POMS PRODUCTION AND OPERATIONS MANAGEMENT

PRODUCTION AND OPERATIONS MANAGEMENT POMS

Vol. 25, No. 3, March 2016, pp. 390–416
ISSN 1059-1478 | EISSN 1937-5956 | 16 | 2503 | 0390

DOI 10.1111/poms.12410

Managing R&D Project Shifts in High-Tech Organizations: A Multi-Method Study

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High-tech organizations maintain a portfolio of R&D projects that address problems with different levels of complexity. These projects use different strategies to search for technological solutions. Projects refining existing products, processes, and technologies, for instance, employ a local search strategy to improve performance, while projects developing new products, processes, and technologies employ a distant search strategy. However, projects can shift in their levels of complexity due to exogenous technological changes, and failure to change search strategy in turn can negatively impact project performance. This study first develops grounded theory via case studies to understand how high-tech organizations manage R&D projects when complexity shifts. The case data come from 142 informants in 12 R&D projects at three high-tech business units. A cross-case comparison shows that three interconnected mechanisms positioned at multiple levels within the organization enable high-tech organizations to identify such shifts and adjust the project's search. We refer to this strategy as *responsive search*. We then conduct agent-based simulation experiments to examine the conditions under which the responsive search outperforms other canonical search strategies. Overall, this study sheds light on the underexplored question of how to make mid-project corrections by effectively identifying and managing shifts in project complexity.

Key words: High-Tech R&D; case studies; NK model; search strategy; project complexity; project uncertainty; combined-methods
History: Received: January 2014; Accepted: May 2015 by Tsan-Ming Choi, after 3 revisions.

1. Introduction

High-tech organizations need to continuously innovate products and processes to address customers' current and future needs (Mallick and Schroeder 2005). They do so by implementing a portfolio of R&D projects that have different levels of complexity (Chao and Kavadias 2008, Levinthal 1997) and, in turn, use different strategies to search for technological solutions (Mihm et al. 2010). For complex problems, projects may employ a distant search strategy that entails developing new products, processes, and technologies (Benner and Tushman 2003, Levinthal 1997). These problems have a large number of decision variables that interact with one another (Sommer and Loch 2004). In contrast, projects for less complex problems may employ a local search strategy that entails enhancing existing products, processes, and technologies. These problems have fewer decision variables with sparse interactions. Scholars have used the terms "exploration" and "exploitation" (He and Wong 2004) or "radical" and "incremental" innovation (Chandrasekaran et al. 2015) to refer to local and distant search strategies, respectively. One challenge organizations face is how to manage R&D projects with different search strategies. Research shows that R&D projects using a local search strategy may crowd out distance search projects because they have lower risks and quicker returns (Chen and Katila 2008, Levinthal 1997, March 1991). To overcome this cannibalization, companies use "strategic buckets" to classify R&D projects based on their search strategies (Chao and Kavadias 2008). Once classified, they employ different project management techniques such as incentives, leadership styles, and decision-making autonomy to manage projects within each bucket (Chandrasekaran et al. 2015).

While a substantial amount of research has investigated how to categorize and manage different types of R&D projects, these studies do not fully capture the operational realities high-tech organizations face. This research effort began with the intent to enhance our understanding of how high-tech R&D organizations manage different types of R&D projects. We conducted extensive fieldwork, tracking the progress of 12 R&D projects within three business units (MicroTech, CommNet, and CommTech) at two high-tech organizations (Microsystems and CommCorp). We specifically wanted to investigate how high-tech R&D units manage tensions across projects—that is, how they monitor and track resources across projects with different search strategies. However, as the study unfolded we found these units experienced other R&D project challenges that the literature has not addressed. What emerged inductively from the case analyses was the realization that the level of complexity of an R&D project sometimes may suddenly change. For example, a project may have begun as a simple refinement to a current product or process technology using existing knowledge (local search). However, as the project progresses, external events such as technological advancements can change the project's complexity, driving a need to develop new technology (distant search) instead of refining an existing one. In other words, an exogenous change in complexity may require managers to alter the project's search strategy to improve performance. We define *project shift* as an exogenous change in a project's complexity during the course of the project. Executives in discussion said their firms faced chronic project shifts, and the failure to identify these shifts and alter the project's search strategy resulted in delayed product launches and inferior market performance. To examine this phenomenon, this study investigates the following question: *How do high-tech organizations deal with R&D project shifts?*

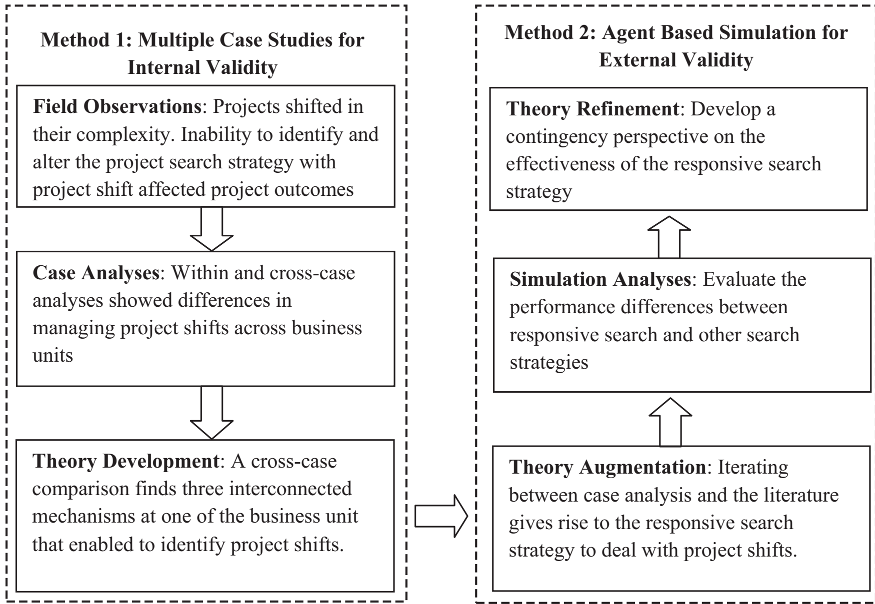
A cross-case analysis of R&D projects shows differences in how business units managed R&D project shifts. Specifically, CommNet and CommTech followed the conventional approaches discussed in the NPD literature to manage R&D projects: Senior managers made decisions about project search strategies on an annual basis and then used different project management approaches based on their search strategies (e.g., Chao and Kavadias 2008, Wheelwright and Clark 1992). Project shifts, however, did not trigger timely adjustments to search strategies. Rather, these business units maintained the original search strategy in spite of a project shift, which led to poor outcomes.

In contrast, senior managers at MicroTech made decisions about project search strategies each month and monitored their decisions each week, using similar processes to track the all R&D projects' progress. Importantly, they did not explicitly differentiate projects based on their search strategies, enabling them to quickly alter search strategy to distant from local when the project shifted. We define *responsive search* as the strategy to quickly alter a project to distant search from local search upon project shifts. The cross-case analysis identifies three interconnected mechanisms at multiple levels that enabled responsive search at MicroTech. These enablers include the following: (i) a universal risk-evaluation metric that continuously tracks risk across all strategically important R&D projects, (ii) a weekly cross-level communication process that facilitates continuous information exchanges across project and strategic levels, and (iii) a continuous planning process that gathers monthly updates on technology and market changes. The continuous planning, then, connects to the universal risk evaluation metric and the cross-level communication process. Although these mechanisms may seem ordinary in isolation, their interconnections helped MicroTech manage project shifts.

The case study finds that project shifts occur in high-tech organizations. The case method also offers rich insights into the mechanisms that enabled responsive search through a cross-case comparison (Glaser and Strauss 1967). The case method does, however, have limitations that should be recognized. For one, the case analysis makes it difficult to isolate the benefits of responsive search from other organizational factors at MicroTech. In addition, it has limited external validity and does not provide insights into the boundary conditions for the responsive search. This is because all projects from our cases operate in environments characterized by high levels of technological turbulence and time-to-market pressures. To overcome these limitations, we augmented the case analysis with agent-based simulation experiments. These varied the levels of technological turbulence and time-to-market pressures to better understand the boundary conditions of the responsive search. The simulation has the advantage of isolating the influence of responsive search on project outcomes, irrespective of other organizational effects. Figure 1 gives an overview of the research design.

The agent-based simulations use the NK model to represent the landscape of an innovation project's possible outcomes (Kauffman 1993, Levinthal 1997). This landscape abstraction has been widely used to characterize search problems with varying levels of complexity (e.g., Fleming and Sorenson 2001, 2004, Kavadias and Sommer 2009, Rivkin and Siggelkow 2003). In the context of high-tech R&D projects, the complexity determines the ruggedness of the project landscape, which—when systematically varied—captures the project shifts found in the case studies. We compare the responsive search from MicroTech,

Figure 1 A Multi-Method Study Design



where search strategy alters between local and distant consistent with landscape shifts, with the conventional approach used at CommNet and CommTech. Specifically, we investigate the following research question using the NK model: *How effective is responsive search under various levels of technological turbulence and time-to-market pressures when compared with other search strategies?* Results show that the responsive search strategy is more effective than others in environments with high technological turbulence and time-to-market pressures. However, these benefits diminish in environments with low technological turbulence and time-to-market pressures. This suggests that the effectiveness of responsive search is contingent on the environment—that is, it is does not universally benefit all organizations. Taken together, the results from both methods offer novel insights on how to identify and manage project shifts to make midcourse project corrections.

2. Background

NPD scholars have taken particular interest in the question of how to manage R&D projects with different search strategies (Chao and Kavadias 2008, Wheelwright and Clark 1992). A brief overview of this literature suggests that factors such as external competition (Chao and Kavadias 2008), firms' competitive priorities (Chan et al. 2007), and industry clockspeed (Fine 1998) help managers determine the "right" mix of R&D projects in their organizations. Scholars also note that decisions on project mix typically occur on an annual basis (Grant 2003, Hamel 1996), and managers tend to use different approaches to manage R&D projects within these portfolios (Hutchison-Krupat and Kavadias 2014, Wheelwright and Clark 1992). For instance, studies show that R&D directors become more involved in day-to-day operations and require more frequent updates on projects adopting distant search but are less involved and require only periodic updates for projects using local search (Chandrasekaran et al. 2015, Holmqvist 2004).

Although research has advanced our knowledge on how to manage different types of R&D projects, it views project complexity from a static perspective and does not account for shifts over time. In a high-tech R&D setting, a project that begins as a simple refinement to an existing product or process design may need to alter its course and develop new technologies due to exogenous changes in technical requirements. Conversely, a project may start out as a search for new technologies but can change course to refine existing technologies in response to changes in customer preferences or other competitive actions. The literature offers limited insights on how to alter a project's search strategy in response to such exogenous changes in project complexity (e.g., Hayes et al. 2005).

A parallel stream of research by organizational scholars has taken a more dynamic approach to conceptualize search (Chao et al. 2012, Lavie and Rosenkopf 2011, Siggelkow and Levinthal 2003). From this perspective, local search represents improvements in existing technology trajectories, while distant search represents "long jumps" to new technological possibilities (Fleming and Sorenson 2004, Posen and Levinthal 2012). It has been argued that local search strategy helps find solutions in low-complexity technology landscapes, while distant search strategy is more effective in those with high levels of complexity (Fleming and Sorenson 2004, Levinthal 1997). Although these studies advance our understanding of search strategies beyond the static approaches, they do not focus on technology landscapes with shifting complexities, be it at the organizational or project levels. Consequently, they do not examine how midcourse project complexity changes affect search strategy, or how organizations can design mechanisms that detect exogenous changes to project complexity. Our research takes a first step toward understanding these issues.

3. Case Method and Data

3.1. Research Sites

The research sites for the cases consist of three theoretically sampled business units (*MicroTech, CommTech and CommNet*) from two high-tech organizations (*Micro Systems Incorporated & Comm Corp Incorporated*). Unlike random sampling, which aims to capture a representative sample of the population, theoretical sampling seeks variation to understand conceptual differences (Eisenhardt 1989, Glaser and Strauss 1967). We selected business units that (i) operated in a high-tech industry with fast industry clockspeed (Fine 1998), (ii) had R&D projects that searched for new technologies as well as refined existing technologies, and (iii) experienced variations in project performance outcomes (successful, delayed). A brief introduction to the research sites follows (see Appendix A for more details).

3.1.1. Micro Systems Incorporated. Micro Systems manufactures precision electronic components such as suspension drive assemblies, disk drive components and medical device components that require miniature design and manufacturing capabilities. It has approximately 6000 employees and close to US $1 billion in annual sales. Micro System's primary business is designing and manufacturing suspension assemblies made by MicroTech.[1] The business unit had high levels of innovation within its R&D units, its chief technology officer (CTO) stating the company "*operates in an industry where one thing is certain: cost always goes down, while product and process requirements always change rapidly*."

3.1.1.1. MicroTech Business Unit: The MicroTech Business Unit leads the industry in the design and manufacturing of electronic components used in computers. R&D spending for this unit accounts for 15% of sales. MicroTech operates as a contract equipment manufacturer in this business segment, with the majority of its customers located in Southeast Asia. It specializes in close-tolerance design and manufacturing that requires chemical, mechanical, and electronic technologies. The components this unit develops are very small (<1 mm) and require high levels of reliability and precision. When asked about the unit's product, the CEO offered the following analogy: "*Imagine scaling up our product to the size of a Boeing 747. In that case, the airplane would be flying at five times the speed of sound, at about 0.125 inch off the ground. And it must maintain that short distance at that speed over ocean waves and mountains and still be counting the blades of grass while doing it*." This business unit leads the industry, with 65% market share, and has three design and manufacturing facilities in the United States. The research team visited two of these facilities and the headquarters site.

3.1.2. Comm Corp Incorporated. Comm Corp is a Fortune 500 company known for its global leadership in high-tech manufacturing that specializes in embedded systems and integrated circuit design. It has three business units (CommTech, CommNet, and Comm Customer Solution[2]) with 60,000 employees and annual sales exceeding US $40 billion.

3.1.2.1. CommTech Business Unit: CommTech employs around 40,000 and is the primary business unit of Comm Corp. It leads the industry's communication and data management technologies. R&D spending accounts for 12% of sales. The unit's design and pilot testing facilities, which the research team visited, are located in the United States, while its manufacturing takes place in Mexico, South America, and Asia. CommTech was the market leader until the late 1990s, when it moved out of the top spot for reasons attributed to a poor innovation decision on a key technology (Tech Z, explained later in the study).

3.1.2.2. CommNet Business Unit: CommNet branched out of the CommTech unit because of a technology competency. R&D expenditures account for 10% of its sales. This unit has over 10,000 employees and operates within the United States. It leads in the design and development of communication systems for the government and public sector. Although CommNet's customers were governmental institutions, their product offerings had a faster clockspeed (Fine 1998) and were comparable to both CommTech and MicroTech.

3.2. Data Collection & Research Methods

The data from these sites include structured and semi-structured interviews, observations at the business units and project meetings and archival materials. We had access to data from 12 R&D projects in these units. Because eight of the 12 projects studied in this research started prior to data collection, part of the data is retrospective and part is collected in "real-time." However, we followed several steps detailed in this section to mitigate retrospective bias.

Table 1 Research Methods for Case Analyses

1. Select cases from Microsystems Inc	1. Theoretically sample Microsystems and contact Microsystems to gain access to the MicroTech 2. Identify the Strategic Level Informants (e.g., CEO, CTO, Senior VPs, Strategic Planning Officers, Intellectual Property Officer, etc.) from MicroTech 3. Begin sampling R&D projects within the MicroTech. Identify the informants for these projects (Project Leaders & Project Team Members) 4. Schedule site visits and interviews in MicroTech
2. Site visit preparation	1. Develop three different protocols based on existing literature for the Strategic Level, Project Leader and Project Team Member Interviews. 2. Develop interview protocols for the Planning and Intellectual Property department interviews. 3. Collect archival data on the organization and its competitors through Research Insights and Factiva databases.
3. Site visits at Micro Systems	1. Two researchers conduct interviews with the strategic level informants, project leaders, project team members 2. Multiple informants are interviewed (e.g., project leader and team member) separately to avoid retrospective bias. 3. Multiple visits to track project progress and gather additional data 4. Researchers immediately discuss and share insights after each interviews. 5. Collect other forms of data (e.g., IP Documents, Planning Reports, Board Meeting Reports, Project Reports, etc.)
4. Post Micro Systems to other sites	1. Transcribe the interviews and other forms of data. Contact the informants for clarification 2. Discuss themes and generate codes after reading the transcripts 3. Identify CommCorp & Terabyte Corp to collect data. Terabyte refused to participate. Select the CommTech and CommNet from CommCorp 4. Modify Interview protocols based on the evidence from Microsystems 5. Sample informants and projects from both the business units
5. Data analysis and coding Process	1. Three researchers code the data individually (open, axial coding). 2. Generate open code lists which are reduced to axial code lists 3. Compute inter-rater reliabilities for the coding process.
6. Additional sampling	1. Selective coding around the “project shifting” theme 2. Collect additional data on project shifts (Drive Innovation from MicroTech and Tech Z from CommTech) 3. Conduct a larger cross-case analysis across three business units
7. Theory development	1. Develop higher level findings from the cases 2. Share the insights from the case analysis back with participants from Microsystems and CommCorp

The seven-step procedure in Table 1, adapted from Cardinal et al. (2004), summarizes the data collection process and research methods. Consistent with the grounded theory building technique, we began with Micro Systems and then proceeded to Comm Corp.

Senior management in these business units helped identify informants at both the strategic and project levels. We designed separate interview protocols for the strategic level managers, project leaders, and the project team members. Interviews at the strategic level focused on senior management's role in decision making and the organizational mechanisms used to manage R&D projects. The project leader and team member protocols focused on organizational and behavioral issues when working on R&D projects. Projects were selected to obtain a mix of developing new products, processes, and technologies outside the current knowledge as well as improving existing products, processes, and technologies by using current knowledge (i.e., using distant and local search). Additional interview protocols for the intellectual property and strategic planning departments were also developed during the course of our study. The interviews included at least two research investigators, one leading the interview and the other serving as an observer and note-taker. The qualitative data for the purpose of this study consisted of 41 interviews (16 strategic level and 25 project level) with over 142 participants across all three business units (all interviews at the project level had multiple participants).

The strategic-level interviews included 16 senior executives in three waves and involved the CEO, CTO, chief quality officer, vice presidents, directors, and business unit managers involved in making R&D project decisions (eight from MicroTech, five from CommTech, three from CommNet). All interviews lasted 1–2 hours and included open-ended questions. Post-interview discussions took place within 24 hours of the interviews and focused on summarizing and cross-validating observations (Gioia and Thomas 1996). We recorded and transcribed all interviews for the qualitative data analysis. This analysis also used other forms of data, including planning reports, training documents, IP documentation, company videos, financial analysis reports, industry publications, and reports from board meetings.

We initially collected data from five R&D projects at MicroTech, all with budgets exceeding $1 million and considered high priority by senior management (average budget: $28.5 million). They included one innovation project (Vision Plus) focused on introducing a new technology and three innovation projects (Tech Yield, Tech Time, and Customer Defects) focused on refining existing technologies. Our sample also included one project (Sigmatel) that started as a refinement to an existing technology but ended up developing new technology. At CommCorp, we initially collected data from five R&D projects (average project size: $24.7 million). This included two innovation projects (Video Share from CommTech, Communicate from CommNet) that focused on developing new technologies and two innovation projects (Cost Reduction from CommTech, Third Party from CommNet) that focused on refining existing technologies. Our sample also included one project (Tablet from CommNet) initially started out as refinement to existing technology that ended up developing a new technology.

Appendix B gives details on all the projects studied. All projects varied in size, complexity, duration, and performance and were recently completed or near completion. We were able to obtain updates on project performance for incomplete R&D projects during follow-up visits. Separate interviews with the project leader and the project team members on the same topics helped minimize retrospective bias. Multiple team members were present during the project team member interviews, improving response reliability. Additional archival data in the form of project presentations, stage-gate reports, team meeting minutes, and internal newsletters also helped minimize the retrospective bias (Langley 1999).

For the data analyses, the research team familiarized themselves with more than 500 pages of transcribed interviews and other related documents, including annual reports and business press articles, and developed a coding scheme to analyze the data. The team (three researchers and two research assistants) followed general guidelines of open, axial, and selective coding during this process (Miles and Huberman 1994), meeting for multiple rounds after the initial site visits to develop a strategy for synthesizing the data. To reduce data during the open coding process, we used the vocabulary of the interviewees, for example, "PPD (Product–Process Development) scorecards," "scanning the market," "cross-level scorecards," etc., as codes. This process resulted in a set of 127 codes representing about 1084 text segments. We reduced these to 31 codes and seven categories during the axial coding process, coding the data in new ways by grouping conceptually similar codes. For instance, "PPD scorecards" used at Micro Systems and "cross-level scorecards" used at CommCorp performed similar functions of connecting strategic and project-level goals. We combined these as "cross-level communication" during the axial coding process. Code lists then were classified as either *a priori* (PC) or grounded (GC) depending on whether they were derived from our interview protocols or emerged inductively from the data. The coding progress involved transitioning to second-order themes from first-order concepts that came from comments, views and facts made by the informants. These themes emerged when we searched for relationships between the bundled first-order concepts. We finally arrived at the aggregate dimensions based on the concepts that they represent.

A minimum of three investigators coded the data using NVIVO, openly discussing disagreements during the coding process and resolving them through evidence from the data. We used the Perreault and Leigh (1989) approach to determine inter-rater reliability[3] (I_r) based on the observed frequency of agreements between judges, the total number of judgments made and the number of possible ways to code each concept. Average inter-rater reliability for the coding process was 0.92 (for 31 axial codes), consistent with previous research (Morse 1997). Having multiple and separate respondents for both the project-level and the strategic-level data across these business units helped establish reliability for the constructs examined herein.

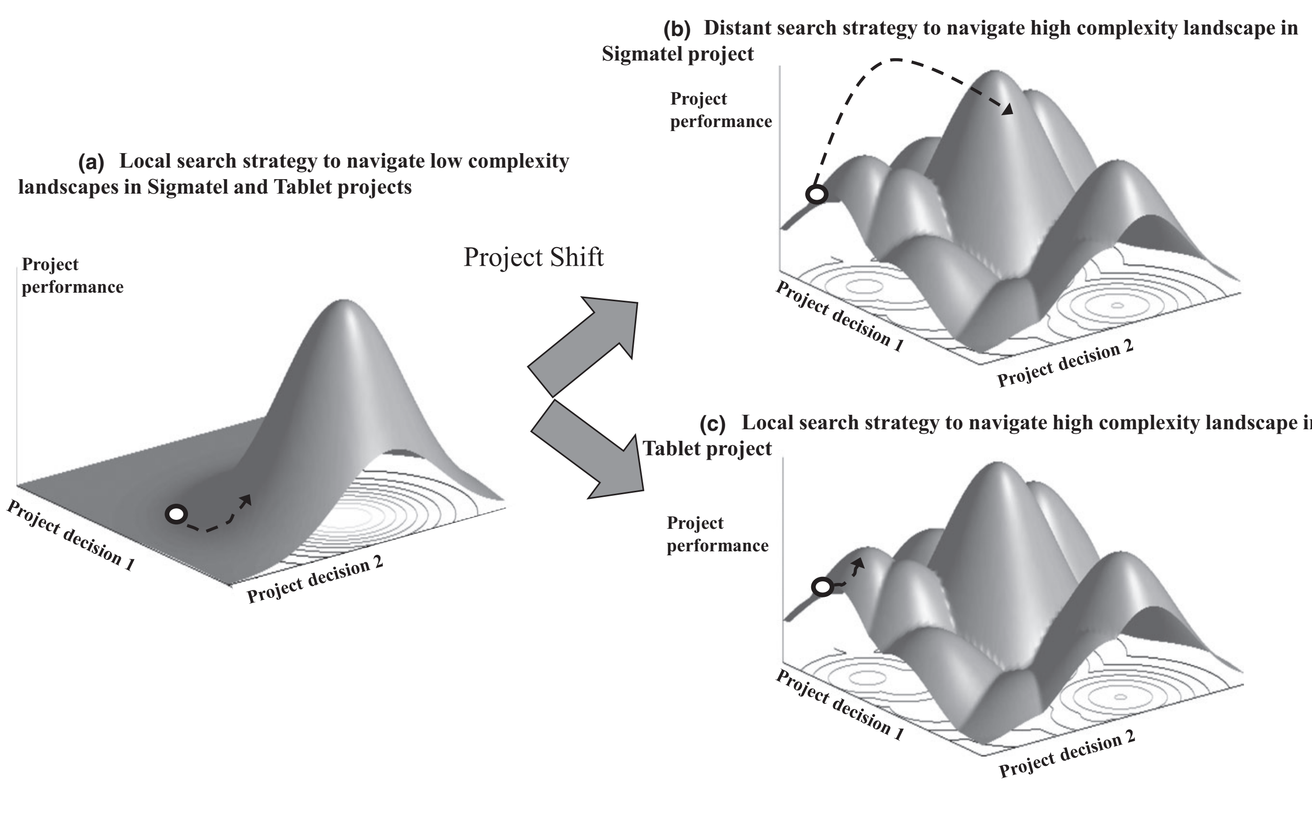
To sharpen understanding of the phenomenon, we moved during the selective coding process to a few theoretical categories from a large number of codes produced from the axial coding process. This is because our codes included topics such as knowledge creation from projects and project portfolio management (Chandrasekaran and Linderman 2015, Chandrasekaran et al. 2015) which are not relevant to this research. As a result, we reduced all our axial codes to understand the project shifts. This process involves "integration and abstraction through comparison of coded passages, as well as comparison to the literature (Volkoff et al. 2007, p. 837)." The selective coding process is complete upon theoretical saturation, that is, when the relationships between categories are supported by sufficient data (Strauss and Corbin 1990). Our initial data collected from all three sites involved two projects (of 10) that experienced project shifts. These data did not offer a sufficiently compelling understanding of how project shifts are managed across these units. Hence, we decided to revisit our cases to search for other instances of project shifts. Going through our interview notes and archival data, we were able to find two more of the units' projects that experienced complexity shifts: (i) Drive Innovation project from MicroTech, which experienced a change to high complexity from low complexity; and (ii) Tech Z from CommTech, which experienced a change to low complexity from high complexity. Analyzing these projects drew similar conclusions to the previous two that experienced project shifts. This supported category saturation from our cases and is developed in the robustness section. The final step in the data analyses included a cross-case analyses to compare and interpret strategic- and project-level data across the three business units (Miles and Huberman 1994). Field data collection ended with feedback sessions in February 2008.

4. Case Findings

The cross-case business unit comparisons revealed complexity shifts in two projects: the *Sigmatel* project at MicroTech, and the *Tablet* project at CommNet. Both projects began by building on existing technologies and capabilities. Sigmatel entailed modifying existing product and process designs for making suspension drive assemblies at MicroTech, while Tablet involved designing a rugged laptop that was a minor improvement over another CommNet design (Figure 2a schematically represents the technological landscapes of these projects). Given the low levels of complexity (with relatively fewer project decision variables and simple interactions between them), these projects initially operated on a less-rugged landscape and used a local search strategy to find acceptable technological solutions. An exogenous technology change, however, brought more complexity (with more project decisions and more involved interactions between them), creating rugged landscapes for these projects, as shown in Figure 2b and 2c. Both projects eventually needed to develop radically new technologies whose deliverables senior management viewed as strategically important. At MicroTech, a quick alteration to the project search strategy to distant search from local search quickly followed the exogenous project shift (See Figure 2b). Here, the project team allocated additional resources to the project and quickly changed its management approach, encouraging more experimentation to create new knowledge. In terms of outcomes, Sigmatel was a big success, industry reports stating it radically changed "*the way suspension assemblies were designed and manufactured*."

In contrast, the case analyses revealed CommNet did not quickly identify the shift in Tablet's project landscape and the search strategy stayed unchanged and local, as shown in Figure 2c. The project team had limited resources and senior management discouraged experimentation and out-of-box thinking, continuing to incrementally change the current product design even after the project shift. Only after several months of months of persuasion and additional tests did the project change to a distant search strategy, ultimately delaying the product launch. Called a "*subpar product*" by the business press, the Tablet was discontinued in 2009. According to senior managers, the company eventually lost its leadership position in the rugged laptop market. The following discussion provides a detailed description of these projects and management's response to project shifts. We then highlight important differences between these pro-

Figure 2 (a–c): Landscape Shifts for Sigmatel and Tablet Projects



jects and compare the findings with other projects and the extant literature.

4.1. Sigmatel Project at MicroTech

Sigmatel started as modification to an existing product and process for making suspension assemblies. The product changes involved using a slightly different raw material that would offer better electrical conductivity, increased mechanical control, and decreased size. The process changes involved adjusting the assembly process for the modified product. In general, project teams drew on MicroTech's existing technological capabilities for both product and process technology changes and all key informants at MicroTech believed they had the relevant knowledge to execute the project. As a result, Sigmatel started with a local search strategy to improve the product design and eliminate any process variations. That is, the project team sought solutions based on their existing knowledge. For instance, when asked about the early phases of Sigmatel, the project leader remarked:

> For the first 3 months of the project, I just had a couple of manufacturing people working on changing the machine specifications, programming them to make these components. We also involved some personnel from the advanced development R&D group to discuss strategies to optimize our manufacturing process. Overall, it was more a routine workload and was based on existing skills [at MicroTech]

Irrespective of the project search strategy, senior management at MicroTech used the same proprietary project management procedure called the PPD to track all strategically important R&D projects. MicroTech had a full-time staff member reporting to the CTO charged with collecting project risk "scorecards" in the PPD process and working with the planning staff to update risk scores. When asked about the role of PPD at MicroTech, she said:

> PPD is MicroTech's quality assurance process that is used to objectively identify and address technical and business issues associated with projects that are deemed to be of strategic importance. These scorecards are completed by the project leaders periodically through the Lotus Notes Database. It is a relatively easy procedure that involves clicking and responding to ten questions related to their respective projects.

The PPD process at MicroTech proceeds as follows: At the beginning of each week, project leaders updated a scorecard through their internal Lotus Notes database to assess the technological and market risks associated with the project. The scorecard consisted of ten questions on topics such as design for manufacturing risks, market entry risks and supply risks, etc., which are measured on a 5-point Likert Scale (1 = No Risks, 2 = Some Risks, 3 = Moderate Risks, 4 = Less than substantial Risks, and 5 = Substantial Risks). Projects with an average score above 2 in the PPD scorecards were considered higher-risk projects, while projects scoring below 2 on this scorecard were considered lower-risk projects. When over four consecutive weeks a previously low-risk project averages above 2, or a previously high-risk project averages below 2, a PPD staff member flags them for further assessments. In general, projects searching for new technologies had more risk than projects refining existing technologies because they faced several decision alternatives (e.g., component size, material used, process parameters, etc.) that had multifaceted interactions, i.e., a rugged landscape. Consequently, changes in project complexity coincided with changes in PPD risks.

It is noteworthy that senior managers at MicroTech used the same project risk tracking approach *universally* for all types of R&D projects, even for low-risk, low-complexity R&D projects that refined existing products and processes. However, during project execution, senior managers, project teams, and project leaders at MicroTech used different tools and procedures depending on the project risk levels e.g., a six-step improvement approach for low risk project vs. a five-step innovation approach for high-risk project. At MicroTech, we found that projects based on existing knowledge typically scored less than 2 in the PPD scorecards, thus carried less risk when compared with projects focusing on creating new knowledge.

During the initial stages of the project (between Nov 2004 and Feb 2006), Sigmatel was considered low risk, scoring less than 2 in PPD assessments. Table 2 gives the search strategy, structured approach, tools, and methods used by Sigmatel during the initial months prior to project shift. As seen in Table 2, the team used tools such as Statistical Process Control charts, Pareto charts, FMEA (Failure Mode Effects Analysis), all of which emphasized efficiency and focused on improving current product and process designs. They also used a six-step structured approach typically used with the local search strategy. According to the project leader, the project-level and organizational-level leadership interacted very little during this phase. In January 2006, a "continuous planning forum" (described in section 4.3) projected changes in the product and process requirements for the suspension assemblies due to exogenous technology and market changes (advancements in a new material technology to make suspension assemblies) that increased project risks over the next 2 years. It

Table 2 Comparing Search Strategy, Tools and Methods used by SigmaTel and Tablet Before and After Project Shifts (Time in Brackets)

Time	Characteristic	Sigmatel	Tablet
Before project shift	Search strategy	(Nov 2004 – Feb 2006) Improve current product and process design; for example, minor changes to sub-assemblies	(June 2006 – Dec 2006) Improve current product and process design; for example, minor refinements to the laptop screen size and processor
	Structured approach	(Nov 2004 – Feb 2006) Define – Understand – Measure - Analyze – Change – Control	(June 2006 – Dec 2006) Define – Measure – Analyze – Improve – Control
	Tools used	(Nov 2004 – Feb 2006) Ishikawa, Pareto, SPC, FMEA, 5S	(June 2006 – Dec 2006) Gap Analysis, Affinity Diagram, SPC, Pareto, Ishikawa.
	Senior management involvement	(Nov 2004 – Feb 2006) Minimal involvement (Only through the PPD risk scorecards)	(June 2006 – Dec 2006) Minimal involvement (No risk tracking)
Project shift happened		(Jan – Feb 2006) New material technology available to make suspension assemblies	(Dec 2006) New developments in the supplier processor technology used in Tablet
After project shift	Search strategy	(March 2006 – Project Completion) Radically change the product and process design; for example, brought in new experts in chemical and metallurgical engineering to develop new assemblies	(Dec 2006 – June 2007) Continue to Improve current product and process design (June 2007 – Project Completion) Radically change the product and process design; for example, brought in new technology experts and supplier for a different screen and processor
	Structured approach	(March 2006 – Project Completion) Define – Measure – Analyze – Design – Verify	(Dec 2006 – June 2007) Define – Measure – Analyze – Improve – Control (June 2007 – Project Completion) Define – Measure – Analyze – Design – Verify
	Tools used	(March 2006 – Project Completion) DFMEA, Quality Function Deployment, Design for Manufacturing, Experimental Design, Decision Analysis	(Dec 2006 – June 2007) Gap Analysis, Affinity Diagram, SPC, Pareto, Ishikawa. (June 2007 – Project Completion) Fault-tree analysis, DFMEA, Design for Manufacturing, X-gates
	Senior management involvement	(March 2006 – Project Completion) More involvement. Weekly meetings open to senior management (PPD risk tracking)	(Dec 2006 – June 2007) Minimal involvement (June 2007 – Project Completion) More Frequent involvement through stage gate reviews (Risks discussed during stage gate reviews)

also revealed that, due to these advancements, a local search strategy may not be effective to enhance the manufacturing of these miniature suspension assemblies. These insights were made available to the product leadership team (CTO, two senior VPs and a business unit manager), which was responsible for evaluating technology investment decisions at MicroTech. The PPD staff member also used this information during her monthly update of these scorecards along the dimensions of manufacturing and supply risks for suspension assemblies.

The updated PPD scorecard the project leader at Sigmatel used in the subsequent weeks indicated higher levels of overall risks (exceeding a score of 3), which triggered discussions among the project leaders, PPD staff member and product leadership team. The product leadership team was aware of these recent updates from the continuous planning forums, and all stakeholders agreed to stop improving the current designs and radically change the product and process designs. During our initial visits in 2006, Sigmatel's search strategy altered to distant from local search in response to this technological change. According to the CEO at MicroTech:

> When we were analyzing our roadmaps on this particular technology, we realized that the increase in development and manufacturing costs along with the future customer demands for Sigmatel can make our current manufacturing process redundant. We needed to find a totally new approach to make these suspension assembly components. This made us reevaluate our status quo [of using existing technology] which ended up in developing this new technology.

Following this shift, Sigmatel's resources expanded to include engineers with specific technical expertise in material science and chemical etching technology. The overall team size of the project increased to 70 FTE and the overall budget increased to $65 million. From this point on, Sigmatel was deemed a high-risk project, and correspondingly, the management approach immediately changed, as shown in Table 2. For instance, the project team began using the Define-Measure-Analyze-Design-Verify approach associated with a distant search strategy (instead of a six-step improvement approach associated with a local search strategy). They also used tools such as DFMEA (Design for Failure Mode Effects Analysis) and experimental design from this point; these promoted more experimentation and variation. This change also triggered an increase in the project's visibility as senior management began to closely monitor the project. Senior management (sometimes even the CEO) became a common sight at Sigmatel's weekly project meetings, resulting in faster communication across the strategic and project levels. The project team member of Sigmatel said this about the structure:

> We have a monthly review, with what we call the market direction team, a group of senior managers, directors, VPs and all the way up to our CEO. And, we put all our information together, process, equipment, manufacturing, long-range manufacturing plans, which are presented to them. We also have weekly meetings that are open to senior management; probably one or two show up every time. They go over the individual process steps or individual project with each engineer and typically go over concerns and questions on that.

In terms of project outcomes, Sigmatel was a major innovation that yielded a breakthrough for producing suspension assemblies, as evidenced by industry reports. Microsystems announced this innovation in its 2007 annual report. Microsystems' stock price increased following this announcement and shipments tripled between 2008 and 2011. Appendix C provides a detailed timeline of the project events. During our final interviews, we found that MicroTech began working with its customers on the development of suspension assemblies for their next-generation disk drive programs, which further corroborates this project's true success.

4.2. Tablet Project at CommNet

Similar to MicroTech's Sigmatel project, CommNet's Tablet project also experienced a project shift. Unlike MicroTech, CommNet's approach did not quickly identify and alter the project search strategy in response to a shift in complexity, which eventually resulted in a subpar and delayed product launch.

The Tablet project involved designing a rugged laptop for use in extreme temperature and pressure conditions, with firefighters and police personnel among target customers. Tablet shared many features with Nexus, an existing CommNet product, but required a wider screen size and a minor processor design change to withstand high temperature and air pressure. The project started in June 2006 as Nexus design refinement. Senior management believed that they had all the relevant technical expertise and knowledge required to improve the product design and associated process, thus it began using a local search strategy. The project, managed by one full-time project leader and eight team members, used in its initial stages the DMAIC approach and the tools listed in Table. In the beginning of the project, the R&D director and business unit manager met with the project team leader to develop the project scope in terms of resources required, project deliverables, and other requirements. These details were aligned with the business unit scorecards for that fiscal year and, once the scope of the project was defined, interaction with senior managers was minimal. While MicroTech used the PPD approach for all R&D projects, senior management at CommNet used different approaches to monitor projects depending on their search strategy. And while MicroTech universally tracked risks for all projects, CommNet did not do so for projects using a local search strategy (e.g., Tablet in its early stages). Even for projects using a distant search strategy, leaders assessed risks only after completing a particular stage-gate phase or project milestone, rather than weekly. For such projects, CommNet maintained four different types of scorecards members from different organizational levels (e.g., project team members, project leaders, R&D director) completed. This information was made available to the product leadership team (comprising of R&D Director and senior managers in charge of new product decisions). For projects using local search, CommNet maintained similar scorecards, but these were not readily available to the product leadership team. CommNet's scorecards were updated annually and were based on the results from their strategic planning forum; in contrast, MicroTech had monthly updates. Overall, CommNet's structured approach facilitated efficient information exchange across levels, and update frequency depended on the project's search strategy, an approach consistent with the extant literature (Hutchison-Krupat and Kavadias 2014, Wheelwright and Clark 1992). It proved also successful for monitoring projects such as Communicate and Third Party, which did not experience any shifts in complexity (based on post-project interviews).

In December 2006, our first interviews at CommNet about Tablet's progress revealed mixed emotions on project progress at both the strategic and project levels. The project was in its *measurement* phase when test results indicated that improved designs of the

Nexus-based architecture and processor were not robust enough to meet the new operating conditions required for the product (high temperature and pressure demanded by the customer). The cross-level scorecards revealed this to the R&D director, who then told the product leadership team, which notably did not have access to the scorecards. The project came to a halt because the product leadership team wanted the project team to conduct additional experiments before abandoning the existing design. The project team spent three additional months collecting supplementary data before presenting it to the business unit manager. They still, however, used the tools and method (e.g., DMAIC—Define, Measure, Analyze, Improve, Control) associated with the local search strategy and had limited resources for experimentation, even after the project shift. After a long delay and several meetings with the product leadership team, they agreed that refining the existing design based on the Nexus platform did not fit Tablet requirements. The project leader said the following about the process:

> There were lot of disconnects between the project team and senior leadership. This was not corrected during the course of our project. It was more like the senior managers defining what the critical success factors were and any disagreements were resolved through additional analysis that were then communicated back through the normal requirement process. Overall this resulted in some delays.

After another 3 months of delay in waiting for the product leadership team's approval, Tablet's project scope in June 2007 shifted to involve developing a component architecture and a processor radically different from the Nexus design. Senior management finally decided to alter the project's search strategy (from local search to distant) and, 6 months after the shift, began using the tools and method (e.g., DMADV—Define, Measure, Analyze, Design, Verify) related to distant search (see Table 2). CommNet selected a new supplier that specialized in this component architecture and processor and added new personnel to the project who had not only design and development skills but advanced degrees (PhDs). Overall project size grew to 25 members while the overall budget increased to $20 million. The project started using a stage-gate approach (X-gates), where senior management and the product leadership team met with the project team at the end of each stage-gate review. These reviews served as the only contact points between senior management and project teams, which delayed information exchanges. In October 2007, for instance, Tablet encountered additional delays in the verification stage due to vibration issues in the new design. Our conversations with the project leader after the project's completion revealed the team was unaware of the technology changes (e.g., material change for the processor technology) that happened externally. Hence, the project team spent time and effort gathering information on the newly available material as well as performing additional tests on this new technology. The R&D Director said the following about this communication delay:

> We did a very poor job in our communication during the last 3 years because look where we are right now. Previous senior leadership team just did not put much emphasis into a formal [communication] process. They wanted to more or less do it by themselves [during gate meetings] and so we are kind of in a retooling mode here.

After several months of delay, Tablet finally hit the market in May 2008.[4] Appendix D provides the detailed event timeline for the project. In terms of project performance, the product suffered from vibration issues when compared with the competitor's product. Business press reviews suggested the laptop's vibration issues affected its battery and processor performance. Reviews blamed the laptop's use of "*sub-par material technology*," which resulted in an inferior product when compared with the competition. The laptop was discontinued in 2009.

4.3. Cross-Case Comparison between MicroTech and CommNet

At the business-unit level, Sigmatel and Tablet show several similarities in terms of the processes used to manage R&D projects. For instance, both projects began as refinements to existing designs and technologies using a local search strategy. Both MicroTech and CommNet used formal processes such as PPD and cross-level scorecards to track projects. At the project level, both business units employed structured approaches (e.g., stage gates and improvement methods) and maintained different tools and processes for these projects. However, several differences emerged upon closer examination. In terms of project tracking, senior managers at MicroTech used the same universal PPD process to monitor projects and assess changes in risks. For instance, we noticed that Customer Defects, Tech Yield, and Tech Time projects involved minor modifications to existing product or process designs using local search, but the project leader still completed PPD scorecards to monitor risk on a weekly basis. The business unit had the same staff member who collected technological and market risk data from all R&D projects. Everyone in the organization was trained on this universal approach to assess risks. When asked about the needed training, a staff member remarked:

> We have a web-based training for PPD that is done to educate all our project leaders on the

> purpose of collecting these risks data. This was implemented in 2001. Before that, it was left to the project leader to fill in risk information that they think is applicable for their project. So that was not very helpful since they were all over the place. Now we have a better approach to gather this information.

In contrast, senior managers at CommNet utilized distinct approaches to track R&D projects depending on their search strategy. Although these projects coexisted, project leaders managed them differently and different personnel were charged with data collection and monitoring. Moreover, the product leadership team did not frequently review innovation projects that were refining existing technologies. Stage-gate reviews tracked project risks only for innovation projects such as Communicate—which were developing new product or process technologies. The same did not apply to innovation projects such as Third Party and Tablet (in its initial stages) that involved minor refinements to existing product or process designs. MicroTech and CommNet also showed major differences in how they communicated decisions between the strategic and project levels (i.e., between senior management and project team personnel). At MicroTech, structured communications took place weekly through the PPD scorecard updates for all R&D projects, while at CommNet, frequent updates were only tracked for projects developing new technologies, but not for projects with minor refinements to existing technologies.

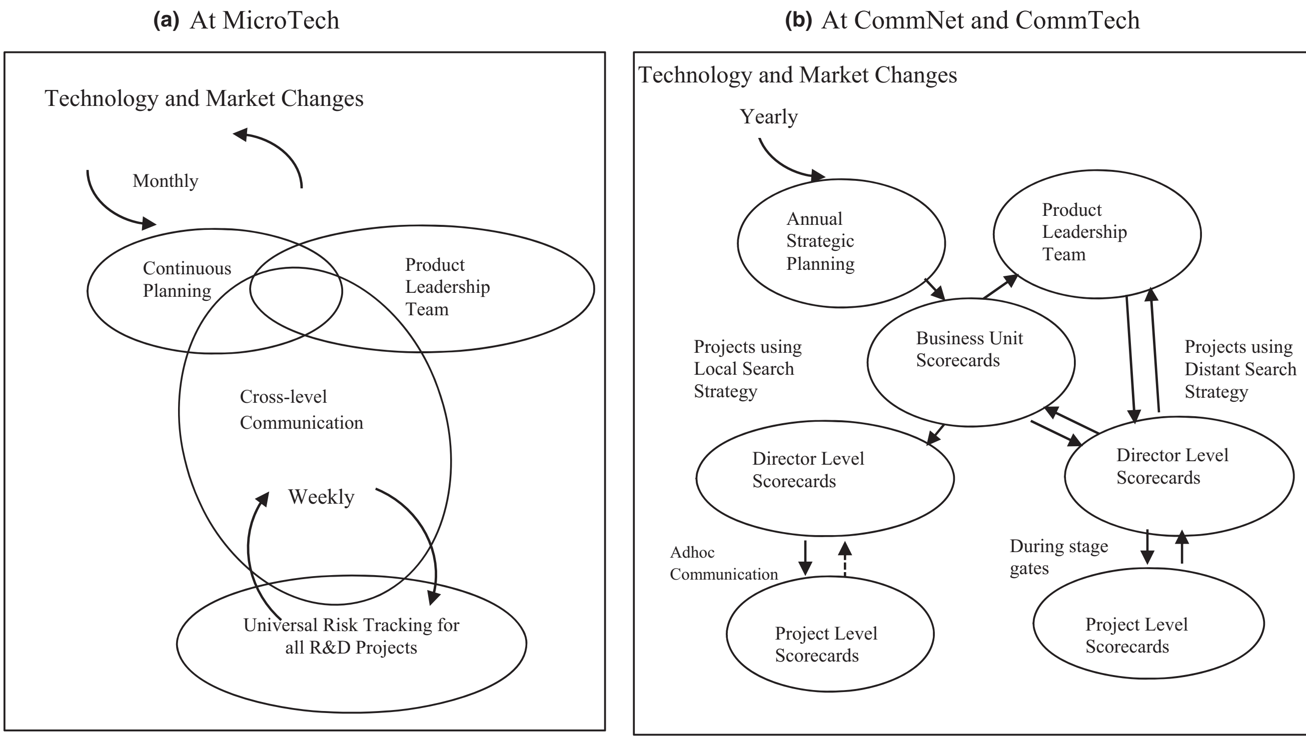
4.3.1. Inputs to PPD and Cross-Level Scorecards. To examine potential reasons for different project outcomes at MicroTech and CommNet, we further considered the inputs into the PPD and cross-level scorecards. MicroTech and CommNet had few differences in the inputs as it related to project search strategy. Both relied heavily on their planning forums for critical information. However, the cross-case comparisons show substantial differences in the way these units held their planning forums.

MicroTech had a continuous planning process with a full-time planning manager who constantly monitored changes in product, process, measurement, service, and supply chain technologies happening externally. This manager also was responsible for developing technology roadmaps that projected the evolution of MicroTech's key technologies. This planning manager worked closely with the PPD staff to determine technology and market risks associated with the roadmaps. The roadmaps themselves involved a sequential process starting with the product, followed by process, metrology, quality, and service roadmaps. The senior leadership team received all this information on a monthly basis. The business unit president told us that the continuous planning approach helped MicroTech reduce its planning horizon to 3 years from 10 years while most of MicroTech's competitors were still on a 10-year planning horizon. Monthly updates to product, process, metrology, quality, and service technologies provided real-time information to the PPD scorecards. When asked about this planning process, the business unit president said the following:

> We have decision processes that are pretty big, which helps us to adjust and readjust our focus. We have got a continuous planning process which happens throughout the year where we are stepping back and looking at our number of key players in the engineering side and the operation side and the metrology side, etc. And we keep revisiting, trying to understand where our marketplace is going: Where are new opportunities? What is happening with the requirements? What does all our market stuff imply for what we really have to do this year, next year, and for the next five, six, seven, 8 years? And so do we have the discipline in our house? So we try to keep an ongoing view of what is our interim issue and what is our long-term issue. And then what does that imply if we were to be a market leader in our business. And in some cases, this may cause us to use our existing capabilities. In other cases, we may have to develop capabilities and technologies that may be completely new, what we have got is enough representation along electrical engineering, chemical, mechanical engineering and metrology.

CommNet also used results from the planning forums as inputs to the cross-level scorecards. However, the strategic planning process at CommNet was an annual planning event and was not updated on a real-time basis. Strategic planning occurred at the beginning of the fiscal year and used information about current and future trends. This weeklong event focused on mapping the company's product and service trajectories based on customer and technological information. It involved various personnel from engineering, marketing, R&D, and senior leadership. The planning horizons at CommNet typically spanned 5–10 years, the industry standard. Results from these forums became inputs to the business unit scorecards to make resource allocation and funding decisions for different types of projects for that year. Unlike MicroTech, CommNet did not have full-time staff to constantly refresh its roadmaps on a monthly basis. Consequently, the scorecards' information about the technology landscape was not up-to-date, so project

Figure 3 (a & b): Managing R&D Project Shifts



team members as well as senior management were less knowledgeable about emerging technologies. In the case of Tablet project, this proved costly as team members were unaware of developments in material technology for the processor that could have resolved the vibration issues in the laptop. Instead, they spent valuable time and effort collecting and analyzing additional data around the existing configuration, which eventually led to losing the race to competitors.

Comparing these planning processes shows major differences in how MicroTech and CommNet identified project shifts and dealt with a shift in technology landscape. At MicroTech, the connection between PPD and continuous planning forums that occurred monthly helped the Sigmatel project obtain real-time information about a shift in the technology landscape. Project team members quickly identified that improving the existing technology using a local search strategy would not resolve the issues making suspension assemblies with the current process. In contrast, Tablet project team members lacked real-time updates about emerging processor technologies, which they said was a major factor in the delayed launch. Real-time updates from the continuous planning process at MicroTech also ensured that both senior management and project personnel were aware of relevant technological changes. As a result, quicker action (i.e., altering the project search strategy) could be taken when PPD scorecards indicated higher levels of risks, as in the case of Sigmatel. Given the absence of these updates at CommNet, senior managers and the project team failed to quickly react on the project shift, which resulted in extensive delays.

In addition, frequent (weekly) communication across different organizational levels at MicroTech facilitated by using the same PPD process for all R&D projects helped identify and manage changes in complexity for the Sigmatel project. In contrast, CommNet used separate scorecards for projects based on search strategy, which failed to identify changes to project complexity for Tablet. Figures 3a and b summarize the processes at MicroTech and CommNet.

4.4. Comparing Findings with Current Literature

We also iterated between the case data and extant literature, which helped both illuminate and contrast our findings with existing theories. Findings from the CommNet case were consistent with existing theories on how to manage different types of R&D projects. For instance, CommNet had an annual strategic planning process that senior managers from various backgrounds (e.g., technology, operations, marketing, etc.) attended to gather technology and market information. CommNet's approach to conducting annual strategic planning forums is generally consistent with the literature (e.g., Hamel 1996). Researchers have attributed variations in the length of planning cycles (annual vs. shorter) to the amount of resources required for this planning process (Grant 2003). The information from strategic planning forums was used when deciding on portfolio project mix for the fiscal year, which is also consistent with the literature (Chao and Kavadias 2008). Senior management at CommNet tracked progress in their innovation projects using different scorecards. For instance, senior management at CommNet closely monitored innovation activities using distant search strategies with frequent "information exchanges" between strategic and project-level members at the end of each stage gate (Andriopoulos and Lewis 2009). They promoted more experimentation and risk-taking behaviors for these project teams to create new knowledge. Similarly, the project management adopted a local search strategy and became more decentralized with little senior management involvement once projects in these units were classified as refinements to existing technologies based on their annual strategic plans. Senior leadership did not encourage experimentation and learned of changes on a "need-to-know" basis. In general, the mechanisms employed at CommTech to manage R&D projects (as seen in Figure 3b) are consistent with the existing literature. However, such an approach failed to identify and to effectively manage shifts in project complexity.

On the other hand, findings from the MicroTech case were inconsistent with existing project-management theories. It is this inconsistency, however, that offers novel insights on how high-tech business units can effectively identify and manage project shifts. The cross-case analyses identify three distinct mechanisms MicroTech used (absent at CommNet) that enabled team members to identify changes to Sigmatel's project complexity and appropriately alter search strategy. We refer to these mechanisms as "enablers of responsive search." Specifically, they include: a universal metric for evaluating project risk across all types of R&D projects, a weekly cross-level communication process, and a process for monitoring ongoing changes in the external environment (See Table 3). These mechanisms were at multiple levels within MicroTech. They were interconnected and enabled responsive search, that is, the project quickly altered between local and distant search. In what follows, we describe the three interacting mechanisms.

(i) Universal Project Risk Evaluation Metric. At MicroTech, senior managers used the same mechanism to continuously assess risks for all R&D projects. This allowed MicroTech to identify exogenous changes in project complexity and risks. It further allowed MicroTech to alter their project search strategy. This finding does not align well with current theories on product development (Wheelwright and Clark 1992). That is, studies suggest using different risk-tracking processes for R&D projects based on their search

Table 3 Project Comparisons

	Sigmatel (MicroTech)	Vision Plus (MicroTech)	Video Share (CommTech)	Communicate (CommNet)	Tablet (CommNet)	Tech Yield (MicroTech)	Tech Time (MicroTech)	Customer Defects (MicroTech)	Third-Party (CommNet)	Cost-Reduction (CommTech)	Drive Innovation* (MicroTech)	Tech Z* (CommTech)
Project Shift?	Yes	No	No	No	Yes	No	No	No	No	No	Yes	Yes
Planning Process	Continuous (monthly updates)	Continuous (monthly updates)	Annual (yearly updates)	Annual (yearly updates)	Annual (yearly updates)	Continuous (monthly updates)	Continuous (monthly updates)	Annual (yearly updates)	Annual (yearly updates)	Annual (yearly updates)	Continuous (monthly updates)	Annual (yearly updates)
Cross-Level Communication	PPD Process (weekly)	PPD Process (weekly)	Innovation Scorecards (during stage gates)	Innovation Scorecards (during stage gates)	Innovation Scorecards (during stage gates)	PPD Process (weekly)	PPD Process (weekly)	PPD Process (weekly)	Adhoc	Adhoc	PPD Process (weekly)	Innovation Scorecards (during stage gates)
Universal Risk Tracking	Done every week	Done every week	Done during stage gates	Done during stage gates	Not Done	Done every week	Done every week	Not Done	Not Done	Not Done	Done every week	Done during stage gates
Performance on managing project shift	Successfully managed shifts	NA	NA	NA	Failed to identify and manage shifts	NA	NA	NA	NA	NA	Successfully managed shifts	Failed to identify and manage shifts

*Sampled after analyzing the cases.

strategies (a more frequent risk-tracking approach for projects using a distant search strategy, and a less frequent and *ad-hoc* approach for projects using local search strategy) (Cooper et al. 2002). Had MicroTech followed this conventional approach, however, it would have taken much more time and effort to shift Sigmatel from local search to improve existing component design (one that could not have withstood product miniaturization) to a distant search of radically innovating a new component design (one that could).

(ii) Weekly Cross-Level Communication Process. MicroTech used the same project tracking approach (e.g., PPD) for communicating between strategic and project levels on a weekly basis. It promoted frequent interactions between senior leadership (e.g., CTO/Senior VPs) and the project teams. The effectiveness of this weekly cross-level communication process challenges existing coordination theories (e.g., Rousseau 1985, Sinha and Van de Ven 2005), which recommend against frequent cross-level interactions due to an increase in workload. Instead, MicroTech's weekly cross-level communication mechanism was fairly simple and involved continuous monitoring of changes in project risks. This approach had dual benefits to both project teams and senior leaders. It promoted both top-down and bottom-up information exchanges without substantial coordination costs (once implemented). For project teams, this communication mechanism also provided weekly updates from continuous planning, creating more awareness of technology and market changes. For senior leaders, this mechanism quickly communicated changes in project complexity, which helped them rapidly adjust strategic level goals.

(iii) Continuous planning process. MicroTech used a continuous planning process that involved gathering real-time updates on technology and market changes every month through the use of a full-time planning staff member. This is in contrast to the literature that describes strategic planning as "a calendar-driven ritual...which assumes that the future is more like the present" (Hamel 1996). The PPD scorecards provided updates from the continuous planning process to the project team members, who used it as a critical input for the risk assessments in the scorecards. Having real-time changes to the risk metrics meant senior managers could revisit the decisions on R&D opportunities even after they made the decisions. The presence of this continuous planning process also differs from current theories that advocate calendar-driven decision making with planning horizons of 5–10 years (Barczak et al. 2009). Rather, the continuous planning shortened the planning horizons to 2–3 years, and senior managers' roles changed from reviewing and approving to debating and deciding on decision alternatives.

Taken together, the three interconnected mechanisms enabled responsive search at MicroTech (seen in Figure 3a). That is, they allowed MicroTech to respond to landscape shifts by altering Sigmatel project's search strategy to distant search from local search. However, strategic-level interviews with MicroTech suggested the enablers of responsive search incurred setup costs. For instance, the business unit president revealed that developing PPD scorecards was an onerous task that required assessing the technological and market risks associated with the product and processes developed in the business unit. In fact, MicroTech's senior management team spent 6 months developing the risk scorecards. In addition, MicroTech needed to train all project leaders on the importance of evaluating project risks on a weekly basis and hired a full-time planning specialist to constantly monitor changes in product, process and technology roadmaps. This resulted in substantial initial investments. According to the president at MicroTech:

> The protocol writing [for our PPD] and the criterion requirements really took us more than 6 months. And this is because, once we designed the initial protocol, we have got everybody to approve it, everybody had changes and we went a few rounds that way. There was quite a bit of work in getting that piece in place.

In spite of the significant implementation cost and the extensive involvement of several personnel (e.g., project leaders, product leadership team, continuous planning staff, PPD staff, etc.), our findings suggest that once implemented, these enablers of responsive search (i.e., all three mechanisms) did not incur substantial additional operating costs. Moreover, these mechanisms were well integrated into their regular responsibilities, thus did not impose additional operating constraints. For instance, the project leader's risk scorecard completion took little time and became a part of the weekly routine. One project leader commented that it was as simple as "*completing a survey regarding the project status*" every week. Toward the end of the project, the risk levels were known and they could stop monitoring the risks. The PPD staff member noted that once a project has completed its manufacturing verification review it no longer required the PPD approach. Overall, the individual responsibilities of project leaders, PPD staff and senior leaders seemed less onerous given the overall task of identifying and managing project shifts. To conclude, the following propositions summarize our findings on the enablers of responsive search and their effectiveness in identifying and managing project shifts.

PROPOSITION 1A. *The combined use of continuous planning, universal risk tracking and weekly cross-level communication enables responsive search.*

PROPOSITION 1B. *Responsive search is positively associated with project performance in environments prone to project shifts.*

4.5. Robustness Checks for case analyses

We conducted several robustness checks to strengthen the findings from the case analyses. First, eight projects in the case study (see Table 3) did not experience any project shifts. This may raise concerns about the frequency of project shifts in these settings. To address these concerns, we revisited our data to examine whether there were any other instances of project shift. Experts from our interviews suggested that two projects, *Drive Innovation* (low complexity to high complexity) from MicroTech and *Tech Z* (high complexity to low complexity) from CommTech, also experienced project shifts. Appendix E gives the details of these projects. More importantly, and consistent with the findings, the responsive search enablers at MicroTech helped identify and alter the search strategy (to local search from distant search) for Drive Innovation, while the Tech Z project experienced significant delays due to the absence of these enablers at CommTech. Tech Z continued to search for new technologies when the customer and market-trend changes required it to use pre-existing solutions available to CommTech. Eventually, CommTech lost significant market share on this technology to its competition.

Second, the case analyses revealed that project complexity changed due to exogenous factors (e.g., customer preferences, technology changes). To rule out any internal project causes, we reanalyzed the data to examine whether any factors in the control of project teams (e.g., project personnel turnover, incentives, and poor management) created these shifts. For instance, one might argue that Sigmatel could have lost key personnel. Our analyses revealed no significant differences among these factors between projects that shifted and those that did not, minimizing such concerns. For example, turnover rates for the Sigmatel project were comparable to that of Vision Plus projects.

Finally, CommNet and CommTech had a few projects that were not completed during our visits but we were able to collect follow-up information. For instance, Video Share and Third Party did not experience any project shifts and concluded successfully at CommTech and CommNet using distant search and local search strategies, respectively. This further minimizes concerns that the Tablet and Tech Z failures were due to CommNet and CommTech's inability to manage R&D projects.

5. Simulation Study: Theory Refinement and Augmentation

Although case studies help gain rich insights on responsive search and its enablers, this approach does not allow us to disentangle the benefits of responsive search from other organization effects at MicroTech. Moreover, all three business units in our cases come from industries with high technological turbulence (i.e., a high likelihood that the level of complexity changes) and time-to-market pressures. Our case approach therefore does not let us assess how varying industry level conditions affect the performance of responsive search.

To address these limitations, we built an agent-based simulation model that captures the rich and non-linear dynamics of complexity shifts in the case study projects. Specifically, we use organizational fitness landscapes to investigate different search strategies, as proposed by Levinthal (1997). This canonical approach adopts Kauffman's (1993) NK model to represent the project's technological performance landscape. The NK model has been widely used and is well suited to capture a project's search strategy on performance landscape (e.g., Kavadias and Sommer 2009, Rivkin and Siggelkow 2003, Siggelkow and Rivkin 2005). Results from the model can help augment the propositions developed from the case studies. That is, the simulations allow us to compare the performance benefits from responsive search found at MicroTech (Figure 3a) to other canonical search strategies in R&D projects. Furthermore, the simulations can help assess how much the speed of sensing and responding to landscape shifts contribute to project performance. We now describe the key model ingredients.

Project Landscapes. In the NK model of a technology landscape, a number of N specifications define the project's current technological configuration, that is, the project's coordinates in the landscape. For instance, in the case of CommNet's Tablet project, specifications for the processor, screen size and other features reflect the technological configuration. Formally, the project configuration is given by a specification vector $\mathbf{s} = (s_1, \ldots, s_i, \ldots, s_N)$, where, for simplicity, each specification s_i is either 0 or 1. The entire landscape, therefore, consists of 2^N potential project configurations. A performance function $\Pi(\mathbf{s})$ maps the N-dimensional project configuration onto a one-dimensional performance measure (a project's current performance on the landscape). By definition, the landscapes of innovation projects differ based on their levels of complexity, with less complex projects having a "smooth" landscape (hence easier to search) and more complex projects having a "rugged" landscape (hence more difficult to search) (Miller and Page 2007). Whether they appear smooth or rugged depends on complexity parameter K. That is, environments of projects such as Tech Yield, Tech Time, Cost Reduction, etc., can be represented by smooth landscapes as project specifications are relatively independent due to low complexity, while projects such as Vision Plus and Communicate have rugged landscapes. Here, specifications have dense interactions. To capture different landscape structures, let π_i denote the performance contribution of variable s_i. Project landscapes appear (more or less) rugged because π_i depends not only on the specification s_i but also on the value of K other specifications; denoted by the vector $\mathbf{s}_{-i} = (s_{i1}, \ldots, s_{iK})$. For every possible combination of $(s_{i1}, \ldots, s_{iK})$, a random draw from a standardized uniform distribution determines the performance contribution $\pi_i(s_i, \mathbf{s}_{-i})$ of the interactions. The overall project performance is the average of all variables' contributions. Formally, we define project performance as

$$\Pi(\mathbf{s}) = \sum_{i=1}^{N} \frac{\pi_i(s_i, \mathbf{s}_{-i})}{N};$$

This function defines the one-dimensional performance for all project configurations on the landscape.

Modeling Shifts in the Project Landscapes. The project landscapes that we consider are prone to exogenous landscape shifts, triggered by technological turbulence, as evidenced by the case studies. Parameter τ represents the probability that the complexity of a landscape shifts in any given period t of the project's search process. That is, τ represents the technological turbulence experienced in these settings. A landscape shift affects $\Pi(\mathbf{s})$ due to changes in landscape complexity or ruggedness. A landscape's ruggedness shifts from $K = K_l$ to $K = K_h$, or *vice versa* from $K = K_h$ to $K = K_l$, where $K_l < K_h$, and where a landscape's initial K is drawn from these two parameters by nature with equal probabilities. A more rugged landscape (as represented by K_h) may emerge when newly identified technologies feature more involved interactions between project decision variables. Such a project shift is exemplified by the advent of a groundbreaking technological change in CommNet's Tablet project, which led to the emergence of a more rugged technology landscape that required distant search. In contrast, a less rugged landscape (as represented by K_l) may appear when initially novel and complex technologies standardize during the course of the project. For instance, dominant designs have appeared that feature well-defined interfaces, which the project can easily adopt into its R&D program. In our case study, the Tech Z project from CommTech experienced such a shift (see Appendix E). This project started out on a complex landscape requiring distant search strategy, but the landscape leveled out in the course of the project, as technologies required were readily available from CommTech's development teams in Europe. Once such a landscape shift has occurred, new values are assigned to $\pi_i(s_i, \mathbf{s}_{-i})$—based on a random draw from a standardized uniform distribution. This renewed valuation corresponds to an updated body of technology information in our project cases. An exogenous landscape shift gives rise to a period-specific landscape structure, which is embodied in and formalized by the period-specific performance function $\Pi^{(t)}$.

Project R&D Search Strategies. We modeled four different strategies to represent a project's R&D search. Three of these were found in our study, while the fourth is well established in the organizational learning literature. A description of the search mechanisms follows.

1. *Local search strategy*—In this strategy, the project only searches locally to improve existing technology. In every period, it iteratively picks a single variable s_i, evaluates whether changing its specifications (from 0 to 1, or *vice versa*) improves project performance $\Pi^{(t)}(\mathbf{s})$, and then updates the project configuration. CommNet's Tablet project initially used local search.
2. *Distant search strategy*—In this strategy, the project only uses distant search to look for new technological possibilities. This approach takes "long jumps" every period, generating a set of new specification vectors $\mathbf{s}$ whose N variables were simultaneously altered to arrive at random position on the landscape. It then evaluates this position and adopts it if the new configuration enhances performance. CommTech's Video Sharing project followed this type of mechanism.
3. *Responsive search strategy*—In this strategy, the project searches distantly if the landscape has recently (i.e., in the last period) changed to a more rugged appearance (from K_l to K_h), but it otherwise searches locally. That is, this approach alters the project's search strategy whenever there is an exogenous landscape shift. It precisely captures the responsive search of MicroTech's Sigmatel project, enabled by weekly communication across levels, universal risk-evaluation metrics and continuous planning process. It does not include any other

organizational characteristic such as good leadership, resource slack, etc., and hence helps isolate the benefits from responsive search observed in the case study.

4. *Ambidextrous search strategy*—This strategy was not observed in the cases, but is well known in the organizational learning literature (Gibson and Birkinshaw 2004). In this approach, the project conducts local search or distant search with equal chance to enhance project performance, irrespective of landscape shifts.

The project outcomes of these search strategies are evaluated for different time-to-market pressures as follows. The project's R&D search terminates after T periods (rounds of search on the landscape), and the project's performance is evaluated and returned as $\Pi^{(T)}(\mathbf{s})$. Hence, the parameter T represents the time available for search, or a project's time-to-market pressure.

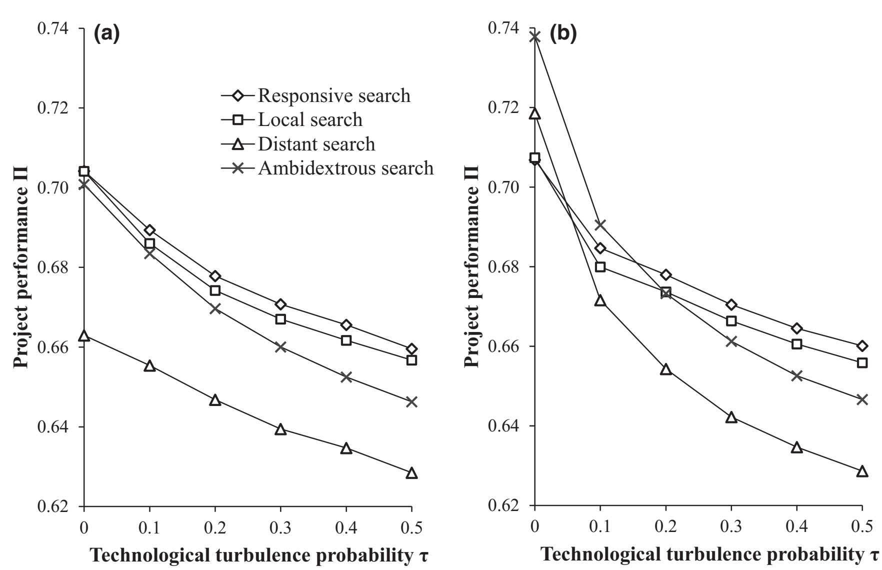
5.1. Comparing R&D Search Strategies under Project Shifts

To better understand the performance benefits of responsive search, we compare it to the three other search strategies under different levels of technological turbulence and time-to-market pressures. We report the findings for $N = 12$, $K_l = 3$ and $K_h = 9$. This parameterization captures a landscape with a sufficiently large but computationally feasible number of specifications with low and high levels of landscape ruggedness (Sting et al. 2011). Beyond varying N, K_h, and K_l for robustness, we systematically varied the technological turbulence parameter τ and the time-to-market parameter T as contingency factors in the analysis. Because random fluctuations occur in the NK model simulations, we conducted 10,000 replications for every scenario of contingencies.

Figure 4a and b show project performance (depicted on the y-axes) as a function of technological turbulence (depicted on the x-axes) for high (Figure 4a) and low (Figure 4b) time-to-market pressure. For all search strategies (represented by the various curves), project performance decreases with landscape turbulence. Intuitively, projects should be able to perform better in less turbulent environments, hence we must interpret the relative positions of the curves as they indicate the relative advantages (or disadvantages) of the various project search strategies. Under high time-to-market pressure (Figure 4a), the responsive search outperforms all other search strategies for all positive degrees of technological turbulence.

The responsive search allows the project to effectively use resources by dynamically altering search when the technology landscape shifts. The project balances the benefits of distant search by altering to distant search when the landscape shifts. But under low time-to-market pressure (Figure 4b), the benefits of responsive search weaken. The responsive search works best only when there is a high probability that the landscape shifts. Otherwise, the ambidextrous search outperforms all other search strategies because the combined use of local and distant search is more effective when the project faces lower time-pressure and the landscape is relatively stable. Overall, these results offer support to Proposition 1b on the benefits of responsive search over

Figure 4 (a & b): Project Performances for High (T = 5, left panel) and Low Time-to-Market Pressure (T = 45, right panel)



other search strategies (including ambidextrous search, not observed in our cases) under high technological turbulence and high time-to-market pressures. In addition, it also helps identify the boundary conditions of the responsive search by elucidating contingency factors that influence the relative benefits of the responsive search mechanism, as indicated in the following proposition:

PROPOSITION 2. *The performance of responsive search is contingent on technological turbulence and time-to-market pressure, that is, responsive search is beneficial for projects under high technological turbulence or high time-to-market pressure. Its performance advantage decreases when both technological turbulence and time-to-market pressure are low.*

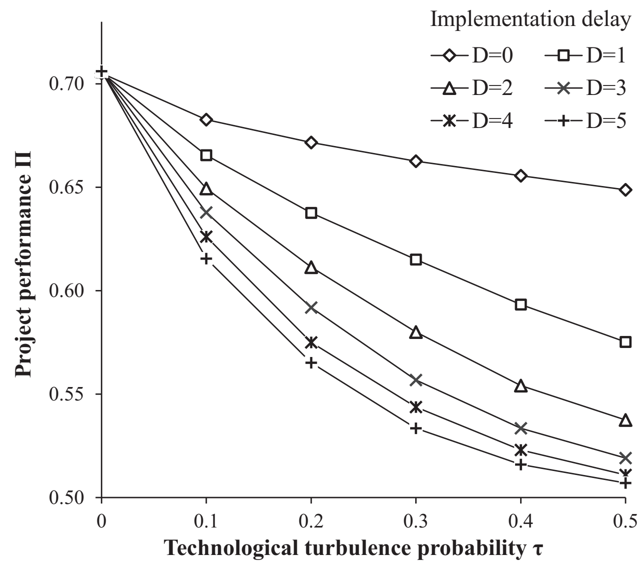
5.2. Examining the Value of Sensing and Responding to Project Shifts

The previous analysis shows that responsive search has the most benefits in environments with high technological turbulence and high time-to-market pressure. The case analysis and Proposition 1a suggest that the three interconnected mechanisms (i.e., continuous planning, universal risk tracking and weekly cross-level communication) enabled responsive search at MicroTech. In this simulation experiment, we examine the extent to which the presence of all three mechanisms contributes to responsive search. We examine this issue by incorporating delays (D) for detecting and responding to landscape shifts and direct its search on the new landscape. This part of the simulation helps augment Proposition 1a on the benefits of responsive search enablers without interference of any other effect at MicroTech. The absence of any of these mechanisms might delay the response to landscape shifts.

Under high responsiveness (delay $D = 0$ time periods, the default reported in Figure 4a and b), a project immediately can sense landscape shifts and adjust its search strategy to the new landscape (responsive search without any delay). Under lower responsiveness, the project will alter its search strategy only after a delay ($D = 1$ or more time periods). Before this delay has elapsed, the project cannot alter its search strategy and continues to evaluate technology configurations as if it were still on the outdated landscape from period t to D. Hence, a lagged project formally adjusts its R&D activities toward the (outdated) landscape performance objective $\Pi^{(\max\{t-D,0\})}$ in every period t.

Figure 5 shows the relative benefits of altering the projects search strategy under varying levels of technological turbulence. First, and most strikingly, we observe that an additional delay period causes the largest difference in performance between a project with a zero time lag ($D = 0$) and a project with a time lag of only one period ($D = 1$). This corroborates the value of responding *immediately* to landscape shifts, and underscores the importance of having all three enablers of responsive search (as evidenced in Proposition 1a). Second, the value of sensing and rapidly responding to a landscape shift is highest when the likelihood for such shifts τ is high. This can be seen by the fact that a project with a timely response is much less affected by additional technological turbulence than a project whose response is lagged. Figure 5 shows the situation where the project faces high time-to-market pressure ($T = 5$), but the results consistently hold under low time-to-market pressure ($T = 25$ and 45). Overall, this result illuminates the importance of implementing all three enabling mechanisms to ensure a timely response.

Figure 5 Project Performances under Varied Responsiveness to Landscape Shifts for High Time to Market Pressure ($T = 5$)



To summarize, the simulation experiments enhance the external validity of our case findings by corroborating the benefits of managing project shifts via responsive search. They also illuminate the boundary conditions of responsive search and show that it is contingent on the level of technological turbulence and time-to-market pressure. In addition, results show that the responsive search has increasing benefits when it can more quickly respond to exogenous changes (approaches $D = 0$).

We also conducted the following additional analyses to ensure robustness of our simulation results. First, we examined the effect of larger project sizes by varying N from 12 to 24. Second, we analyzed how higher levels of project complexity affect the results by setting $K_l = 6$ and $K_h = 12$. Third, we examined the effect of increased resource availabilities by doubling the number of search steps that a project can perform per period. Our results remained stable under all of these variations. (To enhance replicability of our results, we offer a pseudo-code of our simulation model in the Appendix F).

6. Conclusions

6.1. Implications for Theory and Practice

Although research has considered how to manage innovation projects with different search strategies (Hayes et al. 2005, Sommer and Loch 2004, Wheelwright and Clark 1992), it has not examined the operational realities that firms face when an exogenous change in technology occurs. Projects that started out using a local search strategy may need to make a midcourse correction and shift to a distant search strategy due to exogenous changes in the project's level of complexity. This study suggests that the ability to identify and manage such project shifts by altering their search strategy affects project outcomes. Prior research has examined either project selection decisions (Loch and Kavadias 2002, Sommer and Loch 2004, Wheelwright and Clark 1992) or project execution decisions (Carrillo and Gaimon 2004, Swink et al. 2006), while intermediate decisions on altering a project's fundamental search strategy have received scant attention. Supporting this view, Hayes et al. (2005) note that "*top managers often fundamentally misunderstand what is required to manage [an innovation] project funnel. Many confine their involvement to either reviewing project concepts and selecting specific projects (front end of the funnel) or managing the resulting product's production ramp-up and market roll-out (back end of the funnel)…. However, they tend to avoid the tough but essential decisions regarding whether to stop [or alter already ongoing] projects (pp. 232–233).*" Our study contributes to this gap by unearthing the benefits of sensing and responding to technological changes and then altering the project's fundamental direction (the middle part of the innovation funnel). Enabled by tracking technological risks, responsive search offers one approach by adjusting project search accordingly. Traditional approaches to manage R&D projects do not dynamically sense and respond to exogenous technological changes. Projects are not cast in stone once launched, but often need to be adjusted and reoriented after they have been launched. Our findings therefore contribute to the emerging literature on project management that deals with mid-project termination or correction decisions (Chan et al. 2007).

Second, by taking a multilevel view, our study helps explain how high-tech organizations solve the "innovation to organizations" problem of connecting R&D decisions across strategy and operations (Dougherty and Hardy 1996, Hutchison-Krupat and Kavadias 2014). To date, research has taken a piecemeal (either strategic or operational) approach that often has failed to recognize the cross-level connections and interdependencies. Even the limited number of studies that adopt a multilevel approach (e.g., Andriopoulos and Lewis 2009, Dougherty and Hardy 1996) often suggest an organization-level top-down approach, developing an R&D strategy and executing it employing projects with appropriate search strategies (Jansen et al. 2009). In contrast, our study shows that project-level changes in risks can (and will) affect strategic technology decisions at the organizational level in a bottom-up fashion. The responsive search that emerges in this study creates reinforcing feedback loops between project execution and strategic project selection. This finding thus contributes to the emerging literature in NPD that argues how operational-level (i.e., project-level) decisions affect the overall strategic decisions senior managers make (Hutchison-Krupat and Kavadias 2014).

Third, our findings also contribute to the growing research on how to manage different types of R&D projects. For instance, the majority of research on this topic focuses on a static conceptualization of R&D projects (e.g., Wheelwright and Clark 1992, Chandrasekaran et al. 2014, Chao and Kavadias 2008). That is, they do not account for changes in project complexity during its course. Although some studies in this stream take a more dynamic approach to manage R&D (Lavie and Rosenkopf 2006, 2011, Nickerson and Zenger 2002, Siggelkow and Levinthal 2003), they are mostly at the organizational level of analysis and do not explain how to alter project search strategies when the technology landscapes shift at the organizational or project level. Results from our study contribute to this stream by showing that high-tech R&D units can effectively manage project shifts by facilitating responsive search through three interconnected enabling mechanisms, namely: universal risk sharing, continuous planning and cross-level communication for all R&D projects. Although these mechanisms may seem ordinary in isolation, their interconnections enable responsive search—to alter a project's search strategy to distant search from local. Our simulation experiments incorporate delays in responding to project shifts to illuminate how the absence of any one of these enablers could negatively impact project performance.

Finally, the above contributions would not have been possible without taking a multi-method research approach. The case study discovered the mechanism that enabled organizations to identify project shifts. The agent-based simulation helped disentangle the benefits of the responsive search from other organizational effects. It also helped identify contingencies and boundary conditions for which the responsive search outperforms other search strategies. Using multiple methods, therefore, allowed us to unearth multifaceted insights on such a complex phenomenon as project shift.

This study has important implications for both senior managers (e.g., R&D directors) and project leaders. Successfully managing R&D projects in high-tech environments may require monitoring and altering the project's search strategy. Doing this necessitate investments in several interconnected mechanisms across different levels in the organization, which may incur start-up and training costs. For instance, the case study found that mechanisms to continuously monitor and update changes in product, process, measurement, service and supply chain technologies may require additional personnel in the planning department. Similarly, having project leaders periodically assess changes in project risks may require additional training, support structures (e.g., PPD scorecards) and resources (time from senior managers). Consequently, developing and implementing the responsive search mechanism described in this study comes at some initial costs. Nevertheless, evidence from our study suggests that the additional cost can pay off, especially in high-tech organizations. The case findings suggest that when these processes are tightly integrated and institutionalized, the additional administrative burden may not be too heavy. As summarized by the President of MicroTech, "*the biggest challenge is laying the foundation for all these processes. Once established, it was like clockwork and everybody in the organization knew what to look out for*." Our study identifies several practices for managers that allow them to better sense and respond to exogenous technology and market changes in these environments.

6.2. Limitations and Future Research

Several limitations of this research should be recognized. First, some of the projects started before our data collection, which might lead to retrospective bias concerns. This is especially true for Drive Innovation and Tech Z, as we did not conduct any project team member interviews. However, we followed several strategies to minimize retrospective bias, such as selecting the key informants, using multiple informants, asking about "concrete facts," maintaining informant confidentiality, and validating retrospective facts using secondary sources of data such as project team meeting minutes and newsletters (Golden 1992). Second, we limited our research to understand project shifts that emerged inductively from our case analyses. This is not the only form of project shift; projects obviously can change course due to other factors such as scope creep, team turnover and budget issues. Although we did not observe these in our cases, we do recognize them as a potential explanation for project-shifting behaviors. We also recognize that projects may not always pursue local or distant search strategies. Hybrid projects (see Chandrasekaran et al. 2015), for instance, may require a combination of local and distant search strategies. While this combined approach is also interesting, we note that it is outside the scope of our research, which is focused on identifying and managing project shifts.

This study leads to several new research questions. First, the responsive search, with its three enabling mechanisms that emerged from our qualitative inductive case study, offer one approach to deal with project shifts. Other effective approaches to identify and manage project shifts may very well exist. This may require additional in-depth case studies (similar to the one presented in this study) in other high-tech R&D units. We also developed three testable propositions, two based on the responsive search identified in our study and one augmented using agent based simulations on NK model. Future research could incorporate these findings and develop empirically testable hypotheses that can be validated through large-scale studies. We hope our findings will promote an expanded and more dynamic view on the phenomenon of project shifts in other contexts employing both granular and large-scale theoretical lenses.

Acknowledgments

The authors thank the three anonymous reviewers, Professor Jason Choi for their valuable feedback on the paper. They also thank Professors Jaideep Anand, Daniel Levinthal and Roger Schroeder for the feedback on earlier versions of the manuscript. Finally, they thank Professor Murat Tarakci for his help with the landscape figures. All errors and omissions remain the responsibility of the authors.

Appendix A: Description of the Research Sites

Business Unit	MicroTech	CommTech	CommNet
Research Setting	Four plants within the United States	Corporate headquarters and pilot plants within the United States	Corporate headquarters and pilot plants within the United States
Annual Revenues (millions)	$950	$30,000	$10,000
Size (No. of Employees)	6000	40,000	10,000
Age	40 years	80 years	60 years
Primary customers	OEM (Other Equipment Manufacturer)	General public	Governmental and educational institutions
Strategic Level Informants (CEO, CTO, VP)	8	5	3
Number of Projects	6 (retrospective data from 1 project)	3 (retrospective data from 1 project)	3
Project Interviews (Leader + Team Members)	12	8	5
Project Informants (Includes Team Leader and Team Members)	48	23	17
Data Collected	• Recorded interviews • Annual Reports • Review of company, business unit and project documents • Training documents • Banquet Videos	• Recorded Interviews • Annual Reports • Supplementary books on product development approaches • Portfolio Action Committee documents	• Recorded Interviews • Annual Reports • Supplementary books and procedures • Portfolio Action Committee documents

Appendix B: Description of Projects

Project Name	Business Unit	Dimensions	Time Span	Budget	Project Size	Outcome
Sigmatel - New Process tech for manufacturing new electronic components	MicroTech	Product and Process	2004–2008	$65 million	70 people	Success (15% cost reduction in next 5 years)
Vision Plus - Vision Technology to eliminate manual inspection	MicroTech	Product and Process	1998–2006	$40 million	20 people	Success after some preliminary delays
Tech Yield - Improvement of 20% yield in the current process	MicroTech	Process	2005–2007	$7.5 million	20 people	Success
Tech Time - 30% reduction in direct labor by improving the current production process	MicroTech	Product and Process	2003–2009*	$10 million	30 people	Team Issues
Customer Defects - Reducing defect rates by improving the existing product/process designs	MicroTech	Product and Process	2007–2009	$12 million	25 people	Success
Drive Innovation† - Developing a new drive design to improve reading capability	MicroTech	Product	2004–2006	$12 million	30 people	Successful in terms of quality and speed to market
Video Share - Video Sharing through digital signals	CommTech	Product and Process	2004–2009*	$50 million	25 people	Success
Tech Z† - Developing next generation communication technology	CommTech	Product	2005–2007	$10 million	25 People	Management went with Tech W which was not consistent with the industry
Cost Reduction - Reducing the warranty costs through robust design of the new products catered	CommTech	Product	2005–2008	$1.5 million	15 people	Delay
Third-Party - Optimizing the third party component design	CommNet	Process	2005–2009*	$15 million	30 people	Success
Communicate - Development of a new way of communication	CommNet	Process and Product	2006–2008	$45 million	125 people	Success after some preliminary delays
Tablet - Development of a robust computer for usage in extreme conditions	CommNet	Product and Process	2006–2008	$20 million	25 people	Product launched after delays, Stopped Production in 2009

*Projects were not complete at the end our study. We were able to get updates on these projects through email correspondence.
†Projects sampled later in the study.

Appendix C: Event Timeline for Sigmatel Project

Timeline	Events	Description of events	Source/informants
November 2004	Sigmatel project begins	Sigmatel project begins. Idea is to make suspension assemblies using a different raw material composition for better electrical conduction, mechanical control that can allow future miniaturization (Initial Budget: $10 million) Mostly routine changes by refining existing assembling process. Hard deadlines to launch this new production approach in a year 1 Project lead (fulltime) + 8 part-time members working across other projects	Separate interview notes from Project Leader, Team Members and Senior Executives
January 2006	Continuous planning forums Mapping product and process maps	Results from the continuous planning forums indicate that the size of suspension assembly is constantly decreasing and cannot be made using current material technologies This information is communicated to the Product Leadership Team (PLT) members and the members of PPD PPD scorecards are adjusted for these changes	Planning Reports, Planning Personnel, VP R&D and CTO
February 2006	Sigmatel risks changed in PPD scorecard	Project leader when evaluating Sigmatel based on updated PPD finds that the project scored over 3. Triggers conversations among PLT, project team and Senior Management	Project Leader and Project Presentation Reports
March 2006	Change in Sigmatel's search strategy	Everyone is convinced that refining current process technology does not meet the product technology demands for the next 3 years. Sigmatel's project management approach is changed to a distant search for new technologies using different methods and tools. New Budget: $65 million. PLT members help MicroTech changes its organizational goals on producing suspension assemblies. Stake holders are informed on this "ground-breaking" production change in their Annual Reports	CEO, CTO, VP Quality, Division Head, Project Leader and Project Team Members, Annual Reports (2006), Shareholder Events (Webcast)
December 2006	Project progress smoothly through its manufacturing verification review	Senior Management and PLT are frequently updated on Sigmatel's progress PPD also gets updated with continuous planning forum—Sigmatel still remains as a project exploring new technologies. Sigmatel has around 70 team members distributed across four different production sites	Division Head, Project Leader and Project Team Members
August 2007	First phase of production	MicroTech makes first batch of Sigmatel at two of their main production facilities	CTO, Division Head, Project Leader
March 2008	Project ended	Project ends at MicroTech. Project leaders and a smaller set of team members start working closely with their customers on educating them on this technology process	Project Leader, CTO, project interviews, Annual Reports
2008-2011	Market performance	MicroTech reports 500% ramp up in producing Sigmatel across the four facilities	Annual reports and press releases

Appendix D: Event Timeline for Tablet Project

Timeline	Events	Description of events	Source/informants
June 2006	Tablet Project Idea Discussed	Customer (VOC) indicated that the current laptop Nexus has some issues at extreme conditions (temperature and pressure). Idea discussed on how to improve the existing design. More data on the improvements needed sought from the customer	Project Leader Director of Process Improvement
August 2006	Tablet Project Launched	Tablet project launched with the idea of refining Nexus design with updated screen a refinement to processor design supplied by an external supplier—all focused on withstanding high temperatures and pressures Initial team meetings between Division Head, Director Process Improvement, Project Lead (Black Belt). Discussed project scope and other deliverables derived from their annual business unit scorecards. Project charter created with these information (Initial Budget: $2 million). 12 team members (Green Belts) are involved. Followed a structured approach (e.g., DMAIC)	CQO, Director of Process Improvement and Team Members

(continued)

Appendix D Continued

Timeline	Events	Description of events	Source/informants
December 2006	Tablet Project Halted temporarily	Analysis of current design showed reliability (vibration) issues for withstanding high temperatures. Problems also noted on the processor update Issues communicated to the Product Leadership Team (PLT) PLT discourages out of box thinking. Debate goes back and forth for 3 months	Director of Process Improvement, Project Leader, Project Team Members, Power point Decks
April 2007	Conducting more design tests	Project teams conduct additional tests Supplier conducts additional design tests Tests are reported back to PLT	Project Meeting Minutes, Project Leader and Project Team Members
June 2007	Tablet change in search strategy	Test results compared and discussed. Senior management informed on these issues. Finally comes to a decision to abandon optimizing Nexus design Consensus is finally reached to use a distant search strategy for Tablet to explore new processor technologies New goals on using different design. More experiments are conducted by the team members 8 additional team members with design and development skill sets joins the team. New supplier is brought in Budget: $20 million Project Launch Target: December 2007	VP R&D, Project Leader and Team Members
October 2007	Slow & Intermittent progress	Tablet uses a stage gate approach. Gate Reviews are points of contact between senior management and project team. Some vibration issues appear.	Gate review documents, VP R&D, Project Leader and Team Members
May 2008	Tablet Launched	Tablet officially launched during a company-wide event. Initial market reactions were that the product was late and had sub-par technology compared to its rival product. Product discontinued in 2009	Business Press Reports, Company Press Release, CQO and VP R&D

Appendix E: Description of other Project Shifts from Case Data

E.1. Drive Innovation Project—MicroTech

When looking back at our interviews with the senior management at MicroTech, we found other instances where projects changed in levels of complexity. For instance, both the Chief Executive Officer (CEO) and the Vice-President of Manufacturing at MicroTech described another project "Drive Innovation" that began as refinements to existing design at one of their facilities to improve the efficiencies of an assembly process. The project used a local search strategy to achieve deliverables. According to the CEO, during the midcourse, the PPD risks associated with the project changed since the current assembling process could not provide the level of precision required for miniature assemblies as demanded by the customer. Similar to the Sigmatel project, this change was discovered in the PPD process scorecards. This occurred a year before our first interviews at MicroTech. The project made a midcourse correction to innovate a new process technology that resulted in a trade secret in their approach to assemble drives. There was also a corresponding change in their project search strategy. When asked about this project, the CEO made the following comment.

> Drive Innovation is a perfect example in which, they started out on an improvement activity. They came to us with ideas that are quite innovative, quite non obvious and are of value. The PPD approach helped identify this project from one of our facilities and moved it to the next level.

The VP manufacturing gave a similar description of the Drive Innovation project.

> As a matter of fact, it is rather interesting that we had a team from Drive Innovation that had submitted an idea for a trade secret that started out as an improvement to existing design. And no one knew about it, and was brought to our attention through the PPDs. It truly started at the grass root level but it elevated to the point where what they solved was a significant problem to the company and became a trade secret. And now the effort is to transfer it to the rest of the operations to leverage that kind of knowledge.

E.2. Tech Z—CommTech

Revisiting our interviews with the senior leadership at CommTech also revealed another instance of project shift. CommTech developed an innovative technology (Tech W) that senior management believed would be the future of communications technology. It involved radically different product and process design. Senior management made their commitment to Tech W based on early insights from North American consumers that were made available through the annual strategic planning forum. The project started with a distant search strategy using DMADV method. The Vice President of R&D informed us that this approach resulted in ignoring new information on an existing technology, Tech Z, developed by CommTech's overseas development team that was spreading at a faster rate in the European market. Tech Z was based on their existing technology patent at CommTech, and hence would have been a project using current knowledge. However, senior management decided to explore Tech W, they ignored new information about Tech Z from their development teams in Europe (This would have been available to CommTech if they had continuous planning mechanism seen at MicroTech). According to business press reports, this decision proved to be a "*major fiasco*" that allowed CommTech's competitor to gain significant North American market share. When asked about their strategic decision-making process, the Chief Quality Officer at CommTech provided the following response:

> There is a paradox [tension] involved in managing these decisions. I will openly admit it. I do not believe we have figured it out and probably there are other groups that would do better than us. There is got to be an approach beyond just listening to your customers or your engineers. We do not have a process driven innovation approach to evaluate ideas [as they change]. To me, this is something that we all struggle and it a real quandary that we have here [at CommTech]

These additional examples illustrate that the shifts from either low to high complexity (e.g., the Drive Innovation project) or high to low complexity (Tech Z) were fairly common in these environments. They also suggest the value of these responsive search to identify such shifts.

Appendix F: Pseudo-Code of the NK Model Simulation

Basic model pseudo-code	

Require $0 \leq \tau \leq 1, 0 < K_l < K_h < N, T,$ search mechanism σ
$K \leftarrow$ random draw from $\{K_l, K_h\}$
for $0 < i \leq N$ **do**
$\mathbf{s}_{-i} \leftarrow$ sample K indices from $\{1, \ldots, N\}\backslash i$
$\pi_i(s_i, \mathbf{s}_{-i}) \leftarrow 2^{K+1}$ draws from $U(0,1)$
end for
for all s $\in \{\{0,1\}^N\}$ **do**
$\Pi^{(0)}(\mathbf{s}) \leftarrow \sum_{i=1}^{N} \frac{\pi_i(s_i, \mathbf{s}_{-i})}{N}$
end for
$\mathbf{s}^{(0)} \leftarrow$ random draw from $\{0,1\}^N$
	Create the initial landscape and positions

for $0 \leq t \leq T$ **do**
$u \leftarrow$ random draw from $U(0,1)$
if $\tau > u$ **then**
$\Pi^{(t+1)}(\mathbf{s}) \leftarrow$ SHIFT()
else
$\Pi^{(t+1)}(\mathbf{s}) \leftarrow \Pi^{(t)}(\mathbf{s})$
end if
if σ = Local Search **then**
$\mathbf{s}^{(t+1)} \leftarrow$ LOCAL_SEARCH()
elseif σ = Distant Search **then**
$\mathbf{s}^{(t+1)} \leftarrow$ DISTANT_SEARCH()
elseif σ = Responsive Search **then**
$\mathbf{s}^{(t+1)} \leftarrow$ RESPONSIVE_SEARCH()
elseif σ = Responsive Search **then**
$\mathbf{s}^{(t+1)} \leftarrow$ AMBIDEXTROUS_SEARCH()
end if
end for
	Search processes under landscape shifts

return $\Pi^{(T)}(\mathbf{s}^T)$	Return the simulation output

Pseudo-code for the landscape shifts	

SHIFT()
if $K = K_l$ **then**
$K \leftarrow K_h$
else
$K \leftarrow K_l$
end if
for $0 < i \leq N$ **do**
$\mathbf{s}_{-i} \leftarrow$ sample K indices from $\{1, \ldots, N\}\backslash i$
$\pi_i \leftarrow 2^{K+1}$ random draws from $U(0,1)$
end for
for all s $\in \{\{0,1\}^N\}$ **do**
$\Pi(\mathbf{s}) \leftarrow \sum_{i=1}^{N} \frac{\pi_i(s_i, \mathbf{s}_{-i})}{N}$
end for
return Π
	Create a shifted landscape with new valuations and ruggedness

Pseudo-code for the project search mechanisms sub-functions	

LOCAL_SEARCH( )
$\mathbf{s}' \leftarrow \mathbf{s}^{(t)}$
for $0 < n \leq N$ **do**
i = random draw from $\{1, \ldots, N\}$
$\mathbf{s}'' \leftarrow \mathbf{s}^t$
if $s''_i = 1$ **then**
$s''_i = 0$
else
$s''_i = 1$
end if
if $\Pi^{(t+1)}(\mathbf{s}'') > \Pi^{(t+1)}(\mathbf{s}')$ **then**
$\mathbf{s}' \leftarrow \mathbf{s}''$
end if
end for
return s′
	DISTANT_SEARCH( )
	$\mathbf{s}' \leftarrow \mathbf{s}^{(t)}$
	for $0 < n \leq N/2$ **do**
	$\mathbf{s}'' \leftarrow$ draw random position
	if $\Pi^{(t+1)}(\mathbf{s}'') > \Pi^{(t+1)}(\mathbf{s}')$ **then**
	$\mathbf{s}' \leftarrow \mathbf{s}''$
	end if
	end for
	return s′

RESPONSIVE_SEARCH( )
if $\Pi^{(t+1)} \neq \Pi^{(t)}$ **and** $K = K_h$
$\mathbf{s}' \leftarrow$ DISTANT_SEARCH()
else
$\mathbf{s}' \leftarrow$ LOCAL_SEARCH()
end if
return s′
	AMBIDEXTROUS_SEARCH( )
	$v \leftarrow$ random draw from $U(0,1)$
	if $v > 0.5$
	$\mathbf{s}' \leftarrow$ DISTANT_SEARCH()
	else
	$\mathbf{s}' \leftarrow$ LOCAL_SEARCH()
	end if
	return s′

Notes

[1]Micro Systems also had a start-up medical device business, MicroDevice. We collected data from this unit but excluded it because very few projects were refinements to existing technologies.

[2]We studied CommTech and CommNet units because they had innovation projects in their R&D units. Comm Customer Solution was primarily a service entity of CommCorp and did not have R&D of its own. Hence, it was excluded from our study.

[3]Perreault and Leigh's (1989) I_r coefficient is based on the observed frequency of agreements, and is a better approach compared to the conventional Cohen's Kappa, which is based on the expected frequency of agreements.

[4]A follow-up survey of the project team members revealed that Tablet's project prioritized both innovation and efficiency (hybrid in nature) owing to time-to-market pressures.

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