the conditions, contexts, actions, interactions, and consequences of problem solving that hinted association among them. The literature, at this time, was reintroduced into the process. Patterns and distinctions in the data started to emerge, enabling reduction of the 189 clusters to 51 labeled categories. The search for cross-case patterns continued, with the aid of literature, as well as the field notes. In the final analytic level, selective coding, the presence or absence of certain attributes in successful versus less successful problem solving endeavors further shaped the emerging themes. Additionally, the respondents’ answers to the last interview question—about effective ways to capture and disseminate engineering knowledge—were analyzed and tied into the emerging themes. The analysis continued until no new themes emerged, at which time the author and her advisors concurred that theoretical saturation had long since been reached. Inductively moving to and fro between the data and the literature until theoretical saturation, the analysis further collapsed the 51 code clusters to 21, which led to three key findings as discussed next.

Findings

The data demonstrate stark differences between successful and less successful product-related problem solving efforts by engineers in U.S. firms. The analysis points to external conditions that appear to influence the extent of product engineers' success in facilitating root cause investigation. Successful versus unsuccessful problem solving efforts also proceed and end differently in achieving (or not achieving) solution implementation. Perhaps the most intriguing finding is that the data portray product engineers as being not only technical investigators but also managers of relationships among stakeholders in facilitating the problem-solving process. Their ability to effectively manage stakeholders' viewpoints appears to be correlated with important outcomes such as system changes and knowledge distribution beyond the immediate workgroup. These differences in the environmental conditions, outcomes, and processes of the problem solving are elaborated in the remainder of this section.

Finding 1: environmental conditions. In the research sample, product engineers portrayed environmental conditions differently in successful versus less successful problem solving narratives. Five conditions from the textual analysis stood out. Successful problem solving efforts (1) received a *clear guiding vision* from external leadership (2) were *unconstrained*, (3) were associated with *controlled urgency*, (4) had access to a right mix of *resources*, and (5) actively utilized an available framework for knowledge *sharing*. Table 2 below summarizes these findings.

Table 2

Environmental Conditions in Successful versus Less Successful Problem-Solving Efforts

	Clear guiding vision	Autonomy	Controlled urgency	Access to resources	Framework for sharing
Successful	31 of 31	29 of 31	31 of 31	31 of 31	26 of 31
Less successful	0 of 29	0 of 29	0 of 29	1 of 29	1 of 29

The figures in this table denote the number of narratives containing at least one cited instance of the corresponding condition. There is a clear contrast between the successful and less successful narratives, which the remainder of this section elaborates further.

Clarity of external leadership vision. "External leadership," in this study, refers to a source of direction or to the guiding force that is external to the work group engaged in solving the problem. Depending on the nature of problem solving, the firm's management or other constituents such as customers and suppliers played external leadership roles. The analysis results show that external leaders are more likely to provide clarity of vision to team members in successful problem solving efforts than in unsuccessful efforts.

All 31 of successful problem solving stories included descriptions of the positive impact of their leadership in effective resolution of the problem. Instances of leadership influence included a "you shall solve this" decree by senior management, as well as descriptions of close status monitoring by members of management. Many product engineers spoke of "a very strong management team" and "getting things resolved quickly by having our management's support." In one story, a vice president cut his personal vacation short and showed up to the plant to attend to the problem solving effort. One product engineer whose problem solving efforts encompassed several plant locations described his experience as knowing that "whatever we came up with was going to be supported by the management team" not just at his facility but throughout the company. In the instances of problem solving that was initiated by the customer, the "we are in this together" message conveyed from the customer side greatly facilitated the customer-supplier joint teamwork.

In contrast, not only was a mention of clear leadership oversight or guiding vision absent in the 29 less successful problem-solving narratives, 27 of them explicitly cited instances that were contrary. For example, "lack of firm leadership" caused "wheel spinning" or allowed "multiple competing interests" to prevail. In a few cases, managers "scrapped" or "wrapped up" the problem solving effort without discovering root causes. Instances in which members of management were not entirely truthful—or in some cases ignorant—about the nature of the problem were also mentioned. One product engineer described the firm's management as being one that "minimized the value of its workforce." Instances of customer-instigated problem solving degraded into a "bring-me-a-rock exercise"—a metaphor used by one engineer to describe the "unclear" or "confusing" nature of the customer's expectations.

Autonomy. Another pattern that was noted across narratives is the extent to which problem solving proceeds in an autonomous and unconstrained fashion. The textual data draw a sharp distinction between successful and less successful stories in this regard. Twenty-nine of 31 successful problem solving examples were described as "open" and free from "outside influences that might have created road blocks." They involved "very open brainstorming," "open and honest communication," and "open-mindedness to new ideas" of stakeholders. Product engineers had "authority to ask for help" and "direct control over design or process changes if needed."

In contrast, none of the 29 less successful problem solving stories chronicled autonomous characteristics of the successful problem investigations. In fact, 25 of them cited instances of having “limited choices” or “constraints” imposed on the team’s decision making. For example, the existing contracts with their suppliers restricted options, culminating in “a deteriorating relationship” and eventually “resourcing the business to another company at a higher cost.” Customers “forced” materials or designs that were not of the engineers’ first choices. The management created one-sided directives that “were forced down on engineering’s throat.” Politically-motivated agenda having “a lot of . . . hidden agendas, cross purposes, contrary goals and objectives” constrained the problem solving environment.

Controlled urgency. The third environmental factor is the degree to which a sense of urgency existed and the extent to which this urgency created a positive momentum. Successful problem-solving efforts tend to be characterized with a positive tension or a sense of urgency that is controlled, as opposed to inertia or chaos observed in less successful problem solving.

All 31 successful problem solving stories were "rather hot" and “high-paced,” prompted by high pressure from the customer or management, safety-critical nature of the problem, or imminent deadlines for resolution imposed by the organizational process such as product development timelines. The problem solving efforts were driven by “a controlled sense of urgency,” and this urgency was perceived as “exciting” by many engineers.

In contrast, none of the 29 less successful narratives conveyed such a positive sense of urgency. All of them were associated with helplessness arising from either very high tension or inertia due to organizational disinterest. High-tension situations often degraded into chaos—“getting a lot of help and advice from people you don't need,” “going into all kinds of escalation modes,” or “lots of emotions and stress and then . . . panicking.” At the other end of the tension scale was a total lack of urgency. Problem solving failed to gain momentum because “this is the way that we have always done it,” the problem “[had] a low occurrence rate,” or the problem was simply “not visible to the customer.” “Lack of financial pressure” also failed to push for solutions.

Resources. “Resources” here refer to people with particular skill sets, reference materials, and facilities relevant for technical problem solving. The extent to which they were accessible made a difference between successful and less successful problem-solving efforts.

All 31 successful problem solving stories had instances in which the right **mix** of resources—for example, technical experts, technicians, laboratory equipment, and manufacturing lines—were provided internally by the firm or by the external stakeholders such as customers and suppliers. Engineers reported success in “getting the right people involved at the right level quickly” to “put . . . some brainpower into coming to a solution.” They attributed success of their problem solving efforts to “a combination of all these people in addition to people who design tooling . . . who specify the metallurgy of the metal” because “it is always a team effort.” The major success factor, to them, was that they “had . . . most of the needed expertise . . . were able to, at least, have access to the needed skills” when warranted.

Contrarily, of the 29 less successful stories, only one described resources as being satisfactory. Thirteen of them explicitly cited difficulty in accessing personnel and expertise due to a variety of organizational reasons. Corporate restructuring, for instance, caused "degradation of service" because "[w]hen you've cut back, [by] maybe 15 percent . . . that makes it difficult . . . to give you the luxury to look at things with a clean mind." Prompted by workforce reductions, "so many people had left . . . had taken a package and . . . left [so the right] people were not available." Getting "more supplier involvement" was difficult because suppliers "don't have the time" or "are not supportive." Across narratives, people who could have helped with the problem-solving efforts "were spread too thin in terms of this problem" or were "now on three continents and . . . didn't have enough resources to go around and . . . really get to the heart of understanding why it was happening." Sometimes, corporate politics put in place a wrong resource, such as a project lead who "wasn't an engineering person [and] didn't really . . . know" the problem.

Framework for sharing. The final environmental condition is the extent to which knowledge sharing activities were pursued during the course of problem solving. Sharing mechanisms were described in a number of ways, such as corporate processes for engineering changes (e.g., drawing revisions), data bases, expert systems, structured or unstructured forums for meetings and presentations. Successful versus less successful problem-solving narratives exhibited a distinct pattern around the extent to which a context for sharing existed **and** was used.

In 26 of the 31 successful problem solving stories, interviewees reported that information or knowledge sharing was accomplished in many forms at many organizational levels. They may be informal or formal, ad hoc or structured, and intra- or inter-group level. Engineers shared knowledge via existing organizational routines or forums, such as "weekly technology meetings." They also communicated information informally using "a person list" that pointed users to the right person for the information being sought. Engineers reported "communication among all levels" to take place frequently and actively "to just go over the current issues." Special trips to other company locations to present the problem solving outcomes were also cited. Engineers went "to Mexico to present to the [customer's] management . . . and distributed and shared with the people there [the entire presentation]" or traveled "a few times to Europe to share the methodology and the process."

Contrarily, in less successful problem solving stories, only one story reported sharing lessons by inter-company e-mail. Twelve examples explicitly cited instances in which sharing information was difficult. "Collaboration was difficult" because "their system for change control wasn't set up to be rapid enough to allow all engineers to understand what is going on." Structurally or politically induced mental walls also inhibited communication and created "layers" between stakeholders. Engineers' effort to "break down those walls and to drive communication" was "sometimes . . . successful sometimes it wasn't" so "there were no daily meetings . . . little communication between the different groups . . . little pockets of people working but it was hard for them to interface with each other." In one instance, management was cited as having no interest in enhancing communication so "people didn't even know how to use computers . . . [and] things weren't shared very well."

Finding 2: how problem solving ends. Problem solving in the research sample ends differently for successful and less successful stories. The interviewees' narratives illustrate a clear contrast between successful and unsuccessful efforts in the impact they had on the engineering practices. These differences are manifested in problem solving outcomes that are associated with sustained learning and conclusions that truly "make sense."

Positive system changes. Problem solving started because there was a deviation from the norm in some aspects of the product, which needed to be fixed. The patterns that emerged around the data demonstrate that successful problem solving is not only more likely to correct the problem but to take it to a higher level of understanding, which manifests itself in system changes.

In the research sample, virtually all 31 successful problem solving efforts were associated with positive system changes. The efforts not only corrected the immediate problems but profoundly affected the fundamental premises surrounding the product, reflected in such engineering artifacts as product design, manufacturing processes, and testing protocol. Engineers said, "[N]ot only did we get [to] our root cause but we also built up a bigger picture of information about the product and the components and the process so that we understood the sensitivity to variation . . . [leading] into . . . application to other programs." The problem-solving teams "were able to come up with a solution that even better matched or optimized the customer's experience than the initial part." They effected "some design changes to subsequent products that made the products . . . simpler . . . easier to verify, and more cost efficient." The improved product performance was often "even better than the conventional system . . . that surprised all the management team." Problem solving also resulted in "a good long-term learning that changed everything that we did," such as changes in process parameters and supplier management protocols. Root cause analyses "triggered a change to standard procedure" and often yielded "benchmark information [that got deployed] across platforms." Teams "got to put two different technologies together for the first time ever and . . . were able to sort out and standardize all of the investigative tools," winning "a technology award over that." One of the reported outcomes of the investigation was the creation of a new engineering function to address "all the [system] interfaces and interactions [which] became a new business opportunity."

Contrarily, none of the 29 unsuccessful problem solving narratives contain instances of such learning or system changes. Product engineers explicitly reported that there wasn't "anything [that was] really learned or changed" from their problem solving, nor were the stakeholders "any happier than before the project started." The problem "was never studied properly . . . never understood properly," resulting in no "benchmark system or anything changed because of this." There were no lessons learned because "the original design group . . . seems to be still perpetuating some of these designs that are going to be too complex and require extraordinary control plans and are not really going to be that cost efficient."

Sense of closure. Very much intertwined with the presence or absence of system changes is the extent to which the interviewees' narratives conveyed a "sense of complete and satisfactory closure." In the research sample, successful problem solving is more likely to be associated with a strong sentiment that the outcomes that "make complete sense" have been achieved.

All 31 successful problem solving stories ended with everything "falling into place" and "making sense." The entire experience was looked back upon as being "fulfilling," "fascinating," or "something that you felt you had really achieved something." None of the 29 less successful stories, in contrast, conveyed a sense of satisfactory and convincing closure. Instead, their endings were associated with unresolved questions, feelings of regret, and even downright frustration. Figure 2 provides selected quotes from interviews in reference to the ways in which successful and less successful problem solving sagas ended. They illustrate typical responses from each of the two categories of problem solving.

Successful Problem Solving	Less Successful Problem Solving
"[The lessons learned are] still used as Gosh, this is a nice one, way to go!" (Male, 15 – 20 years experience)	*"I felt that the conclusion reached was really not a good conclusion and the project was wrapped up as an illusion of success."* (Male, 5 – 10 years experience)
"[T]he entire team . . . and I still get good feedback from XX [even] now . . . and we learned from each other." (Male, 5 – 10 years experience)	*"[Management] was not interested in solving problems so much. . . . I never really understood why they wouldn't give [it], it wasn't a whole lot . . . it was in the $100,000 range."* (Female, 20+ years experience)
"[Y]ou clearly achieved the goal and you solved the problem and you fixed it and you moved forward, and everyone is high fiving and you move on." (Male, 20+ years experience)	*"[J]ust that we didn't really close the [investigation] the way we wanted. Right now we consider it closed but in my mind it's, it's not . . . we don't really have a clear story [here]."* (Female, 15 – 20 years experience)
"[W]e fixed the problem and the customer was happy with it . . . and then we learned as a company . . . we as a company know now that we can inform our customer if we think this is a design concern." (Male, 10 – 15 years experience)	*"[T]hat really turned me off, it was like I don't even want to work on this anymore because I just spent three days going to XX and didn't, nothing good came of it . . . this might be a scam anyway."* (Male, 15 – 20 years experience)
"Finally . . . we fixed that problem, and since then, this part has run reasonably well . . . there was a series of mistakes [that] we had to go through in order to learn the right way . . . and to me, it exemplified everything about product development." (Male, 10 – 5 years experience)	*"I was never satisfied with this, because they never fixed the manufacturing process. . . . I wanted to go down there, I wanted to beat up the supplier that was shipping these . . . and I wanted to beat up the plant that wasn't using this packaging. The stuff that had to get fixed didn't."* (Male, 20+ years and just retired)

Figure 2. "Sense of closure" in successful versus less successful problem-solving efforts.

Hence, at least in the research sample, successful and less successful problem solving efforts are distinct in the way they reach completion.

Finding 3: how problem solving proceeds. The final area of notable discovery is problem solving process. Distinctive patterns in the way root cause investigations unfold emerged from the data. Successful, more so than unsuccessful, problem solving is likely to be facilitated by a systematic and disciplined five-step process that culminates in knowledge distribution. Further, this process appears to correlate with the degree to which multiple stakeholders' views and beliefs eventually converged. This finding links relationship management aspects to the quality of problem-solving process, as elaborated further below.

Rigorous five-step routines. Problem investigation routines as described by engineers differ in analytic rigor between successful and less successful problem solving examples. The greater richness of detail presented in successful root cause analysis dynamics brings out clearer images of the problem solving process transition. Patterns in the data clustered around visibility of five phases in engineers' narratives: (1) problem discovery / communication; (2) problem investigation; (3) root cause discovery and identification of potential solutions; (4) selection and execution of the **team** solution—as opposed to measures dictated without the team's buy-in; and (5) active attempts to communicate the lessons learned within, and often across, the immediate workgroups. Table 3 contrasts the degree to which the five phases were chronicled in the engineers' narratives between successful and unsuccessful examples.

Table 3

Five-Step Problem Resolution Process

	Phase 1: Problem communicated	Phase 2: Problem investigated	Phase 3: Root cause found, solution identified	Phase 4: Team solution implemented	Phase 5: Learning distributed
"Successful" 31 out of 31	✓	✓	✓	✓	✓
"Less successful" 1 out of 29	✓	✓	✓		✓
6 out of 29	✓	✓	✓	✓	
11 out of 29	✓	✓	✓		
8 out of 29	✓	✓			
3 out of 29	✓				

In all of the 31 successful examples, five elements of the problem solving routines are prominent in their narratives. Although iterative, problem solving efforts pressed on to eventually clear these five stages one by one. A narrative typically starts out with a detailed description of how a failure event set the problem solving in motion, for example, “This part failed, which allowed this to go in, and this to go in, and all of a sudden that component, . . . caused the problem.” Subsequently, the problem solving team “[was] meeting . . . at 6:30 or 7:00 a.m. in the morning for several weeks to resolve the issue” and “would run through the list of issues . . . create a time [schedule] and the team would go out and investigate those and…would be responsible to come back and report . . . the status.” The team “looked at the theory . . . went back to theory and then listed all the potential areas, which could provide this unexpected bad performance.” Following that, the team “started attacking one by one and then basically identified the root cause.” Once the team “had design solutions that [the team] thought might be good,” it “would then send those off for the analysis . . . that would evaluate them.” The team discussed in terms of “what we can do in the short and long term and not getting . . . all sprung up [by] some feedback from executives.” The team members were doing “a good job of hearing the feedback and not trying to rush in a solution . . . to really optimize this experience [by] taking an iterative approach.” In the end, the team “did get to the root cause . . . defined it, came up with a way of making it better [and] documented it and carried the lesson learned by correcting the problem permanently by updating the standard.” Often, the lesson “was communicated through meetings and . . . in our cross functional meeting within our engineering group or weekly or monthly meetings,” as well as “[in] a corporate-wide steering meeting where we were exchanging knowledge [with] the engineering centers around the world.”

In contrast, all 29 less successful narratives are missing one or more of these five elements. In other words, none of the 29 stories are "complete" with all five. Three of the 29 examples did not get past the first phase "because the data was hard to get . . . it was kind of like a phantom," correlating with general lack of interest in starting the investigation. Eight of the 29 cases stopped after the second stage, that is to say, failing to find root causes, because the problem investigation was "closed" or "scrapped" before it had a chance to identify root causes. Eleven of the 29 stories did not move past the third stage or had an "incomplete" fourth phase. They reached the root cause but resulted in either no solution or "suboptimal" countermeasures. They are sometimes a consequence of a deliberate attempt to hide a "failure" of investigation that disclosed flaws in the product design that could not be corrected before a "deadline" or until the current iteration of the program was over, spanning two or so years that the problem had gone uncorrected. Six of the 29 examples were not able to go past the fourth phase. The problem solving teams ultimately implemented optimal solutions, but the product engineers felt that the process was extremely "painful" and "resulted in no learning." No learning occurred because of "the politics of troubleshooting" which made the publicized solution "half true and . . . half lie" or "[the team] didn't want to tell anyone that they had messed up . . . or to let the other part of the business know what happened because they didn't want to admit a mistake . . . didn't want to dwell on this as a learning point." Sometimes the learning was only "partial," for example, "beyond some manufacturing learning, any learning on the design side in terms of how we are going to avoid this in subsequent products" was missing. In one particular problem solving story, the engineer reported that the investigation found the root cause but could not proceed to identification of solution; nevertheless, he transmitted his learning by company e-mail to another group within the firm engaged with development of a similar product.

Cognitive convergence. Finally, the last phenomenon that draws a distinct line between successful and less successful problem solving processes is the manner in which the actors' multiple viewpoints and perspectives play out. The extent to which these views converged, or stayed diverged, differentiate between successful versus less successful problem solving efforts. Such cognitive convergence of stakeholder beliefs, at least in the research sample, is actively managed by product engineers and plays a key role in facilitating a successful resolution.

In all 31 examples of successful problem solving, product engineers reported the ability to harness and leverage the cumulative input and knowledge of a wide variety of stakeholders (e.g., management, customers, suppliers, fellow engineers, etc). Engineers made purposeful and proactive efforts to manage relationships among relevant stakeholders by getting them to "understand the scope of the problem . . . of the solution . . . of the changes" and by "having "everybody on the same page." Teams aimed to have "a partnership to fix the problem and not [to] lay blame here or there" and promoted "learning to develop confidence in each other." Several engineers stated that "the value of getting everybody together" was in itself worthwhile "learning" that came out of the problem solving because "if we had tried to do it in a small group or solve the issues with the two or three people that were directly involved, I don't think we ever would have resolved it." This way, the experience can be taken "forward as part of being more effective team . . . in the future."

In 12 of the successful problem solving examples, convergence was reported to be swiftly accomplished as all stakeholders were "willing to work together . . . and established a mission quickly." In the cases that involved the customers, "supplier-customer lines kind of disappeared . . . for a period" making it possible to have "a cross-functional in between the customer engineering team . . . and . . . ourselves." In the remaining 19 narratives, convergence was more protracted and difficult—but was ultimately achieved despite the relationships being "heated" or "tumultuous at the beginning". Engineers "went to manufacturing management and explained the importance of this DOE to resolve this issue in a timely manner and . . . got their acceptance." They "also went to the manufacturing floor" by themselves and "worked with . . . the operators . . . [and] explained the importance" so that the problem solving "got priority." They pulled together "a quality department, a vibration analysis department, a CAE and . . . PhD's and Fellows . . . [who] were knocking heads" to "bridge the difference between their theories." They had "to be very patient" at first so as not to "have people . . . build . . . walls against each other." Their suppliers "were very reluctant on providing anything," but by forcing collaboration or by going "to their facility at night or on the weekend," they "started having a team where [suppliers] were involved and where [the] customer was involved." Engineers and their immediate team members made a conscious effort to broadcast the "We are not here to lay blame, we are here to fix the problem" message "every time anyone tried to lay blame or point fingers." Once everyone agreed to "get past that," personal interactions became more constructive to form "a very unique bonding experience," "partnership," and even a "symbiotic relationship."

When reporting less successful problem examples, however, the same engineers often referenced the disinterest or confusion of stakeholders about the problem and emphasized the difficulty of aligning their divergent viewpoints. In 28 of the 29 less successful cases, convergence failed to occur. The problem solving efforts were described as "definitely . . .

not a team atmosphere," "all around a bad situation," "one region telling another region how things should be," and "lots of . . . blaming session." Inter-personal relationships tended to be "adversarial," "strained," or "almost hostile." "[A] little mistrust" between team members precluded "a complete agreement on when and where the problem happened, whether it was our problem or their problem" and "contributed to the friction" so the problem "wasn't really clearly owned." Stakeholders "didn't want to be doing what they were asked to do," and "Engineering didn't want to open up the tolerances, manufacturing didn't want to live with the way the situation was, the parts supplier didn't want to change his process." Some problems had a high enough visibility that involved "a lot higher management from multiple groups," ending up with "like three different vice presidents basically telling me what to do" yet their views "don't line up." Often times "emotions got in the way and halted addressing the problem," and the problem solving "became an emotional issue." Because "people gave up" trying to synchronize their viewpoints, the problem "became a political and emotional problem . . . and personal battle between people involved." Unable to cope with a cacophony of having "lots of different people involved," the team "ultimately . . . scrapped [its effort] instead of solving the problem . . . just eliminated, changed the design, changed the whole process to a different process."

Summary of findings. Summing up, the three major findings from the data analysis paint distinct images of successful and less successful problem solving dynamics. The discussion section that follows analyzes these observations in depth and proposes a new concept that integrates them into an elaborated model of EPS dynamics.

Discussion

Hence, the data demonstrated stark contrast between successful and less successful problem-solving efforts—both in terms of their associated environment and the manners in which they proceed and end. The analysis has also pointed to a mediating force that brings all stakeholders' interpretations together to form a unified understanding. These findings have been interpreted using four strands of research in the literature: (1) absorptive capacity (Cohen & Levinthal, 1990) as a dynamic capability in the firm (e.g., Eisenhardt & Martin, 2000), (2) Nonaka's (1994) organizational knowledge creation theory, (3) enactment perspective on organizational sensemaking (Weick, 1979, 1988; Weick, Sutcliffe, & Obstfeld, 2005), and (4) the concept of *ba* (Itami, 2010a, 2010b; Nonaka, Toyama, & Konno, 2000; Yamaguchi, 2006). The remainder of this section discusses the findings through the lenses of these theories. The goal is to complete the conceptual framework laid out at the onset of the study, that is, EPS team as an epistemic group embarked on a unique learning journey. The resulting conceptual model and propositions will be presented at the conclusion of this section.

External conditions. The differences between the successful and less successful problem solving stories in the research sample clustered around five external conditions: *clarity of leadership vision*, *autonomy*, *controlled urgency*, *resources*, and *framework for sharing*. These organizational factors strike a chord with Nonaka and Takeuchi's (1995) five enablers that sustain innovation, as well as the five characteristics of Weick and Sutcliffe's (2007) organizational resilience that avert crises. These attributes are conditions that enhance the social and cognitive processes of the actors in their intended missions, be they new product development or risk management.

Leadership vision and trust. Effectively communicated *leadership vision* provides goal clarification, guiding principles, and commitment to seeing that the problem is solved—a necessary condition for setting root cause investigation in motion. Leadership wisdom that guides learning with clear purpose is particularly important for learning from failure (Bierly, Kessler, & Christensen, 2000; Boal & Hooijberg, 2001; Carroll & Edmondson, 2002) and is a foundation of organizational *mindfulness* (Weick & Sutcliffe, 2007) that makes enterprises more resilient against crises. Nonaka and Takeuchi (1995) underscore the significance of direction setting through *intention*, one of the five enablers in their original knowledge-creation concept. *Intention* is tied to corporate vision and ultimately provides the yardstick with which to measure the knowledge output, in other words, a justification mechanism. In a more recent work, Nonaka and colleagues (2000) augment the notion of *intention* with two additional concepts: (1) *knowledge vision* and (2) *love, care, trust, and commitment* fostered by leaders. They argue that knowledge vision cannot be sustained without *trust* since "[personal] knowledge needs to be **shared** [emphasis added] to be . . . exploited [so] it is important for leaders to cultivate commitment amongst organisation members to motivate the sharing . . . based on the knowledge vision" (Nonaka et al., 2000, p. 28). Factors akin to *intention / vision* and *trust* are, therefore, proposed as two ingredients of EPS environment that propel effective problem solving.

Autonomy. Successful problem solving in the research sample is closely associated with unconstrained environment, free from "political motives, hidden agendas, cross purposes, contrary goals, and contrary objectives." This finding is not too surprising since an underspecified organizational structure is known to promote flexibility of action (Barrett, 1998; Dodgson, 1993; Levinthal & Rerup, 2006), facilitates rapid information flow (Nonaka, 1994; Nonaka & Takeuchi, 1995), and more ably accommodates “shifts of beliefs and actions” (Fiol & Lyles, 1985, p. 805). Further, virtually all successful problem solving examples involved self-organizing or cross-functional work groups (of varying sizes), which is exemplary of Nonaka’s *autonomy* concept (Nonaka & Takeuchi, 1995). As Grant (1996, p. 384) argues, “cross-functional product development teams . . . achieve better integration across broad spectra of specialized knowledge.” In the same vein, *deference to expertise* that entrusts decision making to experts rather than to authority is an essential element of a resilient organization (Weick & Sutcliffe, 2007). *Autonomy*, thus, is also proposed to be an essential element of effective EPS dynamics.

Controlled urgency. Engineers in successful problem solving, in the research sample, operated in a state of controlled urgency. This condition is very similar to Nonaka and Takeuchi’s (1995) *creative chaos* condition, which treads a fine line between “order” and “fluctuation.” Thoughtfully induced, *creative chaos* can trigger self-reflection and impetus for challenging the status quo, in the same way a purposefully constructed system such as Toyota’s lean production environment can produce *creative tension* (Senge, 2006; Womack, Jones, & Roos, 1990). Such a deliberately introduced state of “tension between constancy and change” (Fiol & Lyles, 1985, p. 805) can also raise the quality of organizational attention (Weick & Sutcliffe, 2006) and enable “heightened sense of awareness”—analogous to the *pre-occupation with failure* characteristic engendered by resilient organizations (Weick & Sutcliffe, 2007). For the EPS concept, a well-controlled sense of urgency is proposed as necessary for facilitating effective root cause analysis that leads to meaningful outcomes.

Requisite variety. Absorptive capacity, a firm's ability to deftly leverage new information to build competitiveness, is supported by the “interactions across individuals who each possess **diverse and different knowledge structures** [emphasis added] that will augment the organization's capacity for making novel linkages and associations . . . beyond what any one individual can achieve" (Cohen & Levinthal, 1990, p. 133). This argument denotes *requisite variety*, precisely the reason that access to a variety of knowledge sets made a difference in the outcomes of problem solving exercises in the research sample. Successful engineering problem solving efforts were greatly enhanced by leveraging an appropriate mix of technical skill sets to cope with the complexity of problems, just as *requisite variety* helps organizations cope with the complexity of their environment by enabling a broader repertoire of responses (Nonaka & Takeuchi, 1995; Weick, 1979). *Requisite variety* also reflects the essence of the *reluctance to simplify* principle in Weick and Sutcliffe's (2007) organizational resilience. In this context, *requisite variety* is key to safeguarding the organization against *deviation amplification* (Weick, 1979), a vicious causal loop that can mask critical variations occurring in the environment. Failure to detect them can lead to oversimplification of a situation that warrants high attention (Weick, 1988). An environment endowed with appreciation for and supply of relevant expertise and resources, or *requisite variety*, is proposed as another key enabler of effective EPS.

Knowledge redundancy. The "path dependency" implied in the concept of absorptive capacity (Cohen & Levinthal, 1990) is the reason that firms, each having a distinct mix of resources, come to demonstrate equally superior performance in the markets, i.e., "best practices" (Eisenhardt & Martin, 2000). The interviewees' narratives illuminated many "pathways" through which the knowledge possessed by the stakeholders was leveraged to achieve EPS goals. In problem solving, the individual knowledge has to, first, be **shared** and formulated into a collective capability that takes the team from "zero-level" to a "higher-order" change (Winter, 2003). In the EPS narratives, various information sharing vehicles were used throughout the root cause investigation to "assemble and fuse" participants' understanding, gradually moving towards a solution. The discussion forums, special meetings, and information technology networks chronicled by the engineers helped create "overlap" of knowledge, a *redundancy* condition that "connects individuals and the organization through information, which converges rather than diffuses" (Nonaka, 1994, p. 29). Likewise, from the perspective of Weick and Sutcliffe's (2007) organizational resilience, *sensitivity to operations* creates a structure of "interconnections" among actions and "relations and networks [that] determine outcomes" (Weick & Sutcliffe, 2006, p. 285). Such a web of inter-relations in turn facilitates tapping into tacit knowledge, which can then be dynamically integrated into new capabilities (Grant, 1996). Lacking such a mechanism, the product engineers in unsuccessful problem solving were unable to comprehend how product-related changes would affect others in the organization and could not reach an optimal solution. A contextual setting that creates *redundancy* of knowledge is proposed to enhance EPS effectiveness.

Problem-solving process and outcomes. In the research sample, successful problem solving efforts featured a systematic and rigorous process leading to fundamental changes in the way the product was developed, tested, or manufactured. These changes not only corrected the immediate problem but all took the existing premises to new levels—such as revised standards, processes, new technologies, and new business functions. This entire process is essentially *double-loop learning* in action (Argyris, 1976; Fiol & Lyles, 1985; Slater & Narver, 1995), the only means by which problem solving can result in sustained learning (Tucker & Edmondson, 2003). By positioning EPS as a capability-based practice, the analysis conceptualizes the double-loop learning dynamics observed in the research data as a set of routines that augment this capability to drive the problem-solving process.

Building EPS capabilities. One of the interesting discoveries noted in less successful EPS examples is the way *resources* and *framework for sharing* are portrayed. As already discussed, 13 engineers expressed frustration about the lack of resources, and 12 recounted instances of limited information sharing in their narratives. About half of the interviewees were silent on both. When probed, however, these silent engineers did verify the **existence** of relevant expertise and skill sets, as well as information sharing mechanisms such as intranet-based change management and knowledge repository systems, in their respective problem solving contexts. This intriguing aspect adds an insightful dimension into the EPS, especially with respect to its process dynamics.

Having formal processes and organizational artifacts such as intranet sites and special meetings is one thing. What matters, as Senge (2006, p. 321) argues, is "**what happens** [emphasis added] when people use the artifacts or processes or participate in the meetings." The concept of absorptive capacity clearly distinguishes between a firm's resources and what they may **do** for the organization. From a system perspective, absorptive capacity as dynamic capabilities—the firm's ability to build competence over time in order to dynamically respond to its changing environment (Volberda, Foss, & Lyles, 2009)—restructures the traditional structure-conduct-performance paradigm to include an intermediary force that mobilizes the firm's resources to realize a desired performance (Grant, 1996; Verona, 1999). Applying this framework to organizational learning, it becomes clear that it is the "integration" of knowledge—rather than the knowledge itself—that is relevant for building a competitive resource base (Grant, 1996). Absorptive capacity is, thus, one way to explain the EPS system dynamics that facilitate successful attainment of project objectives by the organizational agents, who are the lead engineers in the stories.

Zahra and George (Zahra & George, 2002, p. 186) define absorptive capacity as “a set of organizational routines and processes by which firms acquire, assimilate, transform, and exploit knowledge to produce a dynamic organizational capability.” Lichtenthaler (2009) has expanded on this concept and modeled absorptive capacity as a higher-order construct that accounts for three lower-order constructs representing various modes of learning. Just as learning is about action (Senge, 2006), capabilities are built through active routines (Eisenhardt & Martin, 2000). In this framework, routines refer not to “what” the organization’s formal processes and procedures are but rather to “behavior that is learned, highly patterned, repetitious . . . founded in part in tacit knowledge—and the specificity of objectives” (Winter, 2003, p. 991). Extending this argument to the EPS context, it is not “which” structured problem solving methodology the engineers followed that matters. Rather, it is "the structure of beliefs, frameworks, paradigms, codes, and cultures" (Levitt & March, 1988, p. 320) that drove their problem solving that is crucial in understanding the EPS dynamics.

Broadly framed, an absorptive capacity model has organizational antecedents, process dimensions, and outcomes (Volberda et al., 2009). McEvily and Marcus’s (2005) study, for example, explores the mediating influence of customer-supplier joint problem solving on the relationship between two organizational antecedents and attainment of new capabilities. Their findings show that the two antecedents, “information sharing” and “trust,” do not fully explain the extent to which new capabilities result from the customer-supplier business relationship. Rather, these conditions serve as precursors to the *joint problem solving*, which in turn directly leads to new capability acquisition. Hence, their findings highlight the prominence of shared routines as the driving mechanism for building capabilities. Drawing on these previous works in literature, EPS routines that build the capability to realize a superior EPS performance are modeled as follows.

EPS routines from a cognitive perspective. As touched upon earlier in Chapter 2, problem solving from a cognitive perspective may be framed as an endeavor to confront and resolve uncertainty (Corti & Storto, 2000). Ideally, therefore, EPS should proceed as the players' cognitive state moves progressively from fuzzy to less fuzzy, and eventually to "completely understood"—if the root cause analysis is successful. The enactment perspective of organizational sensemaking (Weick et al., 2005) helps explain the process by which organizational actors infuse clarity into the system to make it less ambiguous.

Pointing to the relational nature of our physical world, Goldman (2004) argues that the seats of societal forces are found in the networks of clustered relationships. By extension, organizations may be viewed as a "reality" created through the actions resulting from these relationships, that is to say, enactment perspective (Orr, 1998; Senge, 2006; Weick, 1979). In Weick's (1979) view, an organization is more than just the structural hierarchy depicted in its organizational chart but is fundamentally a network of relationships and interactions. Such a network is a "system," enacted by the organizational actors over time. Their enactment routines are essentially sensemaking, a form of information processing to deal with "equivocality" of the system "input" in an attempt to reach or maintain a state that "makes sense" to them (Weick et al., 2005).

Weick and colleagues (2005) propose a three-step model of organized sensemaking, the "ESR sequence." The three steps—*enactment*, *selection*, and *retention* (ESR)—together constitute an iterative process in which the organizational actors perceive stimulus from outside (*enactment*), give it a meaning (*selection*), and ultimately decide on its final interpretation (*retention*). Figure 3 illustrates this concept.

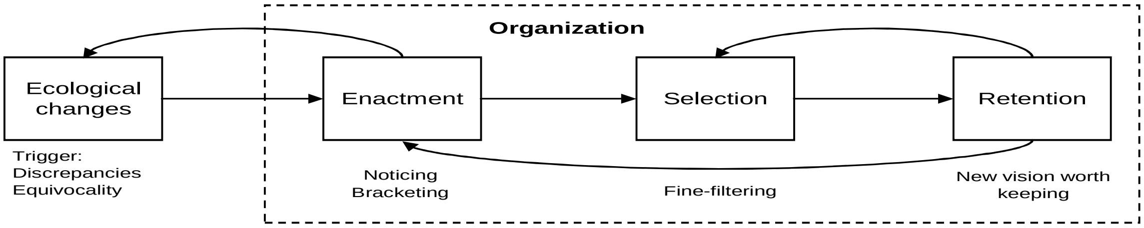

Figure 3. ESR Sequence.
Weick's ESR sequence adapted from "Organizing and process of sensemaking" by K. E. Weick, K. M. Sutcliffe, and D. Obstfeld, 2005, *Organization Science*, 16(4), p. 414. Copyright 2005 by Karl E. Weick, Kathleen M. Sutcliffe, and David Obstfeld.

Engineering problem solving may be seen as a form of organized sensemaking. Orr (1998, 2006) argues that sensemaking occurs by default in any work situation because of cognitive and temporal gaps that exist between the current and previously worked problems, necessitating some amount of improvisation before the operator can apply a set of prescriptive instructions. In engineering, for example, completely duplicative contexts going from project to project are rare. As a result, engineers "solve problems by remembering similar cases and applying the lessons learned from those cases to the new one" (Jonassen, Strobel, & Lee, 2006, p. 140). In other words, engineers are having to deal with, not only the temporal distance between projects, but also the cognitive distance between their mental models and those of the original product designers. Seen from the vantage of enacted sensemaking, EPS can be conceptualized to start when the engineering team first organizes to "make sense" of the product failure, the *enactment* step. The actors' cognitive gap between the ideal and actual states of their product creates equivocality in their world. Root cause investigation that ensues parallels the next ESR phase, *selection*, in which the "bracketed" data go through additional filtering to "extract a meaning" (Weick, 1979; Weick et al., 2005). As conceptualized in the ESR framework, *selection* is the most intense part of sensemaking routine (Weick, 1979; Weick et al., 2005) as witnessed in the successful EPS processes that "looked at the theory . . . went back to theory and then listed all the potential areas . . . attacking one by one and then basically identified the root cause." Finally, the "happy ending" accomplished by successful problem solving efforts mirrors the last stage of ESR, *retention*, which delivers a new vision that is "worth keeping" (Weick, 1979). Thus, product engineers organized to "make sense of equivocal inputs and enact this sense back into the world to make that world more orderly" (Weick et al., 2005, p. 410). Their success depended on the **quality** of their sensemaking.

Sensemaking can be ineffective. It can also collapse completely when equivocality of inputs is high and the social structure weak (Weick, 1993). Unsuccessful problem solving stories in the research sample basically chronicle examples of unproductive sensemaking. Many exhibit characteristics of *deviation amplification loop* (Weick, 1979), as well as of collapsed sensemaking, as exemplified by the following quote:

> [A]ll hell breaks loose. Nothing works as expected. Everybody points . . . doing this [gestures finger-pointing] . . . so you have confusion on the part of manufacturing engineering, product engineering . . . and, many different managerial levels. [One manager says] "This is my focus." But then, [another] says, "No, no, here, I want you to do this." And, another one says, "I want you to do that." And, another one. . . . This is how your small, finite, well-established project is getting bigger and bigger and bigger. And, you wind up with something that you can't do. (*Engineer with 15 – 20 years experience*)

Hence, ineffective EPS routines are akin to ineffective sensemaking, which fails to bring clarity into the picture. Consequently, the system stays fuzzy indefinitely.

EPS routines from an epistemic perspective. As already touched upon in Chapter 2, problem solving may also be viewed as a knowledge state transition from tacit to explicit (Corti & Storto, 2000). Confronting the unknown, the problem solving team would be less inclined to formalize its knowledge until further clarity is gained. In EPS, once the root cause is found and solution identified, that knowledge is implemented through hardware, software, or both. Because "an organization's absorptive capacity is not resident in any single individual but depends on the links across a mosaic of individual capabilities" (Cohen & Levinthal, 1990, p. 133), the seeds of success in resolving product problems reside in the engineers' and their support personnel's tacit knowledge, which must be fully leveraged. To better understand the epistemic aspects of EPS routines, the analysis now turns to Nonaka and Takeuchi's (1995) knowledge-creation model. Figure 4, adapted from Nonaka's and Takeuchi's (1995) work, depicts their five-phase model of knowledge creation.

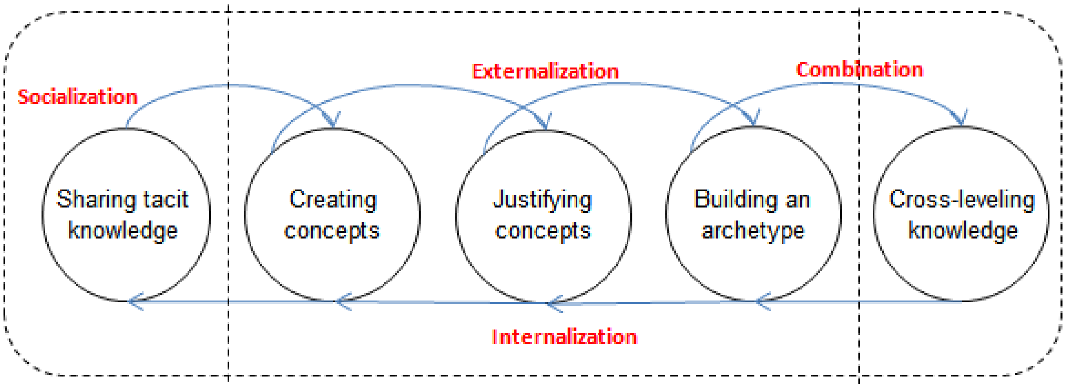

Figure 4. Nonaka's & Takeuchi's five-phase model of organizational knowledge creation. Adapted from *The Knowledge-Creating Company: How Japanese Companies Create the Dynamics of Innovation* (p. 84) by I. Nonaka and H. Takeuchi, 1995, New York: NY: Oxford University Press. Copyright 1995 by Oxford University Press.

The model proposes that innovation develops through five epistemic phases: *sharing tacit knowledge*, *creating concepts*, *justifying concepts*, *building an archetype*, and, *cross-leveling knowledge*. In a nutshell, the model depicts creation of new knowledge as a progression of informal knowledge exchange developing into a final product deployed through the system. Supporting these five milestones is the *socialization-externalization-combination-internalization*—or "SECI"—process that explains modes of knowledge conversion (Nonaka et al., 2000; Nonaka, von Krogh, & Voelpel, 2006). *Socialization* stimulates *sharing* of *tacit* knowledge. *Externalization* takes the shared individual knowledge and translates it into visible *concepts* so they can be validated through the organization's *justification* mechanisms. *Combination* provides the force necessary to aggregate justified concepts to build a final *archetype*. Finally, system-wide deployment of archetype design and specifications *cross-levels* everyone's knowledge about the new product, that is, *internalization*, thus readying the system for the next cycle of knowledge creation. In the "unified model of dynamic knowledge creation" proposed by Nonaka and colleagues (2000), SECI is the fundamental routines that tap into individuals' tacit knowledge and augment it to a higher ontological level, that is to say completely codified and shared organization wide. Further, the process is conceptualized as iterative and spiral, not purely sequential or linear (Nonaka, 1994; Nonaka & Takeuchi, 1995; Nonaka et al., 2000).

Analogous to this five-phase concept, commonly used methods of technical problem solving tend to feature five stages: (1) problem definition, (2) problem analysis, (3) generation and selection of solutions, (4) testing and evaluation of solutions, and (5) routinization (MacDuffie, 1997). Widely used structured problem-solving protocols—for example, 8D, Five Why's, Kepner-Tregoe, or Six Sigma—all prescribe steps that reflect this philosophy (Smith, 1998). Put into the perspective of knowledge state transition, as already explored in Chapter 2, a successful root cause analysis is one in which individual knowledge is leveraged and amalgamated into workable solutions, which are implemented across board to effect system changes. In the research sample, 8D, Kepner-Tregoe, Six Sigma, and other prescriptive methodologies appear, at comparable frequency, in both the "successful" and "less successful" narratives. Thus, the presence of such tools is likely to be providing no more than a guiding framework that helps establish a structure for the group activities.

Successful engineering problem solving stories as recounted by the product engineers have a striking similarity to Nonaka's five-phase model shown above. The process began with the problem communication phase, during which team members exchanged "what they knew" about the problem. Once the initial dialog had taken place, three stages followed: (1) establishment of a hypothesis about the problem (or root cause or potential solution depending on the stage of problem solving), (2) testing of each hypothesis, and (3) selection and execution of the final solution. Finally, the new learning gained from the problem solving culminated in changes in the system. Further, the process was described as a dynamic and continuous sequence of activities that often included reverting back to the drawing board to re-examine the assumptions that the team made on problem definition, root causes, and potential solutions. Based on these findings, the visibility of five phases in the successful problem solving protocols may be evidence that a set of routines akin to the SECI process was at play.

Dynamic capabilities are about adapting to changing circumstances and so imply routines that are "iterative and cognitively mindful, not linear and mindless" pointing to "a richer conception of routines that goes beyond the usual view of efficient and robust processes" (Eisenhardt & Martin, 2000, p. 1117). It is in this spirit that the ESR sequence (Weick et al., 2005) and SECI process (Nonaka et al., 2000) are synthesized to explain the cognitive and epistemic dynamics of EPS that transition the system state from fuzzy to clear, from tacit to explicit. Figure 5 is a pictorial representation of this concept.

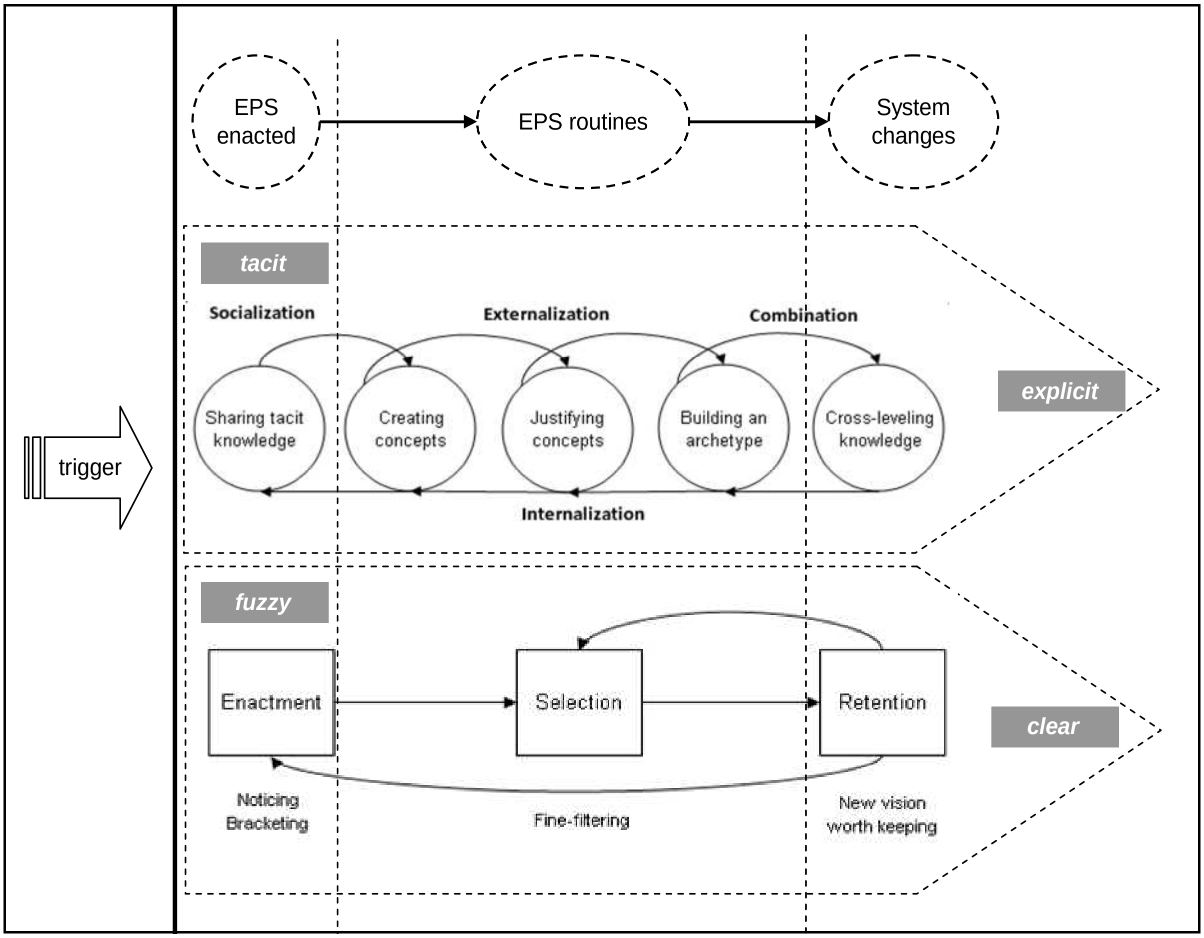

Figure 5. Conceptual image of EPS as a synthesis of ESR and knowledge-creation routines.

Based on the study findings, the EPS routines are conceptualized to be of similar “algorithms” to those of SECI, necessary for bringing sensemaking and knowledge creation to fruition. The next and final section of this chapter will explore one more element of the EPS capability that completes the theoretical framework.

Cognitive convergence and engineering epistemology. There now remains one other characteristic of EPS needing explanation that the study has highlighted: cognitive convergence. As touched upon earlier, in the research sample, successful problem solving efforts are distinguished from less successful ones by the higher frequency of cognitive synchronization. This is not too surprising as shared beliefs have been reported to positively influence group performance in previous empirical studies (e.g., Baba, Gluesing, Ratner, & Wagner, 2004; Cannon & Edmondson, 2001; MacDuffie, 1997). Further, Baba et al.'s (2004) longitudinal case study of global work groups reports that shared cognition is likely to be achieved through two parallel paths: a straight convergence of multiple perspectives and initial divergence that is subsequently overcome. This dual-path convergence was also observed in the study. What is surprising, however, is that the product engineers in the narratives are found operating almost as "agents" of diverse interest groups (Eisenhardt, 1989a; Hill & Jones, 1992), actively working to establish common ground among various stakeholders through technical discourse (Suchman, Blomberg, Orr, & Trigg, 1999). To better comprehend this somewhat unconventional image of "engineers," the process by which "shared cognition" is achieved is examined in detail. The concept of *ba* as a vehicle for creating contextual factors that can induce shared cognition is then discussed. Finally, all of the findings are brought together to form a conceptual model of EPS dynamics.

Ways of knowing and shared cognition. EPS state transition has, thus far, been conceptualized from two perspectives: cognitive and epistemic. In the former, the system makes a transition from fuzzy to crisp; in the latter, from tacit to explicit. Similarly, EPS may also be viewed from a "behavioral" perspective, conceptualizing the process as facilitating a transition from individual and local focus to collective and organization-wide aims. In fact, as already explored, the relevant knowledge generated during the problem investigation must eventually be translated into standardized routines in order for a system change to occur. Such standardization by way of improved design or manufacturing processes helps prevent recurrence of defects (MacDuffie, 1997). Collective learning is achieved through social interactions among individuals contributing their tacit knowledge, so, by extension, the manner in which EPS players socialize deeply affects the quality of EPS output. Socialization greatly influences the cognitive characters of participating individuals (Corti & Storto, 2000) and ways in which their "knowing" occurs. An ancient sage's view of human "knowledge" may be helpful here to better understand this process.

Aristotle (trans. 1934) divides knowledge into several dimensions, three of which are *episteme*, *techné*, and *phronesis*, that continue to serve as useful points of reference for modern scholars of organizational studies (e.g., Baba et al., 2004; Grint, 2007). In technical problem solving, *episteme* and *techné* are analogous to theories ("declarative knowledge") and practical know-how ("procedural knowledge"), respectively. Both are essential in problem solving. *Episteme* leads to "knowing what" to do in order to find solutions, and *techné* directs "how" to do it. The two types of knowledge, therefore, provide "means" and "ends." The means and ends, however, must be "justified." In problem solving, specifically, why certain methods are chosen and to what extent resulting outcomes are accepted in each step are judged using a set of evaluative guidelines. This evaluative guidance, or a capability to "know whether" to take certain actions, is a result of the third dimension of knowledge, *phronesis*. Often translated as "practical wisdom" or "prudence" (Aristotle, trans. 1934), *phronesis* provides the "evaluative knowledge" that completes the triad of "ways of knowing"—significant yet often lacking in organizational discourse (Baba et al., 2004; Grint, 2007).

Phronesis stands on both *episteme* and *techné*, encompassing the characteristics of both (Grint, 2007). *Phronesis* evokes the intellectual power of *episteme*, not in abstraction but in context as is *techné* (Grint, 2007). On an individual basis, *phronesis* may be equated to Senge's (2006, p. 131) "personal mastery" that "goes beyond competence and skills, though it is grounded in competence and skills" akin to the artistry demonstrated by champion ice skaters and prima ballerinas. In organized activities such as EPS, however, *phronesis* becomes more of a "collective discipline" (Senge, 2006). It is the *phronesis* dimension of knowledge that guides the EPS team's course of action—whether or not to acquire more information when problem description is vague, to try a different technique when the initial diagnostics fail, or to pursue one solution over others. While Aristotle makes it clear that all three types of knowledge are critical for one's intellectual virtues, it is p*hronesis* that provides a reservoir of interpretive power that delivers the most appropriate and reasonable judgment in a given context.

It is through collective *phronesis*, the process of amassing various interpretive schemes and unifying them into the best fitting solution to the given situation, that an EPS project is brought to a closure that "makes good sense" to all that are involved. As Hargadon and Bechky (2006, p. 484) argue, "In today's rapidly changing environments, the complexity of problems requires solutions that combine the knowledge, efforts, and abilities of people with diverse perspective[s]." In modern engineering, indeed, complexity is the norm rather than the exception. The quote below succinctly illustrates this point, in the context of noise-vibration-harshness (NVH) problem solving for an automotive powertrain system:

> I forced a collaboration because, originally, I would have had to accept one [view] and reject the other. . . . [H]ow could two people get a PhD and one be very wrong and one be very right? So, I think there was more of a misunderstanding. . . . [Through] collaboration . . . I was able to use brainpower from a wide range of intelligence. . . . [E]verybody brought a lot to the table, so I learned a lot . . . that would have been missing if I handled it alone or only chose one side. And once they got beyond the conflict stage, they were actually more than willing, I got a lot of

> firepower from departments that weren't even on my budget that might not have been available to me [had I chosen sides]. (*Engineer, 20+ years experience*)

This example is a clear case of cognitive convergence after a protracted period of divergence. The lead engineer who provided this quote had to exert a considerable effort to get his team members, all of whom had come with years of NVH experience yet with divergent opinions, to view the problem in what he referred to as the "same boundary conditions." His team was an assemblage of high-powered *episteme* and *techné* (PhDs and highly experienced engineers), but these knowledge holders were initially viewing the problem from disparate angles based on their respective past experiences with NVH. Finally, with the lead engineer's persistent effort, every member of the team concurred that the culprit of their NVH problem was not one particular component—as originally presumed to be—but the interactions of several within the assembly. The team, from that moment on, proceeded to correct the problem and develop award-winning technologies to design and test future similar assemblies.

Huber (1991, p. 102) proposes that "more learning has occurred when more of the organization's units understand the nature of the various interpretations held by other units"— which is essentially what was observed in the study. Engineering is a highly context-sensitive discipline (Goldman, 2004), and so by its nature interpretations are about everything. Getting together a group of experts to solve a problem is one thing. Their views, however, must be aligned with the context in which the product is applied, used, and interpreted. Goldman (2004, p. 163) argues, "Engineering is contingent, constrained by dictated value judgments and highly particular. Its problem solutions are context sensitive, pluralistic, subject to uncertainty, subject to change over time and action directed." Engineering practice, from the epistemological perspective, is essentially about developing useful interpretive schemes, a form of collective wisdom. Engineering value judgment, which is the *phronesis* of EPS, cannot be reduced or abstracted into a set of prescriptive problem-solving routines (Grint, 2007). This concept is proposed as being vital to cognitive convergence in EPS.

Shared cognition in contexts. EPS environment is a socio-technical system, so the quality of engineering knowledge creation depends heavily on the social interactions that take place within an engineering cultural milieu (Corti & Storto, 2000; Dodgson, 1993; Nonaka, 1994; Nonaka & Takeuchi, 1995; Simon, 1991). Just as learning “does not mean acquiring more information, but expanding the ability to produce the results we truly want in life” (Senge, 2006, p. 132), a single unified *phronesis* (Baba et al., 2004) is not likely to be achieved solely with logistic or infrastructural considerations (e.g., special meeting rooms, conferencing technology, information system database, etc.).

In stark contrast to the brilliant success of the NVH example was a case involving an automotive sealant. In this story, the sealant’s odor became a point of dispute between the American members and their European counterparts on the team. The former found the smell objectionable, but the latter did not agree and resisted replacement. Unable to unify the stakeholders’ divergent viewpoints on the disposition of the sealant, the team gave up its autonomy and relegated the decision to the senior management. What this example demonstrates is a shift in the meaning of an artifact in the context that is not fully shared by all stakeholders. In other words, a substance perceived as bad smelling by one group is accepted without objection by another, a re-contextualization process (Brannen, 2004). Human rationality is bounded by one’s cognitive limits (Simon, 1991), and the resulting sensemaking is likely to stay within organizational members’ perceived boundaries unless

deliberate measures are taken to expand their mental horizons (Leveson, 2011; Senge, 2006). Whereas in the NVH case the actors were eventually able to put their respective knowledge and experience into a single, unified context and jointly made sense of the problem, this sealant example was somehow lacking impetus to bring together everyone's interpretive schema. Akin to a host of environmental measures that designers of an embedded control system implement to protect the health of its controller, an appropriate sense-making "forum" where the problem could be better understood and opposing viewpoints worked out should have existed but did not.

Shared cognition, especially in dynamically shifting and contingency-ridden world of engineering, is more than just an exchange of theoretical (*episteme*) or practical (*techné*) knowledge. It is about collectively developing a higher interpretation, the *phronesis* way of knowing. Such "wisdom" to prudently combine "insights from theories and research that draw upon diverse premises" (Nonaka et al., 2006, p. 1196), however, does not develop overnight. As Baba et al. (2004, p. 583) argue, achieving a shared cognition is a rather lengthy process of "suspending our own judgment as we learn the cultural logic and rationality of others' divergent beliefs and values, while also allowing those others to call our own beliefs and values into question as they learn about us."

Shared experiential space. While sensemaking is improvisational, it can also have elements of "coordination" in the same way that "[t]he championship sports team and great jazz ensembles provide metaphors for acting in spontaneous yet coordinated ways" (Senge, 2006, p. 219). A problem-solving framework can be "engineered" to promote healthy and constructive interactions among stakeholders. Such a context is one that all players trust each other to work together in ways that complement each other's contribution, a place of "collective discipline" (Senge, 2006). The concept of *ba* can be used to build such an environment.

Closely related to the concept of enacted environment, *ba* is a Japanese word roughly translated as "place, space, or forum." Kitaro Nishida, a Japanese philosopher, originally proposed the concept, which was further developed by Hiroshi Shimizu (Nonaka & Konno, 1998). Scholars have since then adapted *ba* to various organizational contexts. For example, Itami's (2010a, 2010b) *ba* is a spatial structure that facilitates interconnectedness, which, he argues, is indispensable for understanding a broad spectrum of organizational phenomena to effectively manage an enterprise. Nonaka and colleagues (2000) have adapted the original concept of *ba* to play an integral role in their knowledge creation model. They define *ba* as a "shared context in motion for knowledge" (Nonaka et al., 2000, p. 13) and systematically classify it into different categories based on the nature of the personal encounter that takes place in the shared space (i.e., face-to-face or virtual) and the mode of knowledge exchange (i.e., tacit or explicit). Yamaguchi's (2006) framework for "paradigm-disruptive" innovation entails a "field of resonance," which he portrays as a special type of *ba* in which engineers and decision makers intimately share technical tacit knowledge. Put together, the core ideas of *ba* are that (1) the shared space can be, but need not be, physical, (2) it must be purposeful, and (3) its structure should enhance meaningful interactions among members. Further, because it is a forum of sensemaking, a *ba* must engender and encourage spontaneous exchange. This last point implies that just providing a meeting room or an intranet forum to potential *ba* participants is not sufficient; neither is merely following a set of prescriptive problem-solving procedures.

A *ba* of engineering problem solving may be envisioned as an improvisational theater in which engineers deftly operate as "agents" of diverse interest groups (Eisenhardt, 1989a; Hill & Jones, 1992) to unify different personal visions. "[O]ne of the most reliable indicators of a team that is continually learning is the visible conflict of ideas" (Senge, 2006, p. 232), and so a fully functioning *ba* is likely to first witness exchange of divergent viewpoints followed by their gradual convergence—as was the case for the NVH example and many other successful stories provided by the interviewees. The problem solving stories chronicled formation of, as well as absence of, *ba* where collaboration took place. Unsuccessful problem solving was lacking *ba*. In spite of expertise and resources that existed, they could not be pulled together to form a shared space for carrying out constructive dialog. In one such example, the lead engineer narrates:

> [W]e should get expert[s] involved. [In] the first [case] expert support did make a difference when we faced difficulties . . . but this [less successful] one we dr[o]ve it pretty hard but we didn't really have a chance to really talk to the bearing supplier and also our internal expert. Well we had a review with the expert [but] didn't really get him on board every time [we needed him] in this investigation process. (*Engineer, 15 – 20 years experience*)

The sentiment expressed here is in stark contrast with, for example, a story of manufacturing problem solving in which the team members had every confidence that "whatever [they] came up with was going to be supported" by all concerned parties. This statement denotes the existence of shared mental models throughout the organization.

Given that a successful problem resolution is a result of collective *phronesis*, a set of "beliefs" that support a formation of this unified understanding may be key to unraveling why views diverge or converge (Baba et al., 2004). Beliefs are formed through experience. Likewise, *phronesis*—unlike theories that can be taught in lectures or techniques acquired through practice—can only be secured through **experience** applying them in **specific** contexts (Grint, 2007). Much of what goes on in day-to-day engineering is grounded in particular contexts and involves development of situated logic. Baba et al.'s (2004) empirical study suggests the role of "parallel or similar" experience in a "common" context as potentially a driver for gaining a shared understanding from "distributed" team members spread across geographical and cultural divides. The role of experience in EPS, especially shared experience, may similarly facilitate recalibration of members' past understanding to fit the new context in which the problem is being investigated. "Successful" problem-solving narratives contained many instances of cross-functional team members **together** visiting customer sites, being engaged in experiments, or walking through production lines. Hence, the *ba* of EPS is proposed to be a "shared experiential space."

The new integrated model of engineering problem solving. Itami's (2010a, 2010b) *ba* theory appears to imply two major facets: the formative side and the reflective side. A *ba* is formed by conditions that stimulate the social and cognitive processes of the actors engaged in purposeful activities. The formation of *ba*, in turn, is evidenced by the increased inter-subjectivity among its members. Facility re-design to enhance meeting room amenities, a chief executive officer's declaration about increased investment in a new product venture, and special company-wide events to discuss lessons learned can all trigger a new venue for dialog and inter-organizational collaboration. Among the varied views of absorptive capacity concept that exist, Volberda et al.'s (2009, p. 24) integrative framework draws attention to the "awareness network" to share and obtain "knowledge that can help to solve novel problems" resulting from intra- and inter-organizational linkages. Zahra and George's (2002) model, as another example, posits a two-step process of building a "potential capability" that is successively followed by "realized capability." The *ba* of EPS is conceptualized as an element similar to "potential capability" that creates a network of situated cognition for the EPS stakeholders. It then fuels the knowledge creation routines, akin to demonstrating a "realized capability."

Integrating the constructs that emerged from the study, the EPS *ba* can form when facilitated by the six environmental conditions to which the findings have led. *Controlled urgency* triggers initial dialog and helps keep the EPS system state in positive tension. *Trust* and *autonomy* are especially important when team members and stakeholders begin to share and externalize their views. They should be able to do so in an unconstrained environment without fear of reprisal. Clarity of *leadership vision* serves as an ultimate judgment standard against which to evaluate legitimacy of the team's action and decisions. Access to an appropriate mix of *resources* provides the *requisite variety* crucial for ensuring technical soundness of investigation directions, as well as of the chosen solutions. Finally, a *framework for sharing* provides venues for creating *redundancy* of understanding among stakeholders throughout the EPS phases culminating in routinization. These factors set the context for active and meaningful conversations—a stage for sensemaking and knowledge creation. A well-functioning *ba* is a vortex of human energy reflected in the positive team dynamics. The energy created in the *ba* runs the EPS routines, conceptualized as the multi-directional knowledge flow analogous to the dynamics of SECI (Nonaka et al., 2000). This setup drives the root cause analysis, with a force powerful enough to create "new premises to override the existing ones" (Nonaka & Takeuchi, 1995, p. 44) to realize system changes. Figure 6 below illustrates this integrative epistemological concept.

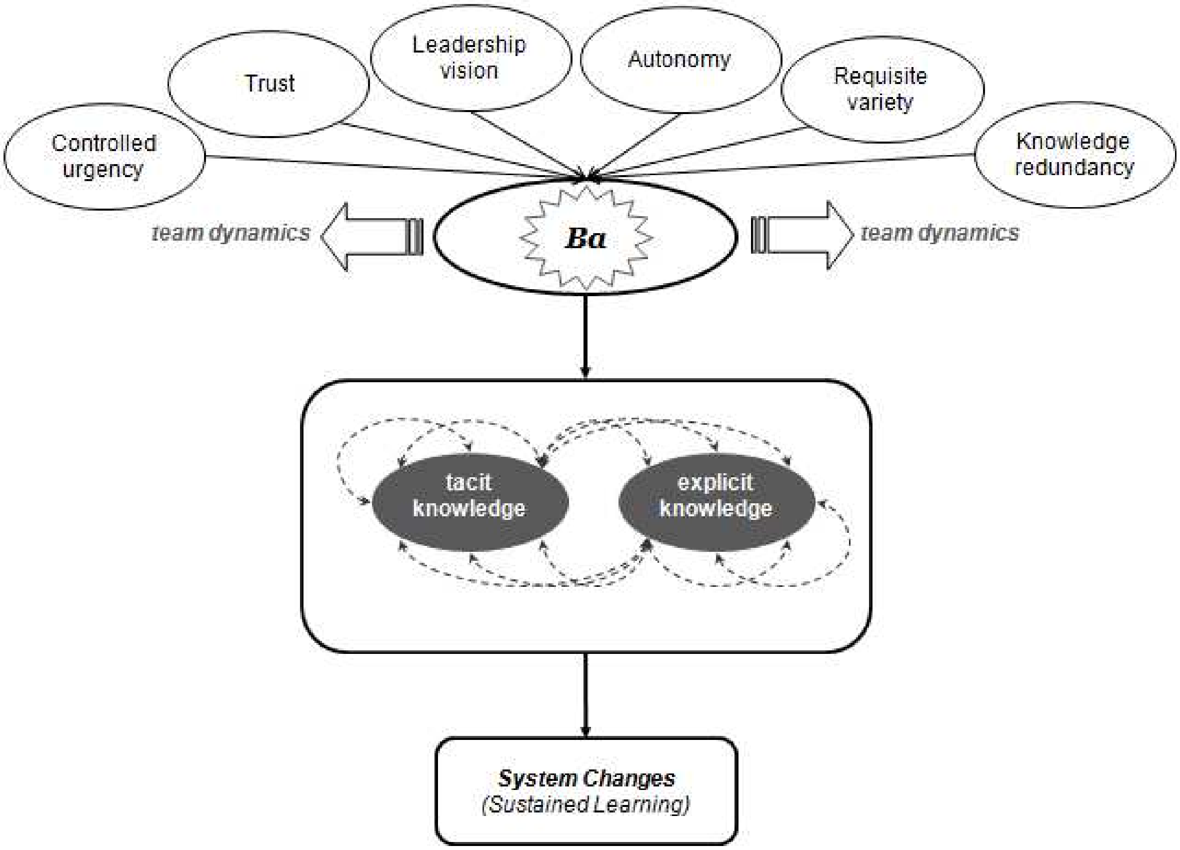

Figure 6. New integrated model of engineering problem solving and knowledge creation.

The chapter now concludes with a set of propositions:

1. The stronger the six environmental conditions, the more effective the *ba* will be, manifested in positive team interactions.
2. The more effective the *ba* is, the more active the SECI dynamics will be.
3. The higher the SECI effort, the more likely it is for EPS to achieve positive system changes.

Thus, the stage is set for the second and final phase of the research—the quantitative study. The extent to which these relationships hold, and generalize across a larger sample, will be explored in the next chapter.

CHAPTER 5: QUANTITATIVE STUDY

The qualitative study, chronicled in Chapter 4, put forward a conceptual model of the engineering problems solving (EPS) dynamics. The model posits that particular organizational aspects can be manifest in positive team behaviors, which in turn energize knowledge creation routines that lead to sustained learning from problem investigation. In this chapter, these concepts are translated into a testable model that is subsequently analyzed quantitatively.

The rest of the chapter is organized as follows. First, a research model is presented with accompanying hypotheses. Operationalization of the model constructs is discussed next. Subsequently, data collection and analysis strategy is presented, followed by a report of analysis results. The chapter concludes with a discussion of the quantitative study findings.

Research Model and Hypotheses

Shown below in Figure 7 is a research model, built on theory and the qualitative study, to guide the quantitative study of EPS dynamics.

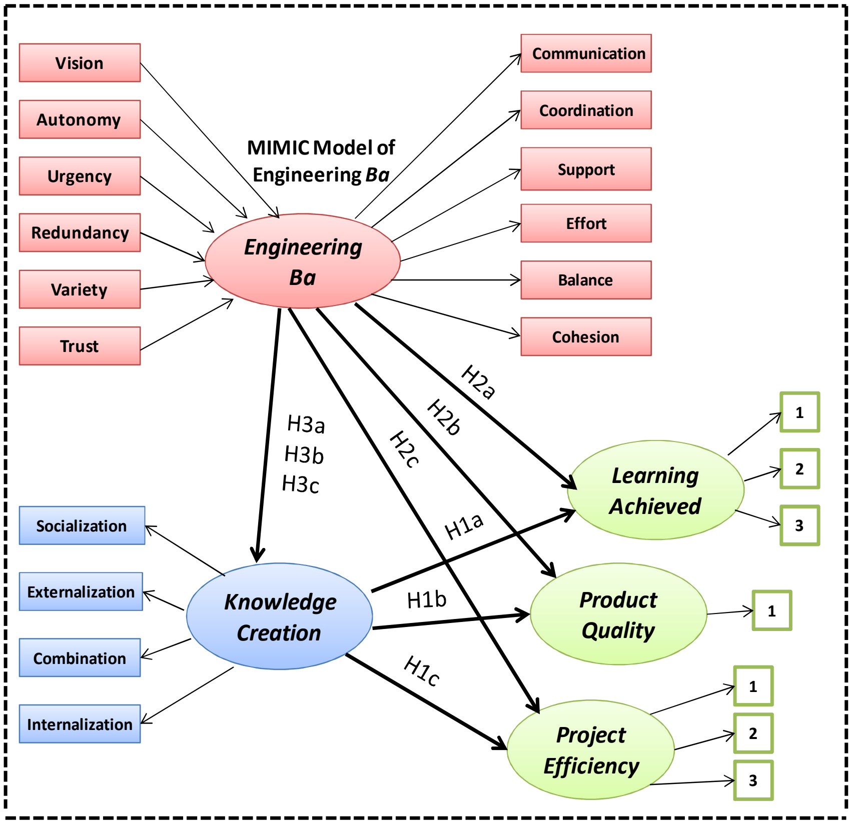

Figure 7. Research model of EPS knowledge creation dynamics.

The model posits that engineering problem solving starts with a formation of an environment called *engineering ba*, which sets the stage for active knowledge exchange to occur. Six enabling conditions are hypothesized to form the *engineering ba*, which in turn is reflected by six indicators of team dynamics. The six EPS enablers, as discussed in depth in Chapter 4, are: leadership *vision*, *autonomy*, controlled *urgency*, knowledge *redundancy*, *requisite variety*, and *trust*. In the *knowledge creation* routines that follow, tacit and explicit forms of technical knowledge are processed and integrated to ultimately produce a unified interpretation. This unified interpretation results in *learning achieved* and problem solving performance that has two components: *product quality* and *project efficiency*. *Learning achieved* refers to fundamental system changes in engineering practice such as new ways of designing, manufacturing, or testing a product. Improved *product quality* is a form of knowledge capture as a result of successful problem resolution, while *project efficiency* is a reflection of effective and systematic problem solving process.

Learning achieved. Team learning is achieved when new practices result from exchanging insights and negotiating meaning (Zellmer-Bruhn & Gibson, 2006). In the qualitative sample, successful EPS endeavors not only delivered a problem fix but also fundamentally altered the organizational routines (Itabashi-Campbell, Gluesing, & Perelli, 2012). These changes improved specifications, upgraded equipment, and even transformed product development processes. *Learning achieved* thus captures the extent to which teams "reconsider[ed] existing practices and search[ed] for ways to improve their work and implement[ed] novel solutions" (Zellmer-Bruhn & Gibson, 2006, p. 506).

Product quality and project efficiency. *Product quality* and *project efficiency* are two typical measures of new product development project success (Schulze & Hoegl, 2006) and are also very relevant in engineering contexts. In the context of engineering problem solving, *product quality* is one of the primary yardsticks with which to measure how well the corrected product meets its requirements. *Product quality* is a multi-faceted concept encompassing such features as functionality, durability, and compatibility with other systems (Omachonu & Ross, 1994). Every respondent of the qualitative study reported how one or more of these product features were compromised at the beginning of his or her problem investigation and how they were improved (or not improved) at the conclusion of the investigation. Along with *product quality, project efficiency* gauges effectiveness of problem solving. It concerns the project's adherence to its objectives—such as schedule, cost, and other requirements—and can be a measure of how efficiently the problem-solving endeavor was brought to closure. Many examples of successful problem solving stories in the qualitative study were associated with solutions that fully met the launch timing and product design requirements while not raising (and in some cases lowering) production costs (Itabashi-Campbell et al., 2012).

Knowledge creation. *Knowledge creation* is a set of routines in which active knowledge exchange occurs, forming a collective engineering interpretation that "enables seeing the old in a new way or novel distinction-making" (Langer, 1989, p. 156). It is the process of learning, which "is facilitated by translation and recontextualization[,] and it rarely occurs without a transformation in the acquired knowledge" (Zellmer-Bruhn & Gibson, 2006, p. 506). In Nonaka's (1994) perspective, this transformation occurs through iterative and multi-directional exchange of tacit and explicit knowledge, a "SECI" process (Nonaka, Toyama, & Konno, 2000). It is through the SECI process the tacit knowledge deeply embedded in individuals and local contexts is aggregated into a new organizational know-how—essential for leveraging "inter-subjective and idiosyncratic nature" of knowledge to create "firm-specific value" that is a basis of competitive advantage (Nonaka et al., 2000, p. 20). Hence, the proposed model conceptualizes engineering *knowledge creation* as having four dimensions that mirror SECI: *socialization*, *externalization*, *combination*, and *internalization*. As the qualitative study demonstrated, teams in successful EPS examples created knowledge through "a step by step approach" to really "drill down" on the issue by asking "what else?" at every juncture of the root cause analysis. Such a high problem solving rigor "stimulates their inquiry about alternative practices, and helps the teams adapt new practices or combine them with their existing repertoire" (Zellmer-Bruhn & Gibson, 2006, p. 506). Hence, the proposed model hypothesizes that

H1a: *Knowledge creation* is positively related to *learning achieved.*

H1b: *Knowledge creation* is positively related to *product quality.*

H1c: *Knowledge creation* is positively related to *project efficiency.*

Engineering *ba*. Borrowing from Itami's (Itami, 2010a, 2010b) and Nonaka and colleagues' (2000) concept of *ba*, an *engineering ba* is hypothesized to have been formed when the six conditions to which the discussion made reference earlier exist. Specifically,

1. Leadership *vision*: Clarity of goals and requirements expressed by leadership external to the immediate problem solving project team, akin to Nonaka and Takeuchi's (1995) *intention* concept
2. *Autonomy*: Open and unconstrained environment that allows freedom, as well as authority, to the problem solving team, identical to the concept of *autonomy* in Nonaka's (1994) knowledge-creation model
3. Controlled *urgency*: A state of "creative tension" (Senge, 2006; Womack, Jones, & Roos, 1990) that keeps problem investigation from degenerating into chaos or becoming inertial, analogous to the concept of *creative chaos* in Nonaka's (1994) knowledge-creation model
4. Knowledge *redundancy*: Ease of and encouragement about information sharing to promote knowledge *redundancy* to enhance interconnectedness (Nonaka, 1994; Nonaka & Takeuchi, 1995)
5. Requisite *variety*: Accessibility to an appropriate mix of expertise and tools that provide *requisite variety* (Nonaka, 1994; Nonaka & Takeuchi, 1995; Weick, 1979) to enrich the resource pool used for problem solving

6. *Trust*: Unquestioned *trust and commitment* that “whatever the problem solving team comes up with will be supported by the management and organization” (as cited by one interviewee from the qualitative study), which is in line with Nonaka and colleagues’ (2000) *love, care, trust, and commitment* concept.

Using Itami’s (2010a, 2010b) framework, the formation of *engineering ba*, in turn, is reflected by a demonstration of positive group dynamics among the team members entrusted to solve a problem. Success of the EPS projects in the qualitative study correlated to the efforts made by engineers to actively manage relationships among relevant stakeholders. Positive EPS outcomes, at least in the qualitative study sample, were associated with the extent to which all stakeholders came “on board” and supported the EPS goal. Based on the findings from the empirical study and the extant literature, the proposed model further hypothesizes that

H2a: *Engineering ba* is positively related to *learning achieved*.

H2b: *Engineering ba* is positively related to *product quality*.

H2c: *Engineering ba* is positively related to *project efficiency*.

Finally, the model posits that

H3a: *Knowledge creation* partially mediates the positive relationship between *engineering ba* and *learning achieved*.

H3b: *Knowledge creation* partially mediates the positive relationship between *engineering ba* and *product quality*.

H3c: *Knowledge creation* partially mediates the positive relationship between *engineering ba* and *project efficiency*.

The next section discusses how the identified constructs were operationalized.

Operationalization of Constructs

Operationalization of the variables was accomplished using previously validated measures as summarized below and explained in further details in Appendix B. Appendix B also maps the original scale items to those used in the final survey questionnaire, which is presented in Appendix C. The final research model has a total of 23 indicators created by aggregating some of the 75 items obtained from the survey instrument as outlined below. A minor deviation made in scale format upon adoption is also discussed.

Engineering *ba*. *Engineering ba* was modeled in a multiple-indicators-multiple-causes, or MIMIC, (Diamantopoulos, 2006; Edwards, 2011) configuration consisting of formative and reflective indicators. Using the construct *ba* from Nonaka et al.'s (2000) knowledge-creation model as a basis, and incorporating Itami's (2010a, 2010b) theory of *ba*, *engineering ba* was modeled as having both the formative (six EPS enablers) and reflective (six team dynamics attributes) dimensions. The formative dimensions were operationalized with Nonaka et al.'s (2000) "six enablers" that "energize *ba*," measured using Lloria and Moreno-Luzón's (2005, p. 231) "Enablers of Knowledge Creation" scale. This six-factor scale was originally developed based on Nonaka's theory. Each of the six enablers—*intention*, *autonomy*, *creative chaos*, *redundancy*, *requisite variety*, and *trust*—is measured with four items (thus, a total of 24 items) using a 7-point Likert response scale. The authors report reliability ranging from 0.689 to 0.903 from a previous study (conducted in a Spanish supply chain management context, N = 167). The scale was adopted in its entirety to measure the six EPS enablers that form *ba*—*leadership vision*, *autonomy*, *controlled urgency*, *redundancy*, *requisite variety*, and *trust*. Summation of 24 items was implemented by taking the average of four items measuring each dimension because it was those six dimensions, rather than the items, were the primary interest. Prior to aggregation, Cronbach's α was used to check acceptable reliability.

Engineering ba's reflective dimensions were hypothesized to be "positive team dynamics," which was operationalized using the *teamwork quality* construct borrowed from Hoegl, Weinkauf, and Gemuenden (2004, p. 52). The construct has six dimensions (totaling 20 items) pertaining to inter-team collaboration processes—*communication, coordination, mutual support, effort, balanced contribution,* and *cohesion*—each of which is measured with two to five items using a 5-point Likert response scale. The scale reliability, Cronbach's α, reported from its original study conducted with 222 firms in the European automotive industry, ranges from 0.70 to 0.89 (see Hoegl et al., 2004). All 20 items were adopted to measure the reflective side of *engineering ba*. Summation of 20 items was implemented by taking the average of two to five items measuring each distinct dimension because it was those six dimensions, rather than the items, were the primary interest. Prior to aggregation, Cronbach's α was used to check acceptable reliability.

Knowledge creation. *Knowledge creation* was modeled using Nonaka's SECI process (Nonaka et al., 2000) and was operationalized using the four-factor "Knowledge-Creation Modes" scale developed by Schulze and Hoegl (2006, pp. 230-233). The original scale was created to model Nonaka's knowledge-creation concept and mirrors the four dimensions of SECI process—*socialization, externalization, combination,* and *internalization*—each being measured by four items on a 5-point Likert scale (totaling 16). The authors report composite reliability ranging from 0.78 to 0.82 from their original study in a European context (new product development projects sampled from 33 German/Austrian/Swiss firms, N = 188). The scale was used in its entirety to measure EPS *knowledge creation* routines. Summation of 16 items was implemented by taking the average of four items measuring each knowledge-creation mode because it was those four dimensions, rather than the items, were the primary interest. Prior to aggregation, Cronbach's α was used to check acceptable reliability.

Learning achieved. The extent to which new processes and practices resulted from problem solving—that is, *learning achieved*—was measured using the newly developed three-item scale by Zellmer-Bruhn and Gibson (2006). The original scale measures each of the three items using a 7-point Likert response scale and reports a Cronbach's α reliability of .84. The authors also report demonstrated item factor loadings ranging from .78 to .87 (Zellmer-Bruhn & Gibson, 2006, p. 509).

Product quality. *Product quality* was modeled using the nine-item "product quality" scale developed by Schulze and Hoegl (2006, p. 229) as part of a study to apply Nonaka's SECI process in a new product development context. The scale has its genesis in the seven-item scale used in the study by Hoegl et al. (2004) (5-point Likert, N = 74, Cronbach's α = 0.89). In Schulze and Hoegl's (2006) study, the scale was augmented to nine items, which were subsequently converted into a "quality index" in their analysis by averaging the item scores. The nine-item version was adopted to operationalize *product quality* in this study and was treated as a summated scale. Specifically, nine items that measure various facets of quality were averaged to form a single indicator. Prior to aggregation, Cronbach's α was used to check acceptable reliability.

Project efficiency. *Project efficiency* was modeled using the *project efficiency* construct borrowed from the same study discussed above (i.e., Schulze & Hoegl, 2006). Along with *product quality*, *project efficiency* was used as one of the outcome variables of

Nonaka's SECI process (Schulze & Hoegl, 2006). It is measured using a three-item scale (5-point Likert, N = 92, Cronbach's α = 0.82). All of the three items were adopted for this study.

Control variables. The survey instrument was designed to query the respondent's roles in terms of his or her (1) engineering function and (2) problem-solving leadership so these two attributes could be used as control variables for all of the outcome variables (i.e., *learning achieved*, *product quality,* and *project efficiency*). As already discussed in Chapters 3 and 4, the qualitative study followed Schein's (1996) definition of "engineers" and sought the voices of those who are "**designers** [emphasis added] of products or systems that have utility" (p. 14). The primary focus of the qualitative study, in other words, was on those technical professionals who had **ownership** of design, application, or manufacture of a product. These recruitment criteria excluded other types of engineers—such as testing, quality, reliability, and field service / warranty analysis engineers—who typically do not have ownership of a product or its manufacturing processes yet oftentimes play key support roles in product-related problem solving. As strategized in Chapter 3, the quantitative study was to open the floor to all types of engineers having problem solving experience. Having both the lead and support engineers, as a consequence, may result in differing perspectives on the problem-solving outcomes. Attribution theory (Kelley & Michela, 1980; Kolb, 1995) posits that actor-observer differences in self-assessment occur due to two major factors: cognitive and motivational. One, actors (or performers) and observers may have different types of information available to them. Secondly, actors and observers may have different interests in interpreting a given event. These factors can result in, for example, team leaders' tendency to overestimate how smoothly the team is functioning (Kolb, 1995).

Scale format. This study made use of established scales by adopting them in their entirety and making appropriate contextual adjustments, with one exception. The scales used to measure the formative dimensions of *engineering ba* (i.e., "Knowledge-creation enablers" by Lloria & Moreno-Luzón, 2005) and *learning achieved* (Zellmer-Bruhn & Gibson, 2006) were converted from their original 7-point to 5-point Likert format to match the rest of the scales used in the study. The conversion was done without changing the scale's anchor points; both the original and the rescaled versions range from "strongly disagree" (SD) to "strongly agree" (SA). Studies (e.g., Dawes, 2008) show that changes in the data characteristics (mean, variance, skewness, and kurtosis) resulting from re-scaling between 5-point and 7-point Likert measures are negligible. A uniform scale format provides greater ease of completing the questionnaire than a mixed format and was thus implemented to maximize survey response rate. Hence, all of the 75 items on the survey were implemented on a 5-point Likert scale that is anchored on "1" denoting strong disagreement (SD) on one end and "5" denoting strong agreement (SA) on the other. These items are presented in Appendix C.

Methods

This section discusses data collection strategy and sample, along with the justification for using the partial least squares (PLS) approach for data analysis. Appendix D provides further details of the sample characteristics.

Data collection. The empirical data to test the hypothesized relationships among the constructs were collected via a self-administered, on-line survey that asks questions about the respondent's experience in problem solving. The target audience was U.S.-based engineering

/ technical professionals who had at least one experience participating in team-based problem solving efforts to resolve product-related issues. The survey explicitly stated that

1. "Team-based" refers to having at least two people, including the respondent, engaged in the resolution of the problem,
2. "Product" may be hardware, software, raw or semi-finished materials, information technology (IT) architecture, or any combination of these, and
3. "Product-related problem" can include any problematic issue that pertains to design, application, testing, manufacturing, servicing, or field usage of the product

to help the potential participants decide whether or not they met the participation criteria. An initial screening question, immediately following the introductory statement that seeks consent to participate, served as the first check point to filter out respondents not meeting the research criteria. A series of questions followed, which queried about the contextual factors of the respondent's problem solving experience. Responses to these questions served to provide additional filters to exclude non-qualifying participants, as well as descriptive characterization of problem solving experiences being contributed. Following these background questions, the survey began asking the 75 questions captured in Appendix C, which directly pertained to the theorized constructs and their relationships. Upon completion, the respondent was directed to answer a few demographic questions. The survey ended with a thank-you statement, which contained a voluntary option to leave contact information in case the respondent wished to receive a summary copy of the survey results.

The survey was launched following completion of pre- and pilot-testing. The pre-test was conducted from late September 2011 through January 2012 using a convenience sample of ten individuals having similar qualifications to those of the target population. All pre-test sessions were administered face-to-face, using a “pen and paper” format. Based on the feedback from these sessions, the questionnaire was put through several rounds of revision through February 2012. From mid-March 2012 through early April 2012, the revised survey was pilot-tested. Pilot-testing was conducted using a web-based survey software application, Qualtrics, in the final intended survey format. Seventeen individuals having similar professional backgrounds to those expected of the target respondents took part in the pilot test. Each participant was given a link to the on-line survey and was requested to provide feedback on the clarity of questions, issues concerning response options, and the length of time required to complete the survey. The test responses were reviewed for any inconsistencies. As a result, minor adjustments were made to the questionnaire prior to launch. The survey was launched in late April 2012.

Once launched, the survey was kept open through early November 2012, during which time on-going efforts were made to solicit participation. The author sent a direct request to 228 individuals asking them to participate, to refer potential participants, or to do both. Additionally, she sent a direct inquiry to three organizations with a request to consider circulating the survey link to their members. At her request, the Industrial & Systems Engineering Department (the author’s home department) at Wayne State University forwarded the survey link to the current members of its Engineering Management Master’s Program (EMMP). She also advertised the study by posting a survey link on a total of 18 on-line discussion groups of which she was a member. They included engineering associations such as Tau Beta Pi Engineering Honor Society and IEEE Reliability Society and, at least as of the time the posting was made, were accessible only to their registered members (i.e., not open to general public). By leveraging the author's personal networks and using a snowballing technique, her recruitment efforts resulted in a total of 334 responses at the time of survey closure.

Sample characteristics. Of the total responses collected, 117 of them were incomplete. The respondents, in this case, either did not pass the first screening question or quit responding before reaching the end of the survey. Because of the "forced response" logic implemented in the survey, participants either responded fully or stopped prematurely. For that reason, "missing data" treatment was not warranted because the "missing" pattern was non-random (i.e., all non-responses are systematically in the latter part of the survey). In addition, even the best case of the incomplete response had only 73% of the questions completed, so imputation of missing values was not justified. Thus, a listwise exclusion of 117 incomplete cases from the total of 334 logged in the survey left 217 complete responses. From those 217 data points, nine more had to be removed due to the respondents' backgrounds not meeting the study's "U.S.-based" criteria. The usable sample size with which to start analysis, therefore, came to be 208.

The 208 respondents consisted of 160 (76.9%) men and 48 (23.1%) women. The women-to-men ratio aligns reasonably well with the national labor statistics considering that women occupied 33.9% of "computer systems analysis" and 13.6% of "architects and engineers" positions in 2011 (U.S. Bureau of Labor Statistics, 2012). The female respondents are likely to fall under one of these categories; so, roughly speaking, their sample ratio mirrors the combined average of 23.8%. For both men and women, their experience levels are skewed toward 10 or more years, indicating that the majority of the participants were at least in their mid-careers. Likely to be correlating with their career stages, an overwhelming majority of both the male and female participants had at least a bachelor’s degree, with many having graduate degrees. It should be noted here that the information provided for “Other – please specify” response option was examined very carefully to determine whether reclassification of the response was warranted. For example, in the case of education, several “Other” responses had to be re-classified into “Graduate degrees” as these respondents listed “PhD” under “Other.”

In terms of contextual characteristics of the EPS example contributed by each respondent, the sample was characterized using six attributes: product involved, industry, product development phase, participant’s functional role, participant’s problem solving role, and geographical location. The first three relate directly to the product that prompted EPS, while the last three are about the respondent as an actor in the EPS. In terms of the product, a slightly over half of the problems concerned hardware finished goods (52.4%), followed by finished goods involving both hardware and software (such as cars and embedded systems, 26.0%). Most of these EPS projects had been generated in the automotive industry (68.3%), again showing the same trend as that seen in the qualitative study. As to the product lifecycle phase in which the problem solving occurred, the sample shows a relatively even distribution between the concept-to-launch and the launch-to-sustainability stages. Within each of these phases, the “engineering verification / validation” of the former and the “full production – field / warranty returns” of the latter show the highest EPS occurrence rate. This data pattern is not surprising as engineering validation and field warranty are the phases in which the product is “put to the test”—as a prototype in the former and a mass produced sample in the latter.

Respondents as EPS actors were characterized in terms of their engineering and problem solving roles, as well as their home locations at the time of problem investigation. Responses from the first two categories were later used as control variables in the model analysis, and the location question served as the second filter to exclude non-U.S. based respondents. In terms of engineering roles, the most frequently occurring category is “product design, development, architecture, or application” (N = 80, 38.5%), followed closely by 71 (34.1%) respondents who played quality, reliability, warranty, or related support roles. Following the first two, “manufacturing” and “product testing” tie for the third place at N = 26 (12.5%) each. The remaining five responses (2.4%) came from “product maintenance / service” professionals. Applying the product ownership criteria based on Schein’s (1996) definition discussed earlier, a slightly over half of the respondents are of “product owner” category (80 product designers + 26 manufacturing engineers = 106) with the remaining respondents falling under the “product support” category.

In terms of EPS project role, a slightly over half (54.3%) of the respondents assumed a leadership role. The remaining 38.0% and 7.7% played support roles, the former as core members of the EPS team while the latter were external stakeholders such as management, customer, or supplier. Finally, an overwhelming majority (74.5%) of the respondents were located in the U.S. Midwest at the time of their surveyed EPS involvement, very likely to be correlating with their automotive industry affiliation discussed earlier.

In summary, a majority of survey participants were experienced and degreed automotive engineers. They were engaged in all facets of engineering, from product design to manufacturing, testing, and various support functions at the time of problem occurrence. Their problems were manifested in hardware-based goods, which were discovered during engineering validation or a warranty phase of the product lifecycle. They were leaders of EPS efforts and were located in the U.S. Midwest at that time. The pre-dominance of seasoned engineers who took lead roles in problem solving is a favorable attribute of the sample. Their observations through experienced eyes and from the perspective of boundary spanners interacting with EPS stakeholders carry credibility and thus contribute to face validity of the measures. Appendix D provides further details of these sample characteristics.

Analysis and modeling approach. The hypothesized relationships among constructs were analyzed using the partial least squares (PLS) approach for structural equation modeling (SEM). The decision to use PLS, rather than a covariance-based SEM (supported by such tools as LISREL and AMOS), was based primarily on the goal and nature of the study. The study's aim was to understand how well the model **predicts** EPS effectiveness and learning, rather than to explain covariance of all measures. The study is based on a not yet completely fine-tuned understanding. The experimental nature of modeling EPS dynamics and the extent to which *ba*, an "empirically under-explored" construct (Nonaka, von Krogh, & Voelpel, 2006, p. 1197), lend themselves to an exploratory data analysis approach. Prediction—rather than explanation—orientation of the study, as well as the lack of a strong theory, makes PLS a very suitable parameter estimation methodology (Chin, 1998; Haenlein & Kaplan, 2004). The choice of PLS also comes with additional benefits that were also relevant to the study. One, the PLS approach is more amenable to the relatively small research sample size. Secondly, with PLS, distributional assumptions such as normality and absence of multicollinearity can be relaxed (Chin, 1998; Haenlein & Kaplan, 2004). The study's measures were produced on a five-point Likert scale, which makes the data susceptible to a non-normal distributional pattern. With PLS, data modeling under conditions of small sample and violations of distributional assumptions is less likely to result in improper solutions (Chin, 1998). Lastly, there is an epistemic need to model *engineering ba* as having both formative and reflective dimensions, and PLS has the ability to handle indicators in different modes (Chin, 1998; Haenlein & Kaplan, 2004).

In summary, PLS was chosen for its “ability to predict and understand the role and formation of individual constructs and their relationships among each other” (Chin, 1998, p. 332). The methodology allows greater flexibility than does covariance-based SEM, while still providing power to simultaneously model unobservable variables—a great advantage that is afforded by second-generation multivariate techniques (Chin, 1998; Haenlein & Kaplan, 2004). PLS-Graph 3.0 (Chin, 1993 - 2003) supported the PLS analysis in the study. In addition, SPSS version 20 (IBM Corporation 1989, 2011) was used for preparatory and auxiliary data manipulation.

Analysis Results

The data analysis was performed in multi stages. First, scale reliability at item level was examined prior to summation. Next, after summation, the data were checked for non-normality (e.g., skewness and kurtosis) and presence of influential outliers. Data transformation was tried concurrently to decide on the best data format to use for final analysis. Squared-term transformation was found to produce the best parameter estimates and was used for subsequent analyses—that is, exploratory factory analysis (EFA), measurement model analysis, and finally the structural path modeling.

Scale reliability. Using the sample of 208, scale reliability was assessed using a Cronbach α statistic (Cronbach, 1951) for each construct being measured. Results are shown in Appendix E. All scales had reliability exceeding .70, meeting the generally recommended minimum threshold of .60 (Hair, Black, Babin, & Anderson, 2010). Consequently, none of the original scale items were deleted, so, all 75 original items were retained. Having verified acceptable internal consistency of the scales, the analysis proceeded to summate some of them as outlined in the previous section (i.e., resulting in 23 indicators).

Data screening. Prior to starting the model analysis, the input data characteristics were examined for extreme skewness and kurtosis. Even though PLS approach works without a distributional assumption and is relatively forgiving to non-normality and small sample sizes (Chin, 1998; Haenlein & Kaplan, 2004), the deleterious impact of non-normal data on PLS estimates is documented (Marcoulides, Chin, & Saunders, 2009). For that reason, an iterative approach of trying different transformations and evaluating their effects on parameter estimates was taken. All 23 measures showed negative skewness, most of which were statistically significant. Many of them also showed statistically significant non-zero kurtosis values. The squared-term transformation, a common method to alleviate negative skew in the data (Hair et al., 2010), was found to most effectively reduce both the skewness and kurtosis of the data. Using the squared-term transformed data, multivariate outlier check was then performed. The Mahalanobis distance calculated on each case indentified three that exceeded the threshold at the .001 risk level ($\chi^2_{\alpha=.001,\ df=23} = 49.728$). A review of demographic characteristics of these three participants did not reveal any oddities. Consequently, the effects of keeping versus removing these data points were iteratively tested. In the end, the decision was made to exclude them from analysis. Therefore, the final sample size used for the PLS analysis was reduced from 208 to 205. Appendix F presents the final dataset used for model analyses.

Lastly, as part of data screening, an exploratory factor analysis (EFA) was performed using the transformed data of N = 205, only on the reflective constructs having multiple indicators (i.e., *ba – team dynamics*, *knowledge creation*, *learning achieved*, and *project efficiency*). The EFA was run to check the extent to which the indicators meet the *a priori* expectations of factorability. The Kaiser-Meyer-Olkin (KMO) measure of sampling adequacy (KMO = .919) and the Bartlett's test of sphericity (approximate $\chi^2_{df=120}$ = 1988.169, significance = .000) show suitability of the data for structure detection. All indicators loaded on their hypothesized factors except for two deviations. The *socialization* measure did not align with the rest of the dimensions posited for *knowledge creation*. Also, one of the three measures of *project efficiency* cross-loaded on another factor. The details are shown in Appendix G. Due to the exploratory nature of the study, the *socialization* measure was re-assigned, and the cross-loading measure of *project efficiency* was retained as initially hypothesized.

Structural equation modeling using PLS. The analysis then proceeded to structural equation modeling (SEM) using PLS. The SEM was done in two stages, first to ensure acceptable fit of the measurement model then to test the causal model.

Measurement model. A confirmatory factor analysis (CFA), in the context of PLS, was carried out to evaluate the quality of the measurement model. Because the hypothesized model contains both the reflectively and formatively modeled factors, two separate procedures and cannons were warranted to account for the differences in their theoretical and nomological nature (Cenfetelli & Bassellier, 2009; Götz, Liehr-Gobbers, & Krafft, 2010). The MIMIC construct of *engineering ba*, in the PLS framework, was modeled using a "Mode C" (Chin, 1998; Dijkstra, 2010) configuration, which requires a formatively measured variable (*Ba – enablers*) to be connected to a reflectively modeled factor (*Ba – team dynamics*) by a structural path. Following this procedure, the first part of the measurement analysis addressed the factorial validity of the reflective constructs, followed by the assessment of the formative factor. For both the reflective and formative measurement models in the PLS context, significance of parameters can be assessed using asymptotic t-statistics generated by re-sampling techniques (Chin, 1998; Geffen & Straub, 2005; Götz et al., 2010). The PLS-Graph 3.0 program enables this operation by its bootstrapping procedures. Finally, common method bias (CMB) was also checked as part of the CFA. The details follow.

Reflective constructs. The factorial validity of the reflectively measured constructs—namely, *Ba – team dynamics*, *knowledge creation* (*Knowledge*), *learning achieved* (*Learning*), *product quality* (*Quality*), and *project efficiency* (*Efficiency*)—was evaluated using factor loadings, composite reliability (CR) scores, average variance extracted (AVE) scores, AVEs against factor correlations, and cross-loadings. Both CR ($0 \leq CR \leq 1$) and AVE ($0 \leq AVE \leq 1$) are commonly used metrics of convergent validity (Hair et al., 2010) and are among the standard outputs of PLS-Graph 3.0. Table 4 below presents the factor loadings with significance (i.e., T-stat.), CR, and AVE.

Table 4

Indicator Loadings, CR, and AVE

Reflective Constructs	Indicator	Loading	T-Stat.	P-Value	CR	AVE
Ba – team dynamics	COMM	0.860	39.189	0.000	0.935	0.706
	COORD	0.794	25.833	0.000		
	SUPP	0.874	51.191	0.000		
	EFFORT	0.824	36.804	0.000		
	BAL	0.899	66.233	0.000		
	COH	0.783	26.127	0.000		
Knowledge	SOC	0.734	17.722	0.000	0.891	0.673
	EXT	0.853	39.990	0.000		
	COMB	0.845	41.665	0.000		
	INT	0.844	33.418	0.000		
Learning	LEARN1	0.887	57.897	0.000	0.892	0.735
	LEARN2	0.877	40.165	0.000		
	LEARN3	0.805	23.799	0.000		
Quality	QUAL	1.000	N/A	N/A	N/A	N/A
Efficiency	EFFIC1	0.816	27.616	0.000	0.880	0.710
	EFFIC2	0.888	56.895	0.000		
	EFFIC3	0.822	29.009	0.000		

As shown in Table 4, all (except for *Quality*, which is a single-indicator variable and is therefore exempted from this analysis) loadings are greater than the acceptable ideal threshold of 0.7 (Götz et al., 2010) and are significant at the 0.001 (two-tailed) level. Both CR and AVE metrics more than meet the acceptable thresholds of 0.7 and 0.5, respectively (Hair et al., 2010), providing evidence of construct reliability and convergent validity. Further, the analysis assessed discriminant validity using AVE figures and inter-factor correlations in combination. Discriminant validity can be established if a latent variable's

AVE is larger than the common variances (Chin, 1998; Götz et al., 2010; Pavlou, Liang, & Yajiong, 2007). Following this guidance, Table 5 below presents the square root of AVE for each construct on the diagonal (in bold) to compare against the correlations among the constructs captured in the off-diagonal elements of the matrix.[6]

Table 5

Square Roof of AVE vs. Correlations among Constructs

Construct	Construct Type	# of Indicators	*Ba* – enabler	*Ba* – team dynamics	Knowledge	Learning	Quality	Efficiency
Ba – enablers	Formative	6	**N/A**					
Ba – team dynamics	Reflective	6	0.745	**0.840**				
Knowledge	Reflective	4	0.667	0.703	**0.820**			
Learning	Reflective	3	0.295	0.316	0.467	**0.587**		
Quality	Reflective	1	0.511	0.545	0.528	0.362	**1.000**	
Efficiency	Reflective	3	0.501	0.633	0.503	0.377	0.506	**0.843**

Note: *Ba* – enablers is a formative construct, so its AVE have no meaning (thus, N/A).

As Table 5 shows, each construct is more closely related to its own measures than to those of other constructs. The analysis results, thus, show evidence of sufficient discriminant validity. Finally, to further assess validity of the measures, a cross-loading table was constructed following the guidance and directions by Liang, Saraf, Hu, and Xue (2007), as well as Geffen and Straub (2005). The table is presented in Appendix H and shows that each item loads much more highly on its assigned construct than it does on others. One exception to this pattern is the *socialization* indicator (SOC_sq). While it does load most highly to its assigned factor (i.e., *Knowledge*), it also loads on another construct (*Ba – team dynamics*) by only a .02 margin. This finding is in line with the EFA results (see Appendix G); and, again, no alteration of the measure was made because of the exploratory nature of the study.

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[6] Alternatively, AVEs (rather than their square root) can be compared against the squared term of each correlation.

Formative construct. The reversed causality posited by formative constructs demands different procedures for interpreting and evaluating the measurement model from those applied on reflectively measured constructs (Götz et al., 2010). The analysis followed Cenfetelli and Bassellier’s (2009) guidance. The *engineering ba* construct, as already discussed, was modeled in a MIMIC configuration. To start, following Cenfetelli and Bassellier’s (2009) procedures, the formative indicators were checked for collinearity. As captured in Table 6 below, the analysis shows bivariate correlations among the indicators that are ranging from .412 to .646. The variance inflation factors (VIFs) range from 1.462 to 2.421, all of which are under the suggested threshold of 3.33 (Cenfetelli & Bassellier, 2009). Based on these results, multi-collinearity does not appear to be a concern.

Table 6

Correlations and VIFs for Formative Measures

		Correlations					
	VIF	VISION	AUTO	URG	RED	VAR	TRUST
VISION	1.600	1.000					
AUTO	1.862	.456	1.000				
URG	2.308	.565	.594	1.000			
RED	2.407	.508	.574	.622	1.000		
VAR	2.007	.475	.511	.590	.644	1.000	
TRUST	2.285	.461	.594	.632	.666	.594	1.000

Next, the indicator weights and loadings were estimated, along with their statistical significance. Table 7 below presents the resulting estimates of the formative indicators.

Table 7

Parameter Estimates for Formative Measures

	Indicator Weights			Indicator Loadings		
Indicators	**Weight**	**T-Stat.**	**P-Value**	**Weight**	**T-Stat.**	**P-Value**
VISION	0.120	1.276	0.204	0.624	8.825	0.000
AUTO	0.399	5.006	0.000	0.845	24.053	0.000
URG	-0.046	0.341	0.734	0.709	12.680	0.000
RED	0.123	1.338	0.182	0.791	16.995	0.000
VAR	0.230	3.206	0.002	0.762	15.517	0.000
TRUST	0.381	4.063	0.000	0.867	24.849	0.000

As Table 7 shows, every one of the six indicators exhibits a high and statistically significant loading, yet only three of them have statistically significant weights. The high bivariate correlation between each indicator and the construct indicates that all indicators are important in an **absolute** sense, while their **relative** contributions vary (Cenfetelli & Bassellier, 2009). Specifically, the contributions of *leadership vision* (VISION), *controlled urgency* (URG), and *knowledge redundancy* (RED) are small relative to the rest. Because "[i]ndicators that have a relatively small contribution to a formatively measured construct in comparison to other indicators may still have an important absolute contribution if that indicator is independently assessed from the other indicators" (Cenfetelli & Bassellier, 2009, p. 693), and because of the newness of the scales, no refinement to the measurement model (e.g., discarding or grouping weak items) was made in the study's exploratory quest for theory development.

The last phase of the formative measurement analysis was the redundancy analysis (Cenfetelli & Bassellier, 2009; Chin, 1998) to explore the strength of relationship between the formative and reflective variables of the MIMIC model. The path coefficient between the two components was estimated by PLS-Graph 3.0 to be 0.79 (*P* = .000). The value is somewhat lower than the minimum threshold of 0.8 that Chin (1998) proposes.

Common method bias (CMB). The data collection instrument for this study was basically a self-report survey, administered to a single-reporting source (i.e., engineers / technical professionals). Such a format often lends itself to method bias, which can be a problem and so needs to be checked. First, examination of the correlation among the latent variables (see Table 5) does not reveal any concern. All correlation values are far below the suggested maximum threshold of .90 (Pavlou et al., 2007). Further to assess the extent of common method bias (CMB), a special CFA was conducted using Podsakoff, MacKenzie, Podsakoff, and Lee’s (2005, p. 894) “a single unmeasured latent methods factor” technique that had been adapted to the working of the PLS methodology by Liang et al. (2007). In this approach, each item is converted into a single-indicator factor that in turn loads to the intended construct, thus, creating a second-order structure. Wetzels, Odekerken-Schröder, and van Oppen (2009) provide procedural guidance on how this may be done in a PLS environment (p. 181). A CMB factor is added into this structure, with its paths to each measure now converted into first-order, single-indicator construct. These CMB factor loadings are gauged against the paths from the second-order factors to their corresponding first-order constructs (representing substantive loading factors) as the diagram in Appendix I illustrates. Specifically, the squared term of each path coefficient is compared between that of the substantive loading and that of the method. The results show that, on the average, the variance associated with the substantive loadings is 25 times higher than method variance. Additionally, most method factor path coefficients are not statistically significant. These findings are also captured in Appendix I. Hence, the method effects are unlikely to be a significant concern for our study.

Structural model. The goal of a variance-based SEM strategy—such as PLS—is to minimize residual variances, and so the battery of tests recommended for testing a PLS model is geared to produce metrics to gauge how well the model describes the effects between the latent variables (Chin, 1998; Götz et al., 2010). The structural model was first analyzed with the two control variables—*engineering role* and *problem solving role*—connected to each of the three outcome variables to evaluate their influence. This first iteration of structural analysis showed that the *engineering role* has no appreciable effects on any of the outcome variables. The *problem solving role* was found to have no influence on *learning achieved* or *project efficiency*; it was, however, found to have a statistically significant (at the 0.05 level) effect on *product quality*. The initial path coefficient estimate of −0.127 indicates that the respondent who played a lead role in problem solving is likely to give a higher rating on product quality than those who were in supporting roles (1 = leader of problem solving team, 2 = core support, 3 = external stakeholder support; see Table D2-5 in Appendix D). To maximize statistical power, non-significant control paths were removed before continuing the analysis.

Path coefficients. Path coefficients (β), along with their T-statistics calculated through a bootstrapping procedure, are shown in Table 8 below.

Table 8

Path Coefficients and Their Significance

Hypothesized Path			**β**	**T-Stat**	**P-Value**	**Significance**
Ba	→	*Knowledge*	0.720	17.969	0.000	Path **is** significant at the 0.05 level (2-tailed).
Knowledge	→	*Learning*	0.489	5.079	0.000	Path **is** significant at the 0.05 level (2-tailed).
Ba	→	*Learning*	-0.033	0.330	0.742	Path is not significant at the 0.05 level (2-tailed).
Knowledge	→	*Quality*	0.282	3.022	0.003	Path **is** significant at the 0.05 level (2-tailed).
Ba	→	*Quality*	0.321	3.469	0.001	Path **is** significant at the 0.05 level (2-tailed).
Knowledge	→	*Efficiency*	0.112	1.431	0.154	Path is not significant at the 0.05 level (2-tailed).
Ba	→	*Efficiency*	0.569	8.847	0.000	Path **is** significant at the 0.05 level (2-tailed).

These results indicate that

1. *Ba* has a positive influence over *knowledge creation*.
2. *Ba* has direct, and positive, effects over both *product quality* and *project efficiency* but not on *learning achieved*.
3. *Knowledge creation* positively influences *learning achieved* and *product quality* but has no effect on *project efficiency*.

Knowledge creation, therefore, potentially mediates both the paths from *engineering ba* to *learning achieved* and from *engineering ba* to *product quality*—but not to *project efficiency*.

R^2 *check*. The R^2 (which applies only to endogenous variables) is one of the key metrics for assessing a PLS model's explanatory power. The analysis evaluated both the magnitude and significance of each R^2 value. Chin (1998, p. 323) states that the R^2 values of .67, .33, and .19 are considered "substantial," "moderate," and "weak," respectively. Further, for an endogenous variable that is predicted by only one or two exogenous variables, a "moderate" R^2 value may be acceptable (Chin, 1998). To test for significance, Falk and Miller's (1992) F-test was used as outlined below:

$$F = \frac{R^2 / m}{(1 - R^2) / (N - m - 1)}$$ where N = sample size and m = number of predictors

Table 9 below summarizes the results of R^2 check.

Table 9

R^2 Values for the Four Dependent Variables

			Critical F			
	R^2	F-stat.	*at .05*	*at .01*	*at .001*	Significance of R^2
Knowledge	0.511	211.794	3.888	6.761	11.150	Significant at P < .001
Learning	0.216	27.761	3.041	4.712	7.149	Significant at P < .001
Quality	0.356	55.832	3.041	4.712	7.149	Significant at P < .001
Efficiency	0.423	73.892	3.041	4.712	7.149	Significant at P < .001

Therefore, all of the four dependent variables (DVs) explain more than 20% of model variance and are significant at the .001 level. The *knowledge creation* variable explains as much as 50% of model variance. Three DVs more than meet Chin's (1998) "moderate" level. The lowest R^2 is 21.6%, which hovers between "weak" and "moderate." Each of these DVs is predicted by no more than two variables, so based on Chin's (1998) guidelines, the model exhibits reasonably good quality from the R^2 perspective.

Effect size (f)^2. Another way a PLS model's explanatory power may be checked is by the effect size, or f^2, metric (Chin, 1998; Götz et al., 2010). An f^2 value reflects the change in R^2 and is calculated as follows:

$$f^2 = \frac{R^2_{included} - R^2_{excluded}}{1 - R^2_{included}}$$

The f^2 metric gauges the extent to which a predictor influences the DV by calculating the change in R^2 with and without the predictor ($R^2_{included}$ and $R^2_{excluded}$, respectively). Chin (1998, 2010) and Götz et al. (2010) suggest the operational definition of 0.02 as "small" or "weak," 0.15 as "medium," and 0.35 as "large" effect sizes. The effect size on each of the three outcome variables was calculated by inclusion and exclusion of *knowledge creation* and *engineering ba* as shown in Table 10 below.

Table 10

f^2 Values for the Outcome Variables

Effect size with or without *Knowledge*

	R^2 with *Knowledge*	R^2 without *Knowledge*	f^2	Effect Size
Learning	0.216	0.101	0.15	Medium
Quality	0.356	0.318	0.06	> small, but < medium
Efficiency	0.423	0.417	0.01	Very small

Effect size with or without *Ba*

	R^2 with *Eng. Ba*	R^2 without *Eng. Ba*	f^2	Effect Size
Learning	0.216	0.215	0.00	No effect
Quality	0.356	0.307	0.08	> small, but < medium
Efficiency	0.423	0.266	0.27	Medium

The effect sizes vary from small to medium, and the differences in f^2 values are in line with the relative strengths of path coefficients shown in Table 5-5.

Goodness of Fit (GoF). Unlike the covariance-based SEM methodology, PLS path modeling does not optimize any global scalar function and so does not naturally lend itself to a global validation metric (such as χ^2 and a host of other model fit indices used in covariance-based SEM). To overcome this issue, Tenenhaus, Vinzi, Chatelin, and Lauro (2004) have recently proposed a global criterion of goodness of fit, a “GoF” index, to “account for the PLS model performance at both the measurement and the structural model with a focus on overall prediction performance of the model” (Chin, 2010, p. 680). A GoF ($0 \leq \text{GoF} \leq 1$, larger the better) is calculated by taking the geometric mean of the average communality (denoted as $\overline{COMM}$) and average R^2 as shown below:

$$GoF = \sqrt{\overline{COMM} \times \overline{R^2}}$$

The GoF of the hypothesized model is 0.533, and using Wetzels et al.’s (2009) baseline criteria, this value exceeds their proposed “cut-off value of 0.36 for large effect sizes of R^2" (p. 187), indicating that the model performs well from this perspective. Further computational details are shown in Appendix J.

Mediation check. Mediation effects were checked by first following Baron and Kenny's (1986) causal-step test, followed by a product-of-coefficients test as Wood, Goodman, Backmann, and Cook (2008) recommend. This last part was accomplished using MacKinnon and colleagues' (2007) procedures to calculate asymmetric confidence intervals on the product of two mediation path coefficients (i.e., Sobel test). The mediation test results confirmed two mediation schemes:

1. *Knowledge creation* fully mediates the relationship between *engineering ba* and *learning achieved.*
2. *Knowledge creation* partially mediates the relationship between *engineering ba* and *product quality*.

Computational details are found in Appendix K. As already demonstrated, mediation hypothesis does not hold for the relationship between *engineering ba* and *project efficiency*.

In summary, the analysis results support some but not all of the hypothesized relationships. Table 11 below captures the extent to which each of the hypotheses is supported.

Table 11

Tests of Research Hypotheses

Hypotheses	Supported?
H1a: *Knowledge creation* is positively related to *learning achieved*.	Yes
H1b: *Knowledge creation* is positively related to *product quality*.	Yes
H1c: *Knowledge creation* is positively related to *project efficiency*.	No
H2a: *Engineering ba* is positively related to *learning achieved*.	No
H2b: *Engineering ba* is positively related to *product quality*.	Yes
H2c: *Engineering ba* is positively related to *project efficiency*.	Yes
H3a: *Knowledge creation* partially mediates the positive relationship between *engineering ba* and *learning achieved*.	No – full mediation
H3b: *Knowledge creation* partially mediates the positive relationship between *engineering ba* and *product quality*.	Yes – partial mediation
H3c: *Knowledge creation* partially mediates the positive relationship between *engineering ba* and *project efficiency*.	No mediation

The final structural model, with path coefficients, is presented in Figure 8 below. Note that only the significant paths (*** $p < .001$, ** $p < .01$, * $p < .05$) are shown.

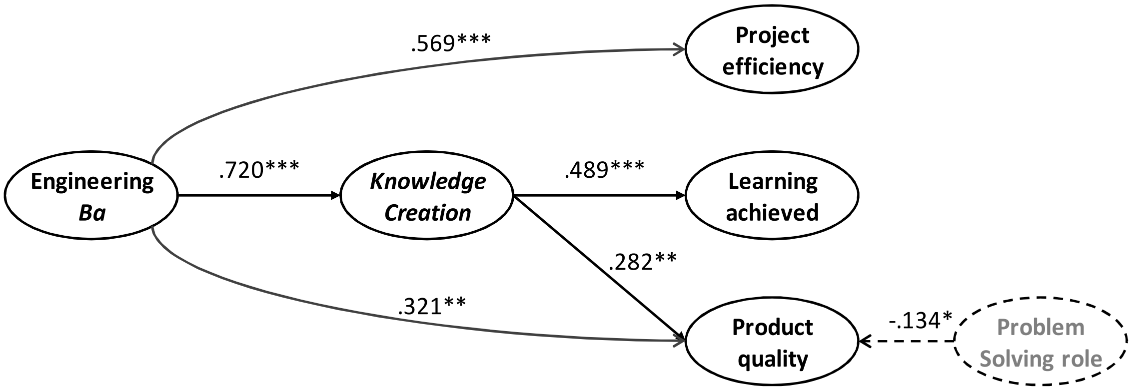


Figure 8. Final structural model.

The final model suggests that, controlling for the effect of the problem solving role, *knowledge creation* mediates two of the outcome variables: *learning achieved* and *product quality*, but **not** *project efficiency*. Further, *knowledge creation* fully—**not** partially—mediates the relationship between *engineering ba* and *learning achieved*. The next and final section of this chapter provides interpretation of these analysis findings.

Discussion

Thus, in order for **sustained learning** to occur—the central research theme of this study—it is essential that knowledge-creation routines take place fully after an EPS enhancing context—that is, *ba*—has been established. As to the other EPS performance outcomes, product quality and project efficiency, knowledge creation activities have reduced impact. Product quality is affected by both the strengths of *ba* and knowledge creation process. On the other hand, project efficiency is not affected by knowledge creation at all and is solely a function of *ba*. Conceptually speaking, these findings make sense. When a product is broken, it needs to be fixed. Engineers normally find a way to correct the problem—by tapping into available organizational resources and knowledge sets—so the product quality is invariably better than its pre-fix state. They, given an environment conducive to team work, are likely to accomplish their tasks efficiently as well. For the EPS activities to result in systemic improvements (i.e., *double-loop learning*), however, overarching knowledge that encompasses not only the know-how for an immediate fix but that fundamentally changes the way the product is designed, tested, or manufactured must be gained. The model is suggesting that such profound learning cannot be facilitated without active knowledge exchange that culminates in system changes. Therefore, the EPS dynamics are far more complex than they can be adequately explained using a routine-based view

(Ndubisi, 2011), with "operational efficiency" being the sole metric to assess its effectiveness. Contextual factors, such as resources and unconstrained structure, do matter to EPS—but without the dynamics that play out once those structural elements are put in place, engineering knowledge creation as a "system" (Senge, 2006) cannot be fully understood. From this perspective, this work contributes to a more comprehensive understanding of engineering as it is practiced in the real world.

To the best of our knowledge, this study is the first to apply Nonaka's knowledge-creation concept to engineering, in a U.S. context—including modeling of *ba*. Just as Schulze and Hoegl's (2006) European study found no evidence of cultural incompatibility of the SECI process (Nonaka et al., 2000), this study, likewise, did not find support for SECI's non-applicability to U.S. setting. Thus, the study adds empirical evidence of SECI's transferability to non-Asian settings. Further, the study makes a novel first attempt to model *ba*. While a few measurement precision issues were identified, a solid first step was taken to operationalize this construct, yielding results that can assist in further developing and refining it. Thus, the study makes a contribution on three research fronts.

With regard to the construct of *engineering ba*, three of its six formative elements in the posited model—clarity of *vision*, controlled *urgency*, and knowledge *redundancy*—were found to be non-significant relative to the remaining three. This interesting finding may owe to the fact that "the collective learning process in an organization is inherently local" (Edmondson, 2002, p. 142). Engineering being a highly technical practice, similar to the cardiac operating units in Edmondson's (2003) study, an EPS team can be equated to one of "highly self-sufficient operating units, such that senior management attention and other resources seem quite far removed from the front-line activities" (Edmondson, 2003, p. 1443).

In such a work context, proximal oversight provided by team leadership becomes more influential and can either undermine or enhance corporate policies and vision statements (Cannon & Edmondson, 2001; Edmondson, 2002, 2003). The "Knowledge-Creation Enablers" scale used for this study had been developed by Lloria and Moreno-Lúzon (2005) based on their interpretation of Nonaka's theory. They conceptualized the knowledge-creation enabling conditions as a diverse set of variables having different natures and origins—such as strategy formulation, organizational design, and human resources management. Each of the six conditions touches on the micro-, meso-, and macro-aspects of an organization at varying degrees. *Vision / intention* is a more macro- than micro-level factor, having its roots in strategic literature, while *autonomy* touches on all three levels of an organization (Lloria & Moreno-Luzón, 2005). *Autonomy*, as conceptualized by Lloria and Moreno-Luzón (2005), also interacts closely with *creative chaos* (equivalent of *controlled urgency* in this study) and *requisite variety* in a positive way. *Trust and commitment*, which Lloria and Moreno-Luzón (2005, p. 229) draw a direct association with the concept of *ba*, is intimately related to *psychological safety* that is well established in the literature to be critical especially for group-level performance (e.g., Cannon & Edmondson, 2001; Edmondson, 2002, 2003). Thus, the speculation at this time is the over-powering influence of *autonomy*, *requisite variety*, and *trust* over the performance of EPS teams.

In the next and final chapter of this dissertation, a summary of both the qualitative and quantitative findings will be presented to set directions for future exploration to further refine this framework.

CHAPTER 6: CONCLUSIONS

Engineering literature provides ample evidence that supports the positive influence of such organizational factors as resources, flexible structure, and trust on problem solving in general. The relevant question that can yield value for both research and practice is, “In what way do these factors contribute?”—and what is missing in the understanding of engineering problem solving (EPS) as an opportunity for new knowledge acquisition and organizational learning. A major contribution of this study is to unlock the black box of EPS dynamics and to show “how” sustained learning can occur. The empirical evidence from this study has demonstrated that, while these well-proven contextual factors fully contribute to project efficiency—and partially contribute to product quality—they do not contribute to system changes unless mediated by knowledge-creation routines. System changes are necessary to prevent the recurrence of problems, and the EPS teams that fail to systematize routines for knowledge creation are less likely to generate true lessons learned. The remainder of this chapter presents the study implications for theory and practice, acknowledging the study’s limitations and concluding this research journey with an eye toward the future.

Limitations

Several limitations of this two-stage study should be noted. For both the qualitative and quantitative investigations, the informants were predominantly automotive engineers, owing to the author’s career background. Most respondents were employed by, and worked at, the home office facilities of U.S. Midwest firms, over half of which were associated with the automotive industry. There is always a chance that regional and industry commonality predisposed the samples to location-specific and industry-prevalent attitudes. Although coherent themes emerged from the data, future research should seek to confirm the study findings among a larger sample of non-automotive engineers.

Secondly, temporal and valence (negative versus positive) issues related to memory recall may also have affected response patterns. In the qualitative investigation, in particular, the tendency to recall recent events and positive experiences more vividly (D'Argembeau & Van der Linden, 2004) may have influenced sensorial details and clarity of contextual information provided in the narratives. In other words, “successful” stories may have been remembered with greater intensity and clarity than “less successful” stories. Additionally, while the interviewees were asked to consider events occurring in the past 24 months, some of them were motivated to narrate more distant experiences. Consequently, the potential effect of time on memory in the stories that resulted has to be acknowledged.

Further, both the qualitative and quantitative investigations were a cross-sectional study, that is to say a snapshot of a single point in time. Because organizations are living entities, a longitudinal study to follow up on the insights gained from this study should further enhance the understanding of EPS dynamics. Additionally, both the qualitative and quantitative investigations utilized a single-informant source (i.e., engineers). A future study incorporating multiple informant sources is strongly recommended. For example, a study may be designed and implemented such that engineers respond to EPS process related questions while managerial responses are collected on EPS outcomes. Such a dual-informant rating system should further strengthen the research design and improve validity.

Finally, specific to the qualitative investigation, the categorization and interpretation of data depended on the perspectives and knowledge of the researcher (i.e., the author)—as is typical of a study like this. A research process is not entirely free of researcher bias, so it is important for researchers “to be continuously aware of the possibility that [they] are being influenced by pre-existing conceptualizations of [their own] subject area” (Suddaby, 2006, p. 635). The author is an experienced automotive reliability engineer, working closely with product design engineers. While every effort was made to stay attentive to preconceptions in exercising interpretive judgment, the potential effect arising from the author’s past and present experience must be acknowledged.

Theoretical Implications and Future Research

The state of this research is still exploratory in nature; the study results and discussion should be viewed as suggestive—rather than definitive—evidence of the phenomena revealed. Despite their preliminary nature, however, the study findings suggest several important implications for theory.

Theoretical implications. First, this research extends the ontologically based view of EPS effectiveness to complement the current understanding of the phenomena by addressing the experiential and cognitive sides of engineering. The study takes EPS beyond popular metrics, structural control, and hard assets (e.g., information databases) by taking an epistemological approach to explain the “how” and “why” of effective EPS. In so doing, the research has illuminated pathways to sustained learning. Secondly, this work contributes—with a combined strength of qualitative and quantitative methods—to the limited body of empirical evidence around mechanisms that leverage engineering knowledge embedded in local contexts to find problem solutions and achieve project goals effectively and efficiently. The work drew heavily from the extant literature on organizational learning; thus, in return, provides “cumulative and integrative work” that “cross-fertilizes and synthesizes the results from previous research” (Huber, 1991, pp. 107-108) to the organizational learning research landscape. Finally, to our knowledge, this study was the first to attempt quantitative modeling and testing of the *ba* construct in a U.S. context. While there is no doubt that further refinement is needed, the modeling results offer one glimpse into how contextual factors play out in EPS team dynamics and in turn influence collective learning. Such "positioning [of] structure within the emotional realm recognizes frequently ignored communication channels that offer an important complement to rational means of structuring organizational relationships" (Hatch, 1999, p. 89). All in all, the study findings are a contribution to a more complete and comprehensive epistemology of engineering practices.

Future research. In addition to the recommendations for addressing the shortcomings of the study discussed in the Limitations section, there are a few very promising areas of investigation to continue the course of this research inquiry. First, at a micro level, the engineering knowledge creation routines—explored epistemologically in this study—can further be examined from other interpretive viewpoints to better understand the "how" of collective learning. Adams and colleagues (2010; 2011), for example, shed light on what "working together across disciplines" really means and specifically what it entails in engineering practice. Their four-tier categorization of cross-disciplinary interactions provides criteria for judging the progression of cognitive synchronization among engineering actors. This categorization could serve as a metric of how well the process is working as engineers working together learn from others and eventually attain higher learning through differences. The manner in which engineering team members co-create knowledge through their disparate knowledge domains and levels is also an important phenomenon to research. Do they, for example, achieve collective learning by "traversing" or by "transcending" their knowledge differences (Majchrzak, More, & Faraj, 2012)? Further exploration of *ba* dynamics in the integration of knowledge differences would be worthwhile.

At a meso or macro level, actor network theory (Latour, 2005) is a possible application to better understand the effects of bounded rationality on the socio-technical network configuration. Engineers trying to solve technical problems constantly build and test hypotheses as forms of argument. It is through complex technical discourse that a lead engineer tries to convince other actors and solicit their "enrollment" (Harty, 2008). Understanding how engineers' aligned interests become an actor network, and, most importantly, how network heterogeneity (Law, 1992) can be leveraged to form a competitive advantage, will be of great interest to engineering firms, to the management of engineering talent, and ultimately to engineering education. Along this line, a deliberate construction of contextual settings that harbor power for effective problem solving can benefit from an analysis of engineering practice at large. An environment that facilitates collective sensemaking in problem solving efforts may be put in Bourdieusian perspective of an organization as a field (Emirbayer & Johnson, 2008; Swartz, 2008). That is to say the engineering context is a cultural milieu situated in a larger field and is configured according to power clusters. Given that problem solving stakeholders (e.g., management, customers, suppliers, as well as engineers) reside in various parts of the field, each entitled to varying intensity of "capital," what routines are at play when they come together? What is the underlying logic of the field that is closely connected to its "habitus"—a system of dispositions that are acquired through past events and that influence current practices? Such characterization may shed further insight into a strategy to create a "field of resonance"

(Yamaguchi, 2006) capable of fostering problem solving that yields knowledge creation for breakthrough solutions.

Finally, micro-, meso-, and macro-level factors are inevitably linked. To fully understand team learning, the influences and resources provided at all levels should be considered side by side (Zellmer-Bruhn & Gibson, 2006). As touched upon in Chapter 5, the enablers of *ba* as conceptualized by Nonaka and colleagues (2000)—which this study explored—are a set of multi-level constructs having diverse origins in the organizational literature (Lloria & Moreno-Luzón, 2005). "[A]dditional research to include factors at multiple levels to tease out the particular organizational features most likely to support or impede [team] learning" as advocated by Zellmer-Bruhn and Gibson (2006, p. 514) should prove useful to further understand how the enablers of *ba* exude influence on EPS effectiveness.

Practical Implications

The study has demonstrated that contextual factors—such as autonomy, resources, and trust—alone are, at best, predictors only of project efficiency. They do not predict learning and only partially predict product quality. These knowledge-related outcomes are mediated by knowledge-creation routines, which denote action. Contextual factors, then, require more than a check-in-the-box approach to management if they are to serve as mobilizing forces of EPS team action. Scholars have often used a jazz metaphor to explain aspects of "organizing." The analogy of fluidity and improvisation in the jazz music has served to describe the temporal, emotional, and ambiguous dimensions of organizational structure (Hatch, 1999); to explain how the dialectic forces of control and spontaneity co-exist and play out in organizations (Weick, 1998); and to propose an organizational design mirroring a jazz band for maximizing learning and innovation (Barrett, 1998). Jazz metaphors have a strong affinity to the *ba* concept as a knowledge-enabling context advocated by von Krogh and colleagues (2001). They argue that such a context "involves a mix of deliberate decisions and going with the flow" (von Krogh et al., 2001, p. 17), requiring a balancing act of "supporting creativity and unhindered communication, yet shaping it to serve the organization's goals" (p. 44). Amalgamation of both the qualitative and quantitative findings, juxtaposed with this *ba*-jazz metaphor, can lead to the following recommendations for practice.

Good listening skills are essential for healthy collaboration. Problem solving, especially in its early stage, is filled with the unknown. "Using ambiguity effectively requires an engaged ability to listen and respond, as the jazz metaphor makes plain" (Hatch, 1999, p. 88). Good listening is essential for good improvisation, which "also requires listening to one's own comments and building on them" (Weick, 1998, p. 547). For engineers to effectively operate as "agents" (Eisenhardt, 1989; Hill & Jones, 1992) of EPS stakeholders, they need to acquire good listening skills. They should be encouraged to actively engage stakeholders—fellow engineers from other disciplines or cultures, customers, suppliers, or whatever the case may be—in the search for a solution. Their efforts to develop the "same language" by openly asking questions, and in so doing suspending judgment from time to time to understand a different set of logics that may be at play in the exchange, should be supported. Only after understanding differences in what people know and how they communicate, can one start to constructively challenge others' assumptions. These skills are particularly important for engineers leading the problem solving efforts.

By extension, it is the manager's duty to enable cultivation of such bridging skills. Both the qualitative and quantitative study results showed "sociality" of EPS processes in bringing out tacit knowledge as an ingredient for the final knowledge outcomes. These processes, akin to jazz, are, in the end, not an individual but a social accomplishment achieved through "continual negotiation toward dynamic synchronization [through a] remarkable degree of empathic competence, a mutual orientation to one another's unfolding" (Barrett, 1998, p. 613). Managerial attention should be provided to help engineers, especially the young engineers, learn to collaborate effectively with diverse talent. As Weick (1998, p. 552) argues, "Young musicians who are laden with technique often tend to be poor at improvisation because they lack voices, melodies, and feeling." Most novice engineers straight out of school do not come equipped with skills to build common ground among varied interests. Such wisdom, or *phronesis*, can only be developed through experience (Grint, 2007).

Trust and psychological safety cannot be over-emphasized. Every manager should be reminded that technical problem solving, especially in its early stage, relies heavily on "experimentation." To experiment is to "reflect while acting" (Weick, 1988, 1998), as jazz players do to keep the improvisatory nature of their performance from totally going out of order (Barrett, 1998). Quality improvement, for example, as Weick (1998, p. 549) argues, "occurs when people are newly authorized to paraphrase, embellish, and reassemble their prevailing routines, extemporaneously . . . are encouraged to think while doing rather than be guided solely by plans." Experimentation flourishes in a "caring" environment. As von Krogh et al. (2001) argue, a "high care" brought to *ba* infuses mutual trust and active empathy and brings everyone on board for knowledge creation; a "low care" on the other hand stimulates hyper-competition and promotes knowledge “seizing” at its worst. It is in every manager’s best interest to ensure that knowledge is freely and actively exchanged in the EPS *ba* without fear of repercussion for expressing or trying out different ideas. The leader of a *ba* should watch over development of team dynamics and insist on the importance of including diverse voices. Simultaneous listening and playing is what produces the give-and-take flavor of live jazz performance (Hatch, 1999). A structured process to give every participant a chance to lead a segment of EPS activities, as well as to value those who make room for others to excel at times, can be among the measures to offset dominant members who may monopolize the platform.

Group sensemaking requires time. Reflection-in-action is essentially about sensemaking (Weick, 1998). This dissertation research has shown that sustained learning is not achieved unless mediated by a set of knowledge-creation routines. The full mediation structure revealed by the study basically denotes a sensemaking process—that is to say, engineers make sense of product-related problems through multi-directional knowledge exchange as a pathway to learning. In successful sensemaking, engineers socialize to exchange tacit knowledge and gradually form a collective interpretation that is fully externalized and deployed in the end. This process is not an instantaneous affair. Good team dynamics that facilitate effective sensemaking are not built overnight. Learning jazz is essentially done by becoming a member of the jazz community, “hanging out” to listen to great music and recordings, exchanging stories, and taking turns soloing and supporting in practice (Barrett, 1998). The notion that team building can be accomplished over one-night beer-drinking sessions merits reconsideration and should be replaced with more mindful tactics to enable healthy interactions. At minimum, the leader of a *ba* should ensure adequate logistics (e.g., meeting room resources) and treat *ba* management not as a one-time venture but as an "on-going temporal coordination" of the jazz ensemble (Barrett, 1998, p. 612).

***Ba* must be managed *in situ*.** Since sensemaking is embodied in improvisation (Weick, 1998), it is virtually impossible to know when a break-through insight surfaces during the EPS routines *ex ante*. The essence of *autonomy*—one of the contextual factors found to be significant in EPS *ba* formation—is "a structure that supports but does not specify" (Hatch, 1999, p. 83) in jazz improvisation. This structure is a part of the process of **becoming**, through players' action and engagement, rather than a state of being (Hatch, 1999; Weick, 1998). Similarly, in problem solving, new perspectives tend to form through unanticipated connections, often facilitated by personal interactions (Hargadon & Bechky, 2006). Such interactions, however, are difficult to predict beforehand and can only be monitored and steered **as they progress**. Engineering practice is dynamic, both contextually and temporally, and so the only way to effectively manage it is to "enter the process" (Hatch, 1999). EPS dynamics in a *ba* must be monitored *in situ*. Effective management of *ba* requires an "in-dwelling" (von Krogh et al., 2001) approach, rather than simple cheerleading, to recognize "how the memories and expectations of organizational actors intersect at any given moment to structure the emotional and temporal dimensions of work and organizing in such a way as to influence action" (Hatch, 1999, p. 94). An effective root cause analysis is more than just following the prescribed steps of 8D, Six Sigma, or other popular methodologies. While any one of these can provide a basic procedural structure for EPS activities, a methodological framework alone cannot facilitate constructive interactions and knowledge exchange. Cognitive synchronization is a result of on-going reframing to evaluate the problem in new contexts as they surface. Encouragement of healthy technical exchange by on-going managerial engagement in the dialog is one of the ways to keep *ba* productive.

Sustained learning cannot be achieved with IT technology alone. For many decades, companies made considerable investments in “knowledge management” technology, infrastructure, and metrics—only to yield rather limited benefits (Hargadon & Bechky, 2006; "Making an internal collaboration work: An interview with Don Tapscott," 2013; Senge, 2006; von Krogh et al., 2001). Information technology (IT) databases are undoubtedly useful tools if one knows precisely what to query. When such moments of task rationality reach the limits, however, and efficiency is no longer the answer, these empty spaces call for opportunities to improvise like good jazz performance (Hatch, 1999). Over-reliance on codification of knowledge as a **sole** means of knowledge management misses the aspects of knowledge that is “attached to human emotions, aspirations, hopes, and intentions . . . embodied [and] closely tied to the senses and previous experiences” (von Krogh et al., 2001, pp. 30-31). Scholars (e.g., "Making an internal collaboration work: An interview with Don Tapscott," 2013; von Krogh et al., 2001) argue that knowledge is not a finite asset, cannot be containerized because it is boundless, and can only be created and diffused through human processes. Success of EPS depends on organizational members’ commitment to actively **use** the existing knowledge management system to solve local problems. Such a system must be enticing ("Making an internal collaboration work: An interview with Don Tapscott," 2013) and thoughtfully put together to enhance users’ ability to reflect on new questions. IT databases neither perform sensemaking nor reframe a past problem in new contexts for the users (Brannen, 2004; Hargadon & Bechky, 2006).

Basic technical training should not be neglected. Last, but certainly not least, while this study emphasized the importance of evaluative knowledge in problem solving, managers should not forget that this knowledge is grounded on both the intellect and technical know-how of engineers. During the qualitative interviews, asked how a company might be able to enhance organizational learning, the participating engineers oftentimes brought up in-house training classes and mentoring programs to enhance the technical knowledge and skill levels of engineering and technical employees. Several younger engineers complained about lack of mentoring and coaching in their workplaces, which, according to them, was once a norm but was rapidly disappearing in the company's attempt to rationalize workforce structure and protocol. "[E]ffective [jazz] improvisation is based on a depth of experience and degree of discipline, a reality that is often camouflaged by the spontaneity of the performance" (Meyer, Frost, & Weick, 1998, p. 541). *Phronesis* is built on *episteme* and *techné*. The criticality of intellectual and practical knowledge as the two legs upon which superior performance stands is consistent with the findings from Trevelyan's (2007) empirical study. He found that, while non-technical, inter-personal coordination is a major aspect of engineering practice, its effectiveness relies critically on the engineer's technical expertise. Therefore, it is in the best interest of engineering organizations to make available to their members venues for continuous skill improvement.

In Closing . . .

Simply put, findings from this study suggest that effective leaders of engineering *ba* must almost be "walking sensors." Their duties are much more than enforcing prescriptive routines of problem solving. They must constantly be monitoring the direction of energy flow, the intensity of human interaction, and send feedback signals into the *ba* system at appropriate times—especially when sensing the imminence of break-though insights. Such rare and fleeting moments do not come announced *a priori*, and grasping them is a perceptual acuity challenge that the *ba* leaders must accept. It may be a tall order, but it is not unrealistic. Today's fast-changing business environment is already re-shaping corporate strategy management. The approach taken to strategic planning and execution is becoming more surveillance-based, looking for subtle cues and near misses that can, one day, shake the business to its core (Evans, 2013). Strategic management is now an "on-going journey" that requires businesses to "constantly re-check their positions" on the map. Such a process requires high attention paid to all aspects of organization, and *ba* management is no different. Firms that are likely to sustain their presence in the complex and dynamic world of today will do so by leveraging all of their resources, including the improvisational, implicit aspects of organization.

APPENDIX A: INTERVIEW PROTOCOL

1. I'd like to start by learning a little about you, both personally and professionally. Please tell me about yourself, starting from where you are originally from and ending with your current job. Tell me how you got to your present job and what you do there.

    - place of origin
    - schooling
    - reason for becoming an engineer
    - reason for choosing that industry / products
    - present position in the company / responsibilities
    - length of time with current job / company
    - hobbies / outside interests, if any

2. I'm interested in learning about your product engineering experience in solving product related problems. Can you think about a particular experience you've had in solving a product related problem that worked out well?

    - customer complaints?
    - lab or field failures?
    - manufacturing defect / returns?
    - warranty claims / spikes, etc.

Please tell me about

- how you discovered the problem?
- what you did next?
- then what happened?
- what was learned from this experience. Who benefited from it? How was the learning shared with others? What did the company do as a result of this problem solving?

Can you now think about a particular experience you've had solving a product related problem that didn't go so well – for example, the problem was not solved smoothly or not solved at all?

3. Now, thinking about those two cases you just told me about,

    a) For the successful case, what was the most challenging part, and what was the easiest?
    b) Please give me three reasons that the first case was successful.
    c) …and three reasons that the second case was unsuccessful.

Talking in generalities, product engineers create tremendous amounts of knowledge day-in and day-out, developing products and solving product-related problems. What could a company do to capture the knowledge you – and your colleagues – have. How can companies in general do a better job capturing, retaining, and sharing that knowledge?

APPENDIX B: CONSTRUCT TABLE

Concept, Construct, Dimensions, and Operationalization	
Concept: *Engineering Ba* is an enacted context triggered by a need to solve a technical problem, hypothesized to have been formed when certain conditions exist and to be reflected in positive group dynamics	
Construct name and definition(s): *Ba* is defined in several ways in literature. A *ba* can be a – 1. contextual space formed or "born" where relationships emerge and positive group dynamics are observed (Itami, 2010a, 2010b) 2. "shared context in motion" for knowledge, which is energized by organizational enabling conditions (Nonaka et al., 2000 Lloria and Moreno-Luzón, 2005) 3. "field of resonance" in which decision makers and innovators share tacit knowledge, without which paradigm-disruptive innovations are not possible **Construct dimension(s):** Formative and reflective dimensions Formative – - Intention / knowledge vision - Autonomy - Creative chaos - Redundancy - Requisite variety - Love, trust, and commitment Reflective – - Positive team dynamics - Inter-subjectivity	**Operationalization and scale properties:** For the formative dimensions – Lloria and Moreno-Luzón's (2005) "six enabling conditions of knowledge creation" scale (7-point Likert; μ, σ, ρ not reported): - *Intention / vision* (CR = 0.903): 4 items [VISION1] – [VISION4] in Appendix C - *Autonomy* (CR = 0.849): 4 items [AUTO1] – [AUTO4] in Appendix C - *Creative chaos / urgency* (CR = 0.691): 4 items [URG1] – [URG4] in Appendix C - *Redundancy / sharing* (CR = 0.689): 4 items [RED1] – [RED4] in Appendix C - *Requisite variety / resources* (CR = 0.738): 4 items [VAR1] – [VAR4] in Appendix C - *Trust* (CR = 0.779): 4 items [TRUST1] – [TRUST4] in Appendix C For the reflective dimension – Hoegl, Weinkauf, and Gemuenden's (2004) "Six aspects of teamwork quality" scale (5-point Likert; μ = 3.67 / 3.63, σ = 0.41 / 0.37, ρ = 0.70 – 0.89): - *Communication*: 5 items [COMM1] – [COMM5] in Appendix C - *Coordination*: 5 items [COORD1] – [COORD3] in Appendix C - *Mutual support*: 4 items [SUPP1] – [SUPP4] in Appendix C - *Effort*: 3 items [EFFORT1] – [EFFORT3] in Appendix C - *Balanced* contribution: 3 items [BAL1] – [BAL3] in Appendix C - *Cohesion*: 2 items [COH1] – [COH2] in Appendix C

Concept, Construct, Dimensions, and Operationalization	
Concept: *Knowledge Creation* is a group cognitive state in which active knowledge exchange occurs, forming a collective engineering interpretation culminating in superior solution and system changes	
Construct name and definition(s): *Knowledge creation* (as modeled using Nonaka's theory) is a multi-directional knowledge conversion process through which tacit knowledge becomes explicit and augmented, a.k.a. "SECI process." **Construct dimension(s):** • *Socialization* = tacit-to-tacit knowledge exchange • *Externalization* = tacit-to-explicit knowledge conversion • *Combination* = explicit-to-explicit knowledge augmentation • *Internalization* = explicit-to-tacit knowledge transfer	**Operationalization and scale properties:** Schulze and Hoegl's (2006) "four dimensions of knowledge-creation modes" scale (5-point Likert) is used. • *Socialization* ($\mu = 3.33 / 3.49$, $\sigma = 0.91 / 0.78$, CR = 0.81): 4 items [SOC1] – [SOC4] in Appendix C • *Externalization* ($\mu = 3.58 / 3.42$, $\sigma = 0.84 / 0.81$, CR = 0.82): 4 items [EXT1] – [EXT4] in Appendix C • *Combination* ($\mu = 3.18 / 3.17$, $\sigma = 0.86 / 0.87$, CR = 0.80): 4 items [COMB1] – [COMB4] in Appendix C • *Internalization* ($\mu = 2.96 / 3.03$, $\sigma = 0.98 / 1.08$, CR = 0.78): 4 items [INT1] – [INT4] in Appendix C
Concept: *Learning Achieved* refers to sustained learning occurring as a result of problem solving	
Construct name and definition(s): *Learning achieved* as borrowed from Zellmer-Bruhn and Gibson(2006) measures the extent to which the team created new processes and practices **Construct dimension(s):** Uni-dimensional	**Operationalization and scale properties:** Zellmer-Bruhn and Gibson's (2006) "learning achieved" scale (7-point scale; $\mu = 4.61$, $\sigma = 1.08$, $\rho = .84$; λ in PCA ranging from .78 to .87) is used. 3 items [LEARN1] – [LEARN3] in Appendix C
Concept: *Product Quality* refers to the extent to which the corrected product meets its requirements.	
Construct name and definition(s): *Product quality* as borrowed from Schulze and Hoegl (2006) measures the extent to which the product meets technical and customer requirements (e.g., functionality, reliability, durability, and compatibility with other systems.) **Construct dimension(s):** Multi-faceted	**Operationalization and scale properties:** Schulze and Hoegl's (2006) "product quality" scale (5-point scale; $\mu = 4.22$, $\sigma = 0.45 / 0.81$, $\rho = 0.89$) is used. 9 items [QUAL1] – [QUAL9] in Appendix C
Concept: *Project Efficiency* refers to the efficiency with which the problem solving endeavor was brought to closure	
Construct name and definition(s): *Project efficiency* as borrowed directly from Schulze and Hoegl (2006) measures the extent to which the project met its objectives such as adherence to schedule and cost-efficiency considerations. **Construct dimension(s):** Uni-dimensional	**Operationalization and scale properties:** Schulze and Hoegl's (2006) "project efficiency" scale (5-point scale; $\mu = 3.40$, $\sigma = 0.97$, $\rho = 0.82$) is used. 3 items [EFFIC1] – [EFFIC3] in Appendix C

APPENDIX C: OPERATIONAL ITEMS TO MEASURE STUDY CONSTRUCTS

Construct: *Ba – Enablers*	**Dimension:** *Intention / Vision*	**Item IDs:** *VISION1 – VISION4*

1. There was a set of requirements or criteria that helped define our problem solving goals.
2. People in leadership positions explicitly conveyed the problem solving goals to stakeholders both within and outside your team.
3. The requirements / criteria were disseminated to stakeholders.
4. The requirements / criteria guided efforts of those engaged in problem solving.

Construct: *Ba – Enablers*	**Dimension:** *Autonomy*	**Item IDs:** *AUTO1 – AUTO4*

1. Team independence in decision making on the tasks carried out was assured.
2. Independence of qualified personnel in decision making in the tasks they perform was respected.
3. The problem solving team was motivated to create, apply, and absorb new information.
4. Each team member was encouraged to create, apply, and absorb new knowledge.

Construct: *Ba – Enablers*	**Dimension:** *Urgency (Creative Chaos)*	**Item IDs:** *URG1 – URG4*

1. As a result of the problem, our leadership exhibited a sense of urgency without loss of control or disciplines.
2. Our leadership communicated a sense of urgency in a positive manner.
3. Our leadership made efforts to positively motivate the team and individuals after communicating the sense of urgency.
4. We felt we were positively challenged during the course of problem solving.

Construct: *Ba – Enablers*	**Dimension:** *Redundancy*	**Item IDs:** *RED1—RED4*

1. My organization promoted interaction between those involved (team members, stakeholders, etc.).
2. My organization supported people moving between groups as needed to share information to facilitate problem solving.
3. There was enough overlap of knowledge or expertise among the team members to understand each other's approach.
4. There were meetings and forums to share knowledge and ideas.

Construct: *Ba – Enablers*	**Dimension:** *Requisite Variety*	**Item IDs:** *VAR1 – VAR4*

1. There was active and sufficient contact between the problem solving team and its external stakeholders (e.g., customers, suppliers, etc.).
2. The organization supported the problem solving team's changing resource needs (e.g., a temporary priority access to test facilities) as new insights unfolded from problem investigation efforts.
3. Team membership and task assignments were re-structured or modified as new insights unfolded from problem investigation efforts.
4. Team members and external stakeholders often crossed boundaries to facilitate problem solving efforts.

Construct: *Ba – Enablers*	**Dimension:** *Trust & Commitment*	**Item IDs:** *TRUST1 – TRUST4*

1. In my organization, mutual trust was a stated value.
2. In my organization, commitment to common objectives was a stated value.
3. We had mutual trust.
4. We were committed to common objectives.

Construct: *Ba – Team Dynamics*	**Dimension:** *Communication*	**Item IDs:** *COMM1 – COMM5*

1. There was sufficient communication within our team.
2. There was active communication between our team members.
3. Team members openly and candidly shared relevant information on problem solving.
4. The team members were satisfied with the timeliness of information received from other members.
5. The team members were satisfied with the accuracy of the information received from other members.

Construct: *Ba – Team Dynamics*	**Dimension:** *Coordination*	**Item IDs:** *COORD1 – COORD3*

1. The team members' tasks were closely aligned to accomplish problem solving objectives.
2. The team tried to avoid duplication of effort.
3. The connected tasks were well coordinated.

Construct: *Ba – Team Dynamics*	**Dimension:** *Mutual Support*	**Item IDs:** *SUPP1 – SUPP4*

1. Discussions to resolve conflicting views and points were constructively conducted.
2. Suggestions and contributions from team members were always respected.
3. Suggestions and contributions from team members were always discussed and developed further as appropriate.
4. There was a cooperative work atmosphere in our team.

Construct: *Ba – Team Dynamics*	**Dimension:** *Effort*	**Item IDs:** *EFFORT1 – EFFORT3*

1. Team members felt fully responsible for achieving the common team goals.
2. Team members exerted full efforts for a successful completion of the problem solving.
3. Team members gave the problem solving highest priority.

Construct: *Ba – Team Dynamics*	**Dimension:** *Balanced Contribution*	**Item IDs:** *BAL1 – BAL3*

1. Team members were equally engaged to achieve the common goals.
2. Team members fully contributed to our objectives.
3. Team members would step in to help other members who might need support.

Construct: *Ba – Team Dynamics*	**Dimension:** *Cohesion*	**Item IDs:** *COH1 – COH2*

1. In our team there was personal affinity among the members.
2. In our team we stuck together during the course of problem solving.

Construct: *Knowledge Creation*	**Dimension:** *Socialization*	**Item IDs:** *SOC1 – SOC4*

1. We had sufficient personal interaction with other people within our team to discuss suggestions, ideas, or solutions outside organized meetings.
2. We had sufficient personal interaction with people from other departments in the company in order to discuss suggestions, ideas, or solutions outside organized meetings.
3. We spent adequate time intensely discussing suggestions, ideas, or solutions in face-to-face meetings with people from other departments in the company.
4. We spent adequate time consciously developing a common understanding of a problem with people from other departments in the company.

Construct: *Knowledge Creation*	**Dimension:** *Externalization*	**Item IDs:** *EXT1 – EXT4*

We spent adequate time…

1. …collectively framing our ideas or solutions with regard to the problem.
2. …consulting subject matter experts outside our team about relevant technologies.
3. …consulting subject matter experts outside our team about customer or user expectations.
4. …creating detailed descriptions (e.g., protocols, presentations, reports) capturing newly developed knowledge from our problem solving efforts.

Construct: *Knowledge Creation*	**Dimension:** *Combination*	**Item IDs:** *COMB1 – COMB4*

As part of our problem solving efforts, …

1. …we systematically compiled and adapted the technical knowledge collected.
2. …we systematically compiled and adapted the knowledge collected about customer or user needs.
3. …we systematically compiled and adapted the knowledge collected about the procedures of developing and validating the product.
4. …we distributed within and/or across the organization our newly gained insights about the product from our problem solving.

Construct: *Knowledge Creation*	**Dimension:** *Internalization*	**Item IDs:** *INT1 – INT4*

We spent adequate time…

1. …experimenting to further our understanding of the functionality of the product technology.
2. …experimenting to further our understanding of the customer or user needs.
3. …experimenting to further our understanding of the procedures of developing and validating the product.
4. …systematically testing our theoretical knowledge about the product and customer / user needs.

Construct: *Learning Achieved*	**Dimension:**	**Item IDs:** *LEARN1 – LEARN3*

On completion of problem solving, …

1. …our team introduced a new way of doing work (e.g., developing / testing products, sourcing suppliers, etc.).
2. …our team came up with new ideas about how work should be done.
3. …our team's ideas were copied by other teams and / or implemented organization-wide (e.g., new designs, requirements, procedures, etc.).

Construct: *Product Quality*	**Dimension:**	**Item IDs:** *QUAL1 – QUAL9*

On completion of problem solving . . .

1. …our team was fully satisfied with the product’s performance.
2. …the product fully met (or exceeded) our customer’s quality expectations.
3. …the product was fully compatible with other systems.
4. …the product fully met (or exceeded) its initially anticipated specifications
5. …the product fully met (or exceeded) its initially anticipated functionality requirements
6. …the product fully met (or exceeded) its initially anticipated reliability requirements
7. …the product fully met (or exceeded) its initially anticipated usability requirements
8. …the product fully met (or exceeded) its initially anticipated durability requirements
9. …the product fully met (or exceeded) its initially anticipated visual / appearance requirements

Construct: *Project Efficiency*	**Dimension:**	**Item IDs:** *EFFIC1 – EFFIC3*

1. On completion of problem solving, the team was satisfied with overall problem solving performance.
2. On completion of problem solving, the problem was solved soon enough to (a) meet its initially anticipated launch schedule in the case of a pre-launch problem or (b) retain its competitive position in the field in the case of a post-launch problem.
3. On completion of problem solving, the overall problem solving project finished by our initially anticipated target completion timing.

APPENDIX D: SAMPLE CHARACTERISTICS

The information presented below provides the descriptive characteristics of the survey sample.

D1. Sample Demographic Characteristics

Shown in the two tables below are respondents' experience level and educational attainment status broken down by men and women.

Table D1

Experience Levels of Participants

Experience in years	Men	Women
2 or more but less than 5	11	4
5 or more but less than 10	13	1
10 or more but less than 20	37	20
20 or more but less than 30	53	16
30 or more	46	7
Total:	160	48

Table D2

Educational Levels of Participants

Education	Men	Women
No postsecondary degree	4	1
Associate or technical certification	7	3
Bachelor's	59	12
Graduate degrees	84	26
Professional degrees (e.g., JD, MD, etc.)	5	6
Other(2)	1	0
Total:	160	48

(2) Most of the original responses in this category were re-sorted into other categories. For example, a few participants listed "PhD" as "Other," rather than "Graduate degrees." The only response kept in "Other" is "P.E."

D2. Problem Solving Contextual Characteristics

Table D3

Product Categories

"What was the product? Choose only one."	*Count*	*%*
Raw materials	11	5.3%
Semi-finished materials (e.g., steel, chemical formulation, textile)	15	7.2%
Finished goods – hardware only (e.g., mechanical parts, electrical hardware)	109	52.4%
Finished goods – software only (e.g., computer program)	9	4.3%
Finished goods – hardware and software (e.g., cars, embedded systems)	54	26.0%
IT architecture / infrastructure	10	4.8%
All other[3]	0	0%
Total:	208	100%

[3] After re-categorization

Table D4

Industry Affiliation by ICB Sector4)

"What industry did the problem solving experience take place in? Choose only one."	Count	%
3350 - Automotive & Parts	142	68.3%
2710 - Aerospace & Defense	16	7.7%
9530 - Software & Computer	13	6.3%
4530 - Healthcare Equipment	7	3.4%
1350 - Chemicals	6	2.9%
2350 - Construction & Materials	6	2.9%
2750-2757: Industrial Machinery	3	1.4%
3720 - Household Goods	3	1.4%
0580 - Alternative Energy	2	1.0%
1370 - Food Producers	2	1.0%
9570 - Technology Hardware	2	1.0%
2770 - Railroads	1	< 0.5%
2790 - Support Services	1	< 0.5%
3760 - Personal Goods	1	< 0.5%
4570 - Pharmaceuticals	1	< 0.5%
8880 - Entertainment	1	< 0.5%
Other - Non-profit	1	< 0.5%
Total:	208	100%

[4] Industry Classification Benchmark by Financial Times and Stock Exchange (FTSE) (http://www.icbenchmark.com/ICBDocs/ICB_%20Product_Spec_Nov2011.pdf)

Table D5

Product Lifecycle Phase

"What was the initial phase and mode of failure discovery? Choose only one."	Count	%
Concept development	13	6.2%
Product design and development	38	18.3%
Engineering verification / validation	42	20.2%
Production trial / launch	31	14.9%
Full production – factory return	32	15.4%
Full production – field / warranty returns	52	25.0%
Other[5]	0	0%
Total:	208	100%

[5] After re-categorization

Table D6

Engineering Roles

"What was your primary engineering role in the problem solving experience? Choose only one."	Count	%
Product design, development, architecture, or application	80	38.5%
Manufacturing, process / equipment design	26	12.5%
Product testing / validation	26	12.5%
Product maintenance or service	5	2.4%
Support role such as quality, reliability, or warranty analysis	71	34.1%
Other[6]	0	0%
Total:	208	100%

[6] After re-categorization

Table D7

Participants' Roles in Problem Solving

"What was your primary problem solving role? Choose only one."	Count	%
Leader of problem-solving team	113	54.3%
Support – core member of problem-solving team	79	38.0%
Support – external stakeholder (e.g., management, customer representative, supplier representative)	16	7.7%
Other[7]	0	0%
Total:	208	100%

[7] After re-categorization

Table D8

Geographical Location

“Where was the facility where you worked located? Choose only one.”	Count	%
USA New England (CT, ME, MA, NH, RI, VT)	2	1.0%
USA Mid Atlantic (DE, MD, NJ, NY, PA, DC)	10	4.8%
USA South (AL, AR, FL, GA, KY, LA, MS, NC, SC, TN, VA, WV)	22	10.6%
USA Midwest (IL, IN, IA, KS, MI, MN, MO, NE, ND, OH, SD, WI)	155	74.5%
USA Southwest (AZ, NM, OK, TX)	10	4.8%
USA West (AK, CO, CA, HI, ID, MT, NV, OR, UT, WA, WY)	9	4.3%
Other(8)	0	0%
Total:	208	100%

(8) Nine respondents excluded from this analysis.

APPENDIX E: SCALE RELIABILITY

Scale Name	***# Items in Scale***	***Cronbach α***	***Improved α if Item Deleted***
Vision	4	.863	None
Autonomy	4	.798	None
Urgency	4	.874	.875 if #4 deleted
Redundancy	4	.773	.796 if #3 deleted
Variety	4	.712	None
Trust	4	.855	None
Communication	5	.865	None
Coordination	3	.785	.790 if #1 deleted
Support	4	.835	None
Effort	3	.838	.847 if #1 deleted
Balance	3	.854	.878 if #3 deleted
Cohesion	2	.753	N/A (2-item scale)
Socialization	4	.841	None
Externalization	4	.748	None
Combination	4	.827	.862 if #4 deleted
Internalization	4	.892	None
Learning	3	.819	.843 if #3 deleted
Quality	3	.917	None
Efficiency	3	.773	None

N = 208

Reliability was checked prior to data transformation and removal of multivariate outliers.

APPENDIX F: FINAL DATA SET

	Mean	Std. Dev.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	
1 VISION	**3.878**	**0.854**	1.000																					
2 AUTO	**4.015**	**0.695**	.451**	1.000																				
3 URG	**3.770**	**0.864**	.546**	.587**	1.000																			
4 RED	**3.945**	**0.710**	.446**	.534**	.608**	1.000																		
5 VAR	**3.801**	**0.691**	.427**	.493**	.562**	.648**	1.000																	
6 TRUST	**3.774**	**0.776**	.431**	.567**	.621**	.656**	.592**	1.000																
7 COMM	**4.000**	**0.677**	.387**	.580**	.462**	.577**	.544**	.593**	1.000															
8 COORD	**3.899**	**0.696**	.464**	.451**	.394**	.449**	.491**	.486**	.627**	1.000														
9 SUPP	**3.946**	**0.691**	.421**	.599**	.535**	.582**	.609**	.651**	.750**	.653**	1.000													
10 EFFORT	**4.042**	**0.738**	.327**	.505**	.388**	.522**	.480**	.474**	.666**	.569**	.618**	1.000												
11 BAL	**3.862**	**0.777**	.310**	.498**	.453**	.436**	.461**	.554**	.703**	.625**	.746**	.721**	1.000											
12 COH	**3.783**	**0.775**	.297**	.487**	.407**	.357**	.413**	.553**	.563**	.482**	.631**	.508**	.702**	1.000										
13 SOC	**3.773**	**0.716**	.384**	.440**	.412**	.524**	.620**	.505**	.633**	.583**	.654**	.558**	.596**	.489**	1.000									
14 EXT	**3.720**	**0.734**	.433**	.450**	.447**	.473**	.553**	.361**	.498**	.456**	.508**	.419**	.469**	.367**	.534**	1.000								
15 COMB	**3.794**	**0.736**	.375**	.357**	.335**	.394**	.369**	.350**	.382**	.467**	.435**	.343**	.429**	.423**	.412**	.644**	1.000							
16 INT	**3.673**	**0.860**	.386**	.404**	.354**	.414**	.448**	.412**	.436**	.512**	.477**	.393**	.511**	.489**	.497**	.592**	.633**	1.000						
17 LEARN1	**3.478**	**1.136**	.215**	.201**	.174*	.185**	.151*	.147*	.243**	.326**	.200**	.157*	.242**	.274**	.194**	.366**	.406**	.348**	1.000					
18 LEARN2	**3.668**	**1.056**	.193**	.210**	.239**	.138*	.139*	.246**	.214**	.283**	.234**	.184**	.280**	.286**	.164*	.311**	.367**	.323**	.721**	1.000				
19 LEARN3	**3.234**	**1.077**	.178*	.215**	.231**	.198**	.229**	.251**	.196**	.210**	.198**	.136	.187**	.173*	.239**	.365**	.356**	.336**	.537**	.538**	1.000			
20 QUAL	**4.029**	**0.637**	.387**	.392**	.403**	.443**	.423**	.383**	.448**	.544**	.460**	.459**	.473**	.352**	.424**	.389**	.411**	.494**	.402**	.284**	.187**	1.000		
21 EFFIC1	**4.117**	**0.764**	.304**	.484**	.405**	.423**	.374**	.433**	.562**	.471**	.564**	.513**	.561**	.465**	.409**	.419**	.394**	.416**	.336**	.340**	.181**	.586**	1.000	
22 EFFIC2	**3.766**	**1.012**	.217**	.436**	.308**	.284**	.315**	.279**	.431**	.366**	.444**	.460**	.532**	.422**	.285**	.335**	.335**	.252**	.260**	.271**	.136	.368**	.594**	1.0
23 EFFIC3	**3.590**	**1.037**	.214**	.296**	.207**	.209**	.228**	.182**	.338**	.325**	.345**	.388**	.406**	.258**	.278**	.341**	.308**	.254**	.242**	.269**	.143*	.270**	.432**	.618

* Correlation is significant at the 0.05 level (two-tailed)

** Correlation is significant at the 0.01 level (two-tailed)

Note: All figures in this table -- both the descriptives and correlations -- are pre-transformation results. Untransformed data are presented here to facilitate ease of interpretation. The actual analyses were performed using the squared term of each raw data point.

APPENDIX G: EFA

The exploratory factor analysis (EFA) was conducted using principal axis factoring (PAF) for extraction and an oblique rotation method (Direct Oblimin) based on the assumption that the underlying factors are correlated (non-orthogonal). The results are shown below.

Pattern Matrix[a]

	Factor			
	1	2	3	4
COMM_sq	.855			
COORD_sq	.698			
SUPP_sq	.836			
EFFORT_sq	.770			
BAL_sq	.844			
COH_sq	.684			
SOC_sq	.703			
EXT_sq				-.654
COMB_sq				-.781
INT_sq				-.620
LEARN1_sq		.859		
LEARN2_sq		.840		
LEARN3_sq		.595		
EFFIC1_sq	.381		.385	
EFFIC2_sq			.882	
EFFIC3_sq			.626	

As shown above, all except for two indicators load on the intended factors. The two problem indicators are SOC_sq that represents the socialization dimension of *Knowledge Creation* and one of three indicators of *Project Efficiency* (EFFIC1_sq). The former loads on the team dynamics dimension of *Engineering ba*, and the latter shows an appreciable cross-loading.

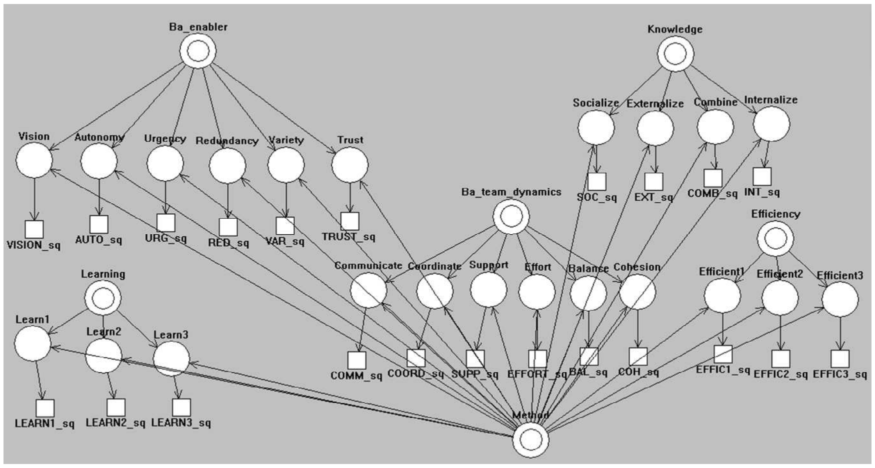
APPENDIX H: CROSS-LOADING TABLE FOR REFLECTIVE MEASURES

	Ba - team dynamics	*Knowledge*	*Learning*	*Quality*	*Efficiency*
COMM_sq	**.860****	.595**	.274**	.453**	.557**
COORD_sq	**.794****	.609**	.312**	.545**	.467**
SUPP_sq	**.874****	.642**	.257**	.459**	.547**
EFFORT_s	**.824****	.528**	.187**	.461**	.542**
BAL_sq	**.899****	.613**	.276**	.470**	.603**
COH_sq	**.783****	.556**	.291**	.357**	.462**
SOC_sq	.713**	**.734****	.236**	.439**	.412**
EXT_sq	.550**	**.853****	.403**	.391**	.448**
COMB_sq	.504**	**.845****	.462**	.410**	.429**
INT_sq	.563**	**.844****	.415**	.498**	.364**
LEARN1_s	.295**	.416**	**.887****	.422**	.372**
LEARN2_s	.288**	.374**	**.877****	.287**	.361**
LEARN3_s	.226**	.414**	**.805****	.212**	.229**
QUAL_sq	.545**	.528**	.362**	**1.000****	.506**
EFFIC1_s	.625**	.506**	.365**	.597**	**.816****
EFFIC2_s	.550**	.391**	.310**	.385**	**.888****
EFFIC3_s	.424**	.379**	.279**	.302**	**.822****

* Correlation is significant at the 0.05 level (2-tailed).

** Correlation is significant at the 0.01 level (2-tailed).

APPENDIX I: COMMON METHOD BIAS EVALUATION IN PLS



		Substantive Factor Loading (λ_S)				**Method Factor Loading (λ_M)**			
	Indicator	λ_S	T-Stat	P-value	$(\lambda_S)^2$	λ_M	T-Stat	P-value	$(\lambda_M)^2$
Ba - enabler *(modeled as a reflective construct)*	VISION	0.786	6.311	0.000 ***	0.618	-0.079	0.636	0.526 *NS*	0.006
	AUTO	0.558	5.806	0.000 ***	0.312	0.247	2.401	0.017 *	0.061
	URG	1.031	14.241	0.000 ***	1.063	-0.222	2.381	0.018 *	0.049
	RED	0.875	13.393	0.000 ***	0.765	-0.036	0.577	0.564 *NS*	0.001
	VAR	0.751	8.583	0.000 ***	0.564	0.045	0.661	0.509 *NS*	0.002
	TRUST	0.782	8.909	0.000 ***	0.612	0.053	0.542	0.588 *NS*	0.003
Ba - team dynamics	COMM	0.761	8.569	0.000 ***	0.579	0.108	1.220	0.224 *NS*	0.012
	COORD	0.695	5.194	0.000 ***	0.483	0.099	0.733	0.464 *NS*	0.010
	SUPP	0.654	6.798	0.000 ***	0.427	0.237	2.335	0.021 *	0.056
	EFFORT	0.987	9.789	0.000 ***	0.974	-0.176	1.630	0.105 *NS*	0.031
	BAL	1.075	14.643	0.000 ***	1.155	-0.188	2.330	0.021 *	0.035
	COH	0.858	8.029	0.000 ***	0.737	-0.079	0.661	0.509 *NS*	0.006
Knowledge	SOC	0.367	3.198	0.002 ***	0.135	0.437	3.829	0.000 ***	0.191
	EXT	0.881	15.026	0.000 ***	0.776	-0.033	0.512	0.610 *NS*	0.001
	COMB	1.026	16.694	0.000 ***	1.053	-0.221	2.976	0.003 **	0.049
	INT	0.952	16.572	0.000 ***	0.905	-0.128	1.899	0.059 *NS*	0.016
Learning	LEARN1	0.878	31.168	0.000 ***	0.770	0.015	0.172	0.863 *NS*	0.000
	LEARN2	0.876	30.688	0.000 ***	0.768	-0.008	0.075	0.940 *NS*	0.000
	LEARN3	0.817	18.911	0.000 ***	0.667	-0.007	0.102	0.919 *NS*	0.000
Quality	QUAL	1.000	N/A	N/A	N/A	N/A	N/A	*N/A*	N/A
Efficiency	EFFIC1	0.627	10.357	0.000 ***	0.393	0.258	3.849	0.000 ***	0.066
	EFFIC2	0.940	27.741	0.000 ***	0.883	-0.074	1.516	0.131 *NS*	0.006
	EFFIC3	0.945	19.892	0.000 ***	0.892	-0.173	2.912	0.004 **	0.030
	Average:				**0.706**				**0.029**

NS Correlation is not significant at the 0.05 level (2-tailed).

*Correlation is significant at the 0.05 level (2-tailed).

**Correlation is significant at the 0.01 level (2-tailed).

***Correlation is significant at the 0.001 level (2-tailed).

APPENDIX J: CALCULATING GoF

The global criterion of goodness of fit (GoF), as defined by Tenenhaus et al. (2004, p. 173), was calculated as follows:

$$GoF = \sqrt{\overline{COMM} \times \overline{R^2}}$$

where $\overline{R^2}$ = average explained variability (R^2)

and

$\overline{COMM}$ = geometric mean of the average communality.

The $\overline{R^2}$ is an arithmetic mean of the R^2 values for the endogenous latent variables (LVs) in the model. In other words,

$$\overline{R^2} = \frac{\sum_{i=1}^{m} R_i^2}{m}$$

where R_i^2 = R^2 of the i^{th} endogenous LV when there is a total of m endogenous LVs (i.e., $i = 1, \ldots, m$).

The $\overline{COMM}$ is the weighted average of the communalities for the LVs that are measured by multiple indicators. The weights are derived from the number of indicators for each LV, excluding those that are single-indicator variables. Thus,

$$\overline{COMM} = \frac{\sum_{j=1}^{n} w_j x_j}{\sum_{j=1}^{n} w_j}$$

where x_j = communality of the j^{th} LV excluding single-indicator LVs

and

w_j = number of indicators for the j^{th} variable

It should be noted, as Tenenhaus et al. (2004, p. 180) emphasize, single-indicator LVs should not be included in this calculation since the communality of a single-indicator variable automatically leads to 1 (i.e., $x_j \neq 1$ and $w_j \neq 1$).

Following the procedures outlined by Tenenhaus et al. (2004, pp. 180-182), the $\overline{R^2}$ and $\overline{COMM}$ estimates for the research model were calculated as shown in the table below:

Block	R^2	Average Communality	MVs	MV Weight	Weighted Average
Ba - enablers	N/A	0.6055	6	0.2727	0.1651
Ba - team dynamics	0.5938	0.7056	6	0.2727	0.1924
Knowledg	0.5106	0.6723	4	0.1818	0.1222
Learning	0.2156	0.7338	3	0.1364	0.1001
Quality	0.3560	1.0000	N/A	N/A	N/A
Efficien	0.4225	0.7066	3	0.1364	0.0964
Average	0.4197			Sum of weighted averages:	0.6762

MVs = manifest variables

Hence, the GoF for the model is calculated to be

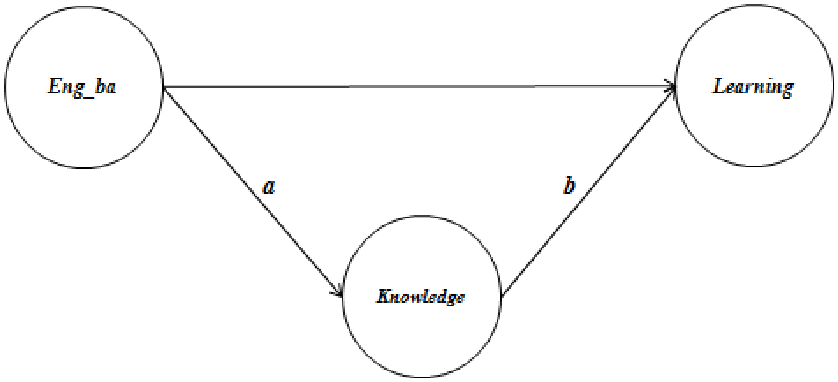
$$GoF = \sqrt{\overline{COMM} \times \overline{R^2}} = \sqrt{0.676 \times 0.420} = 0.533$$

Next, this GoF value was evaluated against Wetzels et al.'s (2009) proposed thresholds: 0.1, 0.25, and 0.36 rated small, medium, and large, respectively. The model's GoF value, 0.533, exceeds the minimum criteria for "large GoF." The predictive performance of the hypothesized model is judged to be reasonably robust.

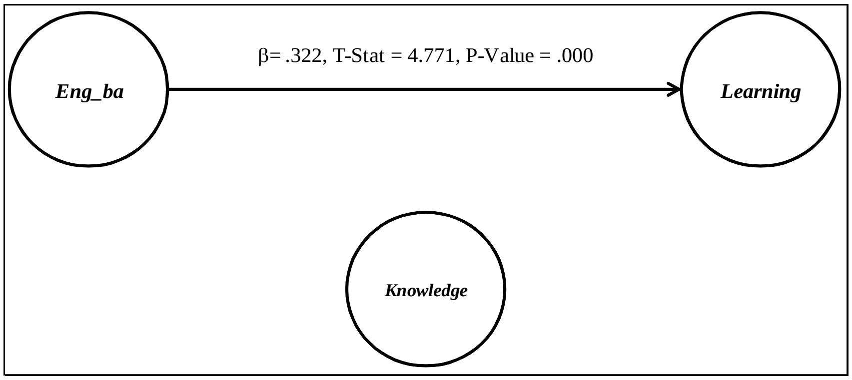
APPENDIX K: MEDIATION CHECK

K1. *Ba* ➔ *Knowledge* ➔ *Learning*

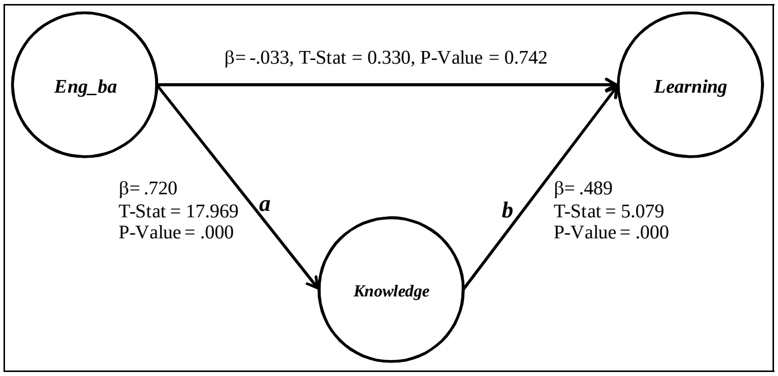
The first step is to check whether the independent variable (IV) is a significant predictor of the dependent variable (DV). In the mediation scheme illustrated below, the IV and DV are *Ba* and *Learning*, respectively.



PLS analysis results show that the path from *Ba* to *Learning* (direct effect) is significant (β = .322, T-Stat = 4.77, *P*-value = .000) as illustrated below.



Having demonstrated that the IV is a significant predictor of the DV, the next step is to confirm the significance of (1) the predictive path from the IV to the mediator (*Knowledge*) and (2) from the mediator to the DV while controlling for the IV. As illustrated below, both (1) and (2) conditions hold. Additionally, with mediation, the direct effect now becomes non-significant (β = -.033, T-Stat = 0.330, *P*-value = .742).



Finally, using the path coefficient (*a* and *b*) and standard error (*SE*) estimates provided by PLS-Graph 3.0, two-sided confidence limits—that is to say lower confidence limit (LCL) on one side and upper confidence limit (UCL) on the other—around the indirect effect ($a \times b$) were calculated through MacKinnon, Fritz, Williams, and Lockwood's (2007) procedures. MacKinnon and colleagues (2007) provide a host of programs—including Fortran-based "PRODCLIN" and "PRODCLIN2" tools[7], as well as a web-based "RMediation" application[8]—all of which compute asymmetric confidence intervals on the product of two mediation path coefficients (Sobel test). If the interval does not contain zero, the mediation effect is significant. Using one of these applications, two-sided confidence limits on the posited mediation path were calculated. The results are summarized in the table below:

a =	0.7196	SE_a =	0.0398	**a x b = 0.3520**
b =	0.4892	SE_b =	0.0961	

	LCL	UCL
At .05 level (two-tailed) of significance	0.214	0.496
At .01 level (two-tailed) of significance	0.172	0.544
At .001 level (two-tailed) of significance	0.123	0.600

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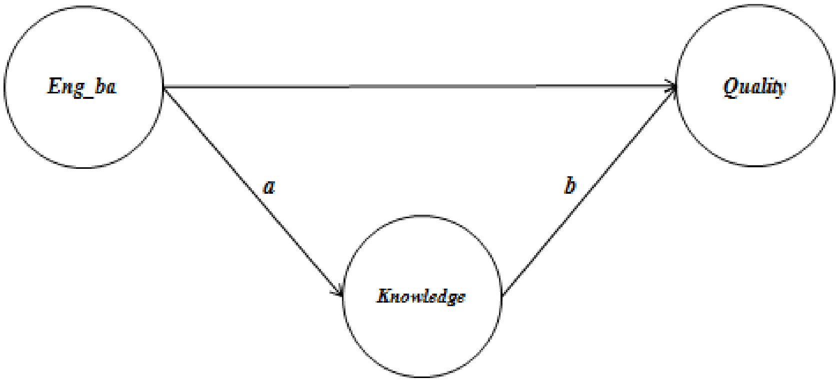
[7] Available at http://www.public.asu.edu/~davidpm/ripl/Prodclin/

[8] Available at http://www.amp.gatech.edu/RMediation

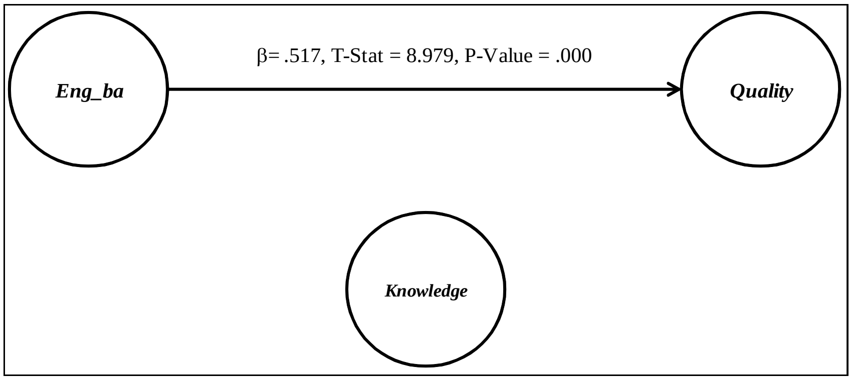
Confidence bounds were drawn at three different α levels (.05, .01, and .001). None of them contain zero, implying support for a non-zero indirect effect and thereby support for mediation. Therefore, full mediation is established for the path from *engineering ba* to *learning achieved* that is mediated by *knowledge creation*.

K2. *Ba* ➔ *Knowledge* ➔ *Quality*

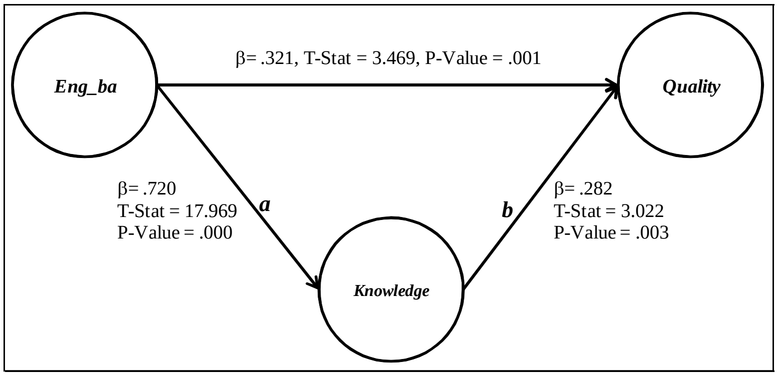
Same steps were followed to evaluate the significance of *Knowledge Creation* as a mediator for the relationship between *Ba* and *Product Quality*.



The PLS analysis results show that the path from *Ba* (IV) to *Quality* (DV) is significant (β = .517, T-Stat = 8.979, *P*-value = .000), confirming the significance of direct effect, as illustrated below:



PLS estimation results also confirm significance of the IV as predictor of the mediator, as well as significance of the mediator as predictor of the DV while controlling for the IV. Further, with the inclusion of the mediation variable, the magnitude of direct effect decreases but remains significant (β = .321, T-Stat = 3.469, *P*-value = .001), as illustrated below:



Confidence limits on the indirect effect based on *a*, *b*, and *SE* estimates, calculated by applying MacKinnon et al.'s (2007) procedures, are summarized in the table below:

a =	0.7196	SE_a =	0.0398	**a x b = 0.2029**
b =	0.2820	SE_b =	0.0923	

	LCL	UCL
At .05 level (two-tailed) of significance	0.072	0.337
At .01 level (two-tailed) of significance	0.032	0.381
At .001 level (two-tailed) of significance	-0.016	0.433

The confidence bounds support non-zero mediation effect at the .01 level of significance—but not at the .001 level. From a practical perspective, we conclude that mediation is supported. Thus, partial mediation is established for the path from *engineering ba* to *product quality* that is mediated by *knowledge creation*.

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ABSTRACT

ENGINEERING PROBLEM SOLVING AND SUSTAINED LEARNING: A MIXED METHODS STUDY TO EXPLORE THE DYNAMICS OF ENGINEERING KNOWLEDGE CREATION

by

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This dissertation research explores processes by which engineering problem solving (EPS) results in sustained organizational learning. Approaching from a constructionist perspective, the study empirically examines the knowledge creation dynamics instigated by product-related problems using a mixed methods research approach. The research has identified the Japanese concept of *ba*, defined in this study as "shared experiential space," as a key construct that explains the phenomena of interest. A new framework that the study has developed, which interprets EPS as an epistemic journey to attain system-wide improvements, is highly complementary to the traditional structured routine based approaches to engineering operations and management.

Operational sustainability is an important issue for every enterprise's survival, to which engineering contributes by managing product and customer requirements. Effective product management is made possible by seamless feedback of lessons learned, which are generated by problem solving. While the literature offers ample evidence of the relationship

between problem solving and organizational improvements, however, "how" this linkage is actually facilitated is not well understood. Studies in industrial engineering and operations research have traditionally emphasized measurable outcomes and the rational aspects of technical problem solving but have yet to saturate the research landscape with more qualitative exploration of the actual processes that leverage engineering knowledge embedded in local contexts.

Motivated by the gaps in research, a two-stage empirical study was conducted to probe deeply into the "black box" of engineering knowledge creation. The study used the exploratory sequential mixed methods research approach to uncover potentially relevant factors for EPS efforts to attain sustained learning, which was defined and subsequently operationalized as "positive system changes." In the first phase, a qualitative investigation using grounded theory helped to develop a conceptual model of EPS dynamics. In the second and last phase, this model was tested quantitatively using partial least squares analysis to assess the extent to which the theorized concept can be generalized across a larger engineering sample.

The study findings show that contextual factors alone are not sufficient for EPS efforts to result in sustained learning. While these factors have direct effects on operational efficiency and partially affect the effectiveness of problem correction, the EPS processes do not accomplish system changes without first carrying out knowledge creation routines. These routines are a form of sensemaking posited as necessary for cognitive convergence and achievement of a unified interpretation. To the best of our knowledge, this study is first to quantitatively model the concept of *ba* as a deliberately created environment that promotes such routines, as well as to apply it in a U.S. engineering context. A set of recommendations for engineering knowledge management are provided for practice. For theory, the outcomes of this research illuminate the little addressed link that connects EPS to organizational learning and by so doing contribute to a more complete epistemology of engineering practices.

AUTOBIOGRAPHICAL STATEMENT

Rachel Itabashi-Campbell has 18 years of career in automotive quality, reliability, and most recently, safety engineering. In her automotive career, she has traveled extensively to collaborate in product development projects around the globe. She is a member of the 2008 Global Executive Track (GET) cohort and a 2009 - 2012 King-Chavez-Parks (KCP) fellow. She is certified as both Quality Engineer and Reliability Engineer by the American Society for Quality (ASQ) and has memberships with the ASQ, Golden Key International Honour Society, and Tau Beta Pi Engineering Honor Society.

Since coming to the GET program, Itabashi-Campbell has published three scholarly publications directly connected to her academic research pursuit. In addition, she has authored and co-authored a number of practitioner-oriented publications in quality and reliability engineering, including eight Society of Automotive Engineers (SAE) conference papers, three of which made their ways to the SAE Transaction Journals as among the best published. A conference paper in system safety is due for publication through the Institute of Electrical and Electronics Engineers (IEEE) in April 2013. She is currently engaged in a book writing project with a group of engineering education scholars.

Itabashi-Campbell holds a certificate in computer hardware engineering technology (Oakland Community College), a B.A. in French (University of California, Los Angeles), an M.B.A. (Elon University), and an MS in Industrial Engineering (Wayne State University). She is a native of Hamamatsu City, Japan. She received her primary through secondary education in Brussels (Belgium), Tokyo (Japan), Sayama (Japan), and Los Angeles (USA). She has been an American citizen since 1989.