Powering Through The Turn: Finding Time for Concept Exploration Before Industry Stagnation

by

Connery Noble

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Abstract

The dichotomy of exploration and exploitation has been used in literature for many years to distinguish the needs of exploring new innovation/creating new markets versus exploiting existing capabilities/markets. This concept has been studied across various disciplines, such as organizational learning, leadership, and innovation strategy.

In this thesis, we examine how this tensions plays out in large corporations, specifically in how engineering teams prioritize activities in early stage development. We argue that engineering teams inherently trade-off between exploration and exploitation during development but would benefit by more intentionally and explicitly considering their strategy, in order to ensure their efforts stay aligned with the long-term goals of the organization.

Using survey data collected from over 900 system engineers and managers across a range of industries, we analyzed how engineers and organizations consider early stage development efforts, and what factors affect their importance. Notably, we observed that as an organization's market growth decreases, attention to architecture and design innovation within engineering teams also decreased. Eventually there is a tipping point in which market projections are so dire that engineering teams appear to undergo a drastic shift to refocus on exploration efforts. We also find that engineers struggle to maintain a consistent mental model of how much time and effort their organization currently wants to (or should) spend between product development phases. We argue these findings show the lack of an effective innovation strategy at the product development level, as it is inline with common pitfalls identified in other innovation strategy literature.

Thesis Supervisor: Bruce Cameron
Title: Director, System Architecture Group

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Chapter 1

Introduction

An organization's ability to innovate and adapt to changing environments is crucial to its long-term survival. While there are many aspects of an organization that needs to adapt, its ability to create desirable products is key. Innovation and product development are complicated processes that have been studied extensively. One concept, the interplay of exploration versus exploitation, is often utilized in helping an organization understand and improve its ability to innovate. So far, much of the focus and research has been aimed at the senior levels of an organization. Less is known about how the trade-off occurs lower down in the organization, particularly in the engineering department.

1.1 The Need to Innovate

Innovation has been called the single most important business challenge of our era [44]. McKinsey found that organizations capable of dynamically allocating resources based on market opportunity will be worth 40% more than less adaptive organizations after 15 years.

The increasing speed of environmental changes is the most important factor that companies need to deal with. In the last few decades, we're experiencing offshoring of R&D to global engineering, pervasive software technologies being introduced in every industry and an ever quickening product development lifecycle. As the world becomes ever increasingly complex and volatile and organizational environments become more global and dynamic, the need for organizations to be able to adapt and innovate will only intensify [45].

Failure to handle innovation properly can be potentially fatal to an organization, no matter how large or established it may be. Although long term forces for competitive advantage generally remain the same and good firms seem stable, many companies have spectacularly failed over the years due to a failure to innovate and keep up with their changing environment. Well-known names like Polaroid, Nokia, Sun Microsystems, and Yahoo. While other companies have managed to successfully transition from one era to another, like IBM or Microsoft. Albeit even those companies are no longer in the same dominant positions they once were. So what makes a success innovation strategy to maintain long-term survival?

Unfortunately, the traits required to foster innovation are extremely complex. The leading literature often involves contradictory or paradoxical concepts that need to maintained in a delicate balance. For example, too much exploration and you'll never adequately develop any ideas to be successful. While, too much time exploiting existing solutions and you'll fail to adapt as environments change.

Furthermore, what was a good strategy yesterday, may not be appropriate today. Microsoft found that the recent transition to remote work has had a positive impact on engineering productivity by providing more freedom and flexibility to the work day and reduce wasted time. However, they also found that as a result of the transition, their innovation efforts have seen a downturn [1]. Despite the increase in productivity, why have the engineering teams innovation efforts faltered? How do engineers understand and consider their organizations innovation strategy?

1.2 General Objective

Engineering departments are a vital source of product innovation for an organization. In this thesis, we would like to analyze and understand how engineers think about their engineering processes and its impact on the organization's innovate strategy.

More specifically, we want to understand how engineers think about the importance of concept exploration and its alignment to their organization's innovation strategy.

1.3 Innovation Research

The literature is clear, in the world today organizations need to be able to adapt and innovate in order to survive. Countless papers have been dedicated to understanding how organizations can improve and foster effective innovation to achieve the best long-term performance.

The literature uses the dichotomy of exploration and exploitation to distinguish the needs of exploring new innovation/creating new markets versus exploiting existing capabilities/markets. For decades, this concept has been studied in organizational learning and innovation strategy literature.

Through this research, broad managerial tactics and processes have been developed to help organizations and managers navigate the complexity of balancing exploration and exploitation. Yet, rarely have the tensions of exploration and exploitation been explicitly applied to engineering product development efforts, despite the fact that product development is an integral component of an organization's innovation strategy.

1.4 Product Development

Early stages of engineering product development involves determining a high level design and concept for the product. To select a design concept, often product development teams will undergo a so-called "concept exploration" phase, where multiple potential concepts are explored and assessed, until ultimately one is selected. This stage of exploration is instrumental in identifying innovative technologies and solutions for new and existing products alike.

Unfortunately, the breadth and depth of this exploration could be potentially endless. So how much time and resources should be dedicated to this endeavor, and how do you know if it's an effective use of these scarce resources? How well do engineering teams understand and align these decisions with the organization's innovation strategy?

Without strong strategic direction or guidance, people naturally gravitate towards easier and less risky decisions [10]. In practice, organizations often pursue a very narrow focus to the concept exploration [37], despite strong evidence suggesting that a broader more thorough exploration of the solution space leads to higher quality results [19]. Therefore, rather than exploring a wide range of concepts, engineering tends to favour exploit existing concepts and apply incremental changes/improvements.

1.5 Outline

While there is extensive literature on how exploration and exploitation are (or should be) incorporated into innovation strategies overall, less attention has been paid to how this happens on the ground so to speak.

We propose to look at this aspect in some detail using survey data of 900 engineers. We look at how these two activities are carried out and comparing that with other factors including type of industry and the expected growth of the company. After presenting our results, we then identify areas for improvement and provide some suggestions on what to implement.

Our investigation starts with a review of existing literature on disruption, innovation strategy, exploration versus exploitation, and engineering practices and processes related to concept exploration. We also look at related research done at the level of the engineering department.

The next section is an overview of the data used in this research. This includes characterizing the data sources, and providing some initial analysis of known biases, challenges, and assumptions made with our analysis the data.

In Chapter Four, we describe four hypotheses that we test using the data we have collected. After describing them, we talk about the results and outline the process and justification for each result.

After that, we discuss how our results can be interpreted and suggest potential implications and learning for managers and future research.

We end with a summary of our findings and discussion.

Chapter 2

Background

Innovation and innovation strategies within organizations have been extensively studied, and we begin by highlighting various ways to think about disruption and innovation. Then we look at different models in the literature that aim to help companies think about disruption and develop practical innovation strategies. It is here that we discuss how exploration and exploitation are different approaches to innovation and how the tension between them can be managed. Other factors that impact innovation such paradoxical thinking and market growth are also briefly discussed.

We then turn our attention to product development studies within engineering noting the work done on concept development, new-product development and exploration versus exploitation. We identify gaps where there can be much more in depth study in how innovation strategy plays a role.

2.1 Disruption and Innovation

"Change is the only constant in life" —Heraclitus of Ephesus.

All environments and industries are changing. Whether it's evolving customer needs and markets, tightening competition, or new technology and capabilities, no industry stands still. Every organization needs to be able to adapt and grow with the changes to their environments, or risk being left behind [38].

Often changes are not disruptive i.e. they are small and incremental and are relatively easy for the industry as a whole to adapt to. However, if these small changes go unnoticed or recognized by incumbents for too long, organizations may react too late to be able to successfully adapt [10].

Alternatively, truly radical changes can quickly shift the landscape of an industry seemingly overnight. This could range from sweeping societal changes like war or a pandemic [22, 34]. More often though, it comes from new breakthrough technology that can quickly change the needs and capabilities of a market, or even generate new markets.

When a major innovation causes a disruption that leads to the failure of leading technology companies, it is often called "Disruptive Innovation". This term was coined by Clayton Christensen [10]. A Disruptive Innovation begins as an innovation that creates a new (or untapped) market by addressing novel or otherwise unmet needs/values. The innovation typically starts as a low-cost or low-margin product. However, as the innovation improves and grows, it eventually expands into (and ultimately overtakes) existing markets, disrupting the current market leaders and products [17].

His work initiated extensive excitement, research and discussion around the effects of disruptive technology changes and the importance of innovation on firms and industries [17]. Particularly in response to how organizations can strive for disruptive growth, and how established incumbents can protect themselves from disruptive challengers [10, 12, 17].

Christensen categorized two primary types of innovation that led to disruptions he observed. "Sustaining Innovation" is focused around an organization's existing primary customer and their needs, while "Disruptive Innovation" targets under-serviced customers that are not currently the primary profit centers of the organization [13].

We've already talked about disruptive and sustaining innovation, and can see a clear similarity with the concepts of exploration and exploitation, as well as experimental and reactive actions.

Similar dichotomies repeated themselves time and again in the broader innovation literature but under different names. Abernathy discusses the distinctions between radical and evolutionary innovation [2], while others have made comparisons between radical and incremental innovation [41, 39], or continuous and discontinuous innovation [48].

All these terms generally reduce to a similar base idea. There are two distinct, competing components to successful innovation that must be traded-off between. One component generally results in smaller, incremental changes, that are faster and provides short term gains, while the other results in larger, more drastic change, but is more difficult and requires longer term/big picture planning.

Organizations need to be monitoring their environment and develop plans to address both types of changes that can impact their success. Generally, the response is some form of innovation either incremental if the environment is changing slowly or radical if there is a significant disruption.

2.2 Innovation and the Process of Change

An organization's ability to adapt is crucial to its long-term survival and there are different types of innovation implying different strategies proposed in the literature to help organizations improve their innovation efforts and increase their long-term survivability.

2.2.1 Disruptive Innovation

When Clayton Christensen defined "Disruptive Innovation", he argued that it's very difficult for an incumbent to pursue disruptive innovations themselves. Incumbents already have high profit and growth expectations that they need to continue to meet and exceed. For an incumbent to pursue Disruptive Innovation would require them to divert focus from their primary customer towards far less profitable niche segments [10]. Small organizations, on the other hand, have very few existing expectations and are able to adapt quickly and take on risk.

Christensen also identified another category of innovation which he called "Sustaining Innovation" and felt that the two types of innovation are not complimentary.

In fact, it would be very challenging for a single organization to successfully executed both simultaneously. So, despite the fact that incumbents know disruption will happen eventually, it is not a viable option for them to directly pursue it themselves [10].

To solve this dilemma, Christensen proposes that incumbents found and/or acquiring subsidiary organizations [10]. He argues that if the organizational units are sufficiently siloed from one another, they can operate effectively without interference. So, these subsidiary organizations are less restricted and able to pursue disruptive innovations. If a subsidiary ultimately succeeds at disrupting one of the primary organizations market segments, the corporation as a whole still benefits [10, 12].

Gaps in Disruptive Innovation

Christensen's Innovators Dilemma is founded around a specific trajectory of a disruptor that he has observed [10]. Not all forms of disruptive innovation cause this trajectory. Christensen has mentioned how it is often miss-applied or is over generalized to all forms of disruption [13]. As an example, Uber is often miss-characterized as a Disruptive Innovation. Despite the drastic hit to the taxi business, Clayton M. Christensen, Michael Raynor, and Rory McDonald argue that Uber did not follow the disruptive innovation trajectory [13]. Rather than starting out with a lower-quality or unmet market, Uber brought together multiple sustaining innovations that enabled them to out-compete the taxi industry with their primary customer by developing a better, cheaper, more convenient product [13].

Researchers have also come up with other ways to distinguish and categorize what is considered an innovative disruption. Christensen's Disruptive Innovation is sometimes also explained as an innovation that primarily centers around a new innovative business model, rather than a technological innovation [38]. For example, the Android operating system could be considered a potentially disruptive innovation. Android OS did not introduce any particularly new technology that Apple and Microsoft were not already using, but it was being given away for free, which was very different from both Microsoft and Apples OS business models [38].

Other researches have gone on to question the premise that sustaining and disruptive innovations need to be operated separately in the first place [24]. A study on the response of 88 businesses to disruptive change found that the source of innovation plays a role in how organizations should respond. The study characterized two types of innovation, market-driven innovation, and technology innovation. The study showed how organizations responding to disruptive market-driven innovations are able to succeed in managing both disruptive and sustaining innovation without separate business units, whereas those responding to disruptive technologies benefited from creating separate business units [24].

2.2.2 Exploration and Exploitation

The comparison of exploration and exploitation has been used in literature for decades [16, 28, 31, 27]. It has a rich history in computer science [27], economics [28], and decision science [16]. However, the term was largely popularized by James March in his 1991 paper on organizational learning [31].

March's seminal paper on organizational learning used the terms of exploration and exploitation to characterize how organizational structures and processes can affect the way in which an organization learns and adapts over time. He used the dichotomies to distinguish the act of exploring new possibilities from the exploitation of old certainties [31].

Using a computer program to simulate the transfer knowledge and experience between "coworkers", March was able to model how different organizational practices influenced the overall capabilities, adaptability, and effectiveness of organizational teams. He argued that organizations that refine exploitation more quickly may have more effective results in the short term, while potentially being self-destructive in the long run [31].

March's work on exploration and exploitation instigated extensive research and discussions in a wide variety of management literature, ranging from organizational design, managerial economics, and innovation strategies [5, 6, 9].

Exploration is broadly used to characterize any process or outcome related to such things as search, discovery, experimentation, risk taking, and innovation. Exploitation on the other hand represents efforts of refinement, implementation, execution and efficiency [28, 31, 5, 9].

Trade-off of Exploration and Exploitation

However, exploration and exploitation are distinctly different concepts that need to be traded off between [31, 35, 32]. This is because exploration and exploitation introduce conflicting tensions that potentially counteract one another [32].

Exploitation is said to improve competence of existing procedures, products, and skills. However, this can make experimentation of other alternatives seem less attractive [31, 36, 23]. Conversely, exploring new alternatives comes at the expense of improving existing ones [31, 23].

Although exploration has the potential to produce significant results, exploitation of incremental changes is not be discounted. In fact, research has found that incremental changes generally result in more than half of the economic gain from an organization's improvement efforts [2].

Balance

Research has strongly suggested that a balance of both exploitation and exploration yield the best long term performance. However, there is controversy on how to best achieve the balance.

There has been a long tradition in organizational literature to address exploration and exploitation as separate activities [42]. Similar to Christensen's conclusion, some researchers have found that organizations perform best when they adopt mutually exclusive processes and organizational structures to tackle exploration and exploitation separately [32].

However, other studies have shown that organizations can embrace a combination of exploration and exploitation to drive innovation. A balance of the two approaches has become a key concept in organizational success [35, 42].

Finding the right mix of exploration and exploitation is not easy though. Many studies have shown that organizations often over emphasis exploitation, to the detriment of their exploration needs.

2.2.3 Paradoxes and the Ambidextrous Organization

Organizational life is filled with all sorts of plurality, tensions, and contradictions. Exploration and exploitation aren't the only tensions organizations need to balance. They also struggle with many other concepts like being collaborative and competitive, focusing on mission or market, having global integration or local distinction, and an endless list of other paradoxes [45].

Researchers have been exploring the depths and breadth of organizational paradoxes for decades, however there is still much more to understand [45]. This will only continue to intensify as the world increases in complexity and volatility and organizational environments become more global, and dynamic [46].

However, rather than shy away from these paradoxes, embracing the tensions they offer can help leaders and organizations be more innovative [3]. Paradoxical thinking is a process of identifying and defining contrasting characteristics in order to consciously bring about their positive characteristics [21]. It has been shown to be effective at fostering innovation by leveraging the paradoxes as a means to question the status quo [21, 3]. Additionally, organizations led by paradoxical thinkers are thought to be better at managing organizational tensions and foster innovative behaviour [29, 3]

The Ambidextrous Organization attempts to address the paradox of balancing exploration and innovation. Similar to how an ambidextrous person might use their right and left hand equally, an ambidextrous organization is said to be an organization that successfully uses both exploration and exploitation [35].

Literature on ambidextrous organizations focuses on understanding the challenges and benefits of developing a capability with the two underlying conflicting components of exploration and exploitation [35]. Ambidexterity acknowledges the paradoxical relationship between exploration and exploitation, but looks to unlock the benefits of developing and leveraging the paradox of both underlying components [32].

The tighter alignment of exploration and exploitation of ambidextrous organizations has been shown to enable organizations to learn and adapt faster and with better synergy across the organization [40, 39, 43, 30].

2.2.4 Effects of Market Growth

Anticipated market expansion is theorized to motivate managers to commit more resources towards product innovation. The emergence of new niches encourages manages to find ways to capture the additional business before their competitors do [33].

Contrary to that, other theories believe that a shrinking market, rather than a growing one, drives the motivation for change. This is because market decline forces managers to reassess how they compete in order to keep their companies going. It induces managers to explore new ways to complete, requiring increased innovation efforts [33].

2.3 Product Development and Engineering Processes

To increase the chances of success, many product development methodologies exist to help guide a project through its lifecycle. These processes break product development into various stages. It is generally well understood that earlier stages are less resource intensive than later stages and, the decisions made early on have the potential to drive significant costs in all later stages.

2.3.1 Concept Exploration

One of the earliest stages of many development cycles is the idea of concept exploration. After identifying the problem that needs to be solved, but before defining all the details of how the solution will work, engineering need to determine a high-level concept of what the system will do.

For example, In 1976, the development processes for navy ship building typically began with a “basis” design of an existing vessel. Engineers would then apply incremental modifications to this design to meet their new set of requirements and needs. They called this processes Modified Repeat Study. Unfortunately, if the project required any measure of significant changes from previous models, then the modified repeat method was not actually cost effective [15]. Thus, “Concept Exploration” was added to the development processes. Concept exploration would not start from a basis model, and instead would explore and evaluate multiple preliminary design options.

Starting from with a fresh design was actually found to be easier and cheaper than performing modified repeats [18]. More importantly though, the concept exploration stage allowed the designers to explore a wider range of initial designs, and they were able to produce better end products.

Since then, many systems engineering methodologies include concept exploration and selection stages before moving on to more detailed design work.

Concept exploration and selection is a crucial stage in the product development lifecycle as it sets the stage for all subsequent stages. Decisions made during concept selection have the potential to drastically impact the success of a project.

Not only is concept exploration meant to select the most appropriate design concept, it also provides an avenue to explore less common designs, or designs that incorporate new technology advancements, which could potentially spur new innovation.

As a final point, if a company does not spend enough time exploring alternative concepts, it is unlikely to ever generate new or innovative solutions.

2.3.2 New-Product Development

New-product Development is meant to describe a development process that is specifically geared towards developing new radical or discontinuous products [7, 47].

However, research shows that the majority of new-product development research is focused on the development of evolutionary products, rather than truly discontinuous new-products [48]. Robert Veryzer found that the development processes for engineering teams pursing discontinuous new-products was organized significantly different from the typical new-development process [48]. Namely, there was heightened focus on delivering prototypes earlier in the process, and typically market research and financial analysis occurred later [48].

Takeuchi observed this trend a decade earlier, and he proposed the "New new-product development" process. Instead of developing projects linearly and passing the development from team to team as it progresses, Takeuchi suggested development should be done as a single integrated and comprehensive team, where everyone is working together simultaneously to get the product developed. Takeuchi used a sports analogy to illustrate his point. He characterized the old processes as being a relay race, while he called for the new new-product product development process to be more like a game of rugby [47].

Stemming from Takeuchi's paper about using a development processes more akin to a game of ruby, the Agile methodology and "scrum" emerged. This highly iterative development processes is popular in the innovation and startup communities. Interestingly, agile methodologies are obsessively customer focused, and the development process consists of many small incremental changes delivered quickly. Throughout the entire cycle, there does not appear to be any time that lends itself to the idea of exploration.

2.3.3 Exploration verses Exploitation in Engineering

Beyond the concept exploration phase itself, the distinction between exploration and exploitation is less commonly found in engineering management literature.

A recent paper referenced the ideas of exploration and exploitation as analogous to the product development phases of concept design and detail design phases, respectively [52]. The authors explicitly differentiated between exploration and exploitation efforts by emphasizing the exploratory nature of concept exploration [52], and characterizing the process of detailed design as a source of design exploitation.

However, this is not particularly common despite how relevant the trade-offs of exploration and exploitation are to the design processes.

2.4 Implementing an Innovation Strategy

A strategy is a commitment to follow a set of policies and behaviours that aim to achieve specific goals. Organizations commonly set business strategies to clarify objectives and priorities, and promote alignment across business functions. An innovation strategy aims to align an organization's innovation efforts with their overall business strategy [38].

An organization's ability to innovate stems from a complex set of interdependent processes and structures that come together to dictate how an organization searches for novel problems and solutions. An innovation strategy helps an organization make trade-off decisions and choose the elements of their innovation system, which in-turn help to keep the innovation efforts across the organization aligned with the primary business strategy [38, 8].

Given the importance of innovation to an organization, there is plenty of research on implementing a successful innovation strategy. There are also a number of studies on what can go wrong.

2.4.1 Successful Innovation Strategies

Strategy and leadership are critical factors to successful and effective product innovation management [14, 38]. Haphazardly adopting any of the various innovation practices is unlikely to be successful without a clear or concise overall strategy that is aligned with the corporate strategy [38].

Koryak et al. showed how organizational attention and focused on exploration and exploitation, combined with a clear written vision is crucial to an effective innovation strategy [30].

The Role of Management

Engineering managers and management processes play a pivotal role in directing innovation efforts and conveying innovation strategy to their teams. Effective product innovation relies on co-operation across the organization, and it's imperative that managers develop consistent priorities with all their teams [14].

A study of 422 small and medium-sized enterprises in the UK found that the focus of managerial attention had a direct effect on the development of their exploration and exploitation capabilities [30].

A field study by Burton et al. looked at high-technology engineering firms and how management processes impacted exploration and exploitation projects. They were able to demonstrate the importance of management systems alignment/misalignment on project performance. They found that the alignment of management systems had a significant impact on the outcome of exploration projects. Whereas, exploitation projects were far less affected by alignment/misalignment of management processes [6].

Portfolio Approach

Portfolio management for product innovation has emerged as a critical function for senior managers [14]. Rather than attempt to balance innovation efforts and alignment within a project, a portfolio approach treats all development projects as a portfolio of projects.

Each project is evaluated similar to how a fund manager might assess a stock by comparing risk, return, time, etc. Together all the projects in the portfolio should be a manifestation of the organizations corporate and innovation strategy [14].

This approach has been shown to be an effective tool to help managers evaluate and prioritize which projects to pursue in order to better align their total engineering efforts with the innovation strategy [43, 14].

2.4.2 Innovation Strategy Problems

Overemphasis on Exploitation

As discussed in Section 2.2.2, there is extensive research supporting the benefits of balancing exploration and exploitation. Despite this, research shows that organizations often overemphasize exploitation efforts to the detriment of long-term performance

[31, 49, 19, 42].

This situation is sometimes referred to as the “success trap” [49]. There are various theories attempt to explain why so many organizations suffer from these phenomena.

Most commonly it is attributed to strategic myopia [49]. People are naturally risk adverse and favour immediate rewards [11, 23]. Therefore, engineers and leaders may find it more appealing to exploit existing concept and apply incremental changes/improvements, rather than spending the time and resources to explore a wider range of concepts [37].

Additionally, people are naturally risk adverse [11, 23]. Therefore, managers, executives and corporate planners may be more tentative to pursue exploratory efforts simply due to the unknown nature of it [49].

Poor Engineering Alignment

A strategy can only ever be as good as those who carry it out. Employees determine the organization’s ability to adapt in increasingly turbulent environments [50]. In the 1980s Western Electric attempted to make widespread strategic change to the organization in response to deregulation. However, in their planning and implementation of the strategic change, they neglected to ensure the engineering teams were properly aligned with the new strategy. This lack of alignment ultimately resulted in a failure to implement the strategy [50].

2.4.3 Inertia and Resistance to Change

Inertia can provide many benefits to an organization. For example, economies of efficiency/routine or greater reliability in delivering a robust and feature-rich product [33].

Although inertia can be a good thing at times, inertia can have drastic consequences on an organization’s ability to adapt to changing environments. Hodgkinson found that cognitive inertia can cause firms experiencing a down-turn to unintentionally perpetuate their demise because strategists fail to adapt their mental models fast enough to the changing environment [26].

Conversely, good past performance can contribute to competitive inertia [33], which in-turn encourage a focus towards exploitation and a move away from exploration efforts. Politics is also a strong barrier to implementing ambidextrous capabilities [40]. Inter-department politics, funding policies, miss-aligned incentives, and other forms of organizational politics can pose friction and resistance to change.

A research paper by McKinsey found that organizations who were able to minimize sources of political inertia and cognitive bias were able to considerably better than other organizations. The ease in which capital was able to flow from one business opportunity to the next supported stronger shareholder returns [25].

2.5 Summary

The literature on the need for an innovation strategy is extensive. In the world today, organizations need to be able to adapt and innovate in order to survive. Countless papers have been dedicated to understanding how organizations can improve and foster effective innovation to achieve the best long-term performance.

Unfortunately, it becomes abundantly clear that the issue of innovation is complex and there is no simple answers. The literature quickly diverges into a broad range of organizational management disciplines. Each bringing up an array of paradoxes and trade-offs that all need to be considered and balanced. Literature does agree on one thing though. No matter the tactic, having the organization aligned to a clear innovation strategy is crucial to success.

One common thread that occurs throughout the organization and innovation literature is the trade-off between the efforts of exploration and exploitation. The tensions between exploration and exploitation was first applied to organizational learning to draw the distinction between exploring new capabilities versus exploiting known certainties. It has since been applied and adapted across a wide range of organization and innovation strategy topics to help articulate the conflicting tensions of exploring new things versus exploiting existing ones.

Through this research, broad managerial tactics and processes have been developed to help organizations and managers navigate the complexity of balancing exploration and exploitation. Yet, rarely have the tensions of exploration and exploitation been explicitly applied to engineering product development efforts.

We find this to be a notable gap because product development should be an integral component of an organization's innovation strategy, and the dichotomy of exploration and exploitation seems particularly relevant to the engineering challenges of architecture design and development.

Chapter 3

Method

In this section, we discuss the data sources and analysis methods and assumptions used in this paper. First, we outline where and how our data was collected. Next, we characterize the population breadth and diversity. Then we discuss the computational methods used to analyze the data. Finally, we discuss the limitations within our data, and our measures used to overcome or mitigate their effects.

3.1 The Data

Data used in this paper was collected through surveys conducted with participants in an online course in 2019 on the Architecture of Complex Systems. The course is geared towards engineering professionals, looking to expand their knowledge and expertise in the use of system engineering and architecture design.

Participants were not graded on their poll submissions, and completion of the surveys was entirely optional. All participant names and identifying information have been removed in the descriptions that follow.

3.1.1 The Participants

In total, 946 participants responded to the surveys. All respondents come from within engineering organizations, and the majority are the majority of them have system engineering experience. Figure 3-1 illustrates the breakdown of respondents by years of experience as a system engineer.

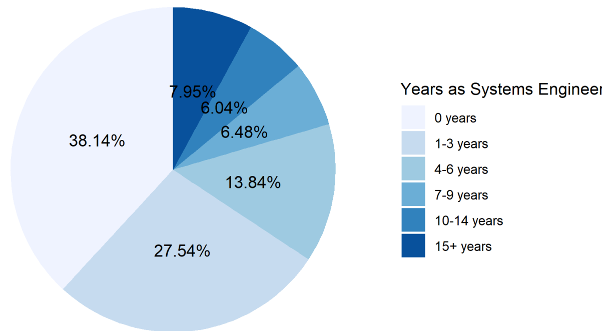

Figure 3-1: Distribution of respondents by experience of as a System Engineer

Participant Professional Goals

In Question 2 and Question 6, we asked respondents what job title they currently have, and what title they wish to have in 2 years from now. We use these two questions to roughly categorize participant's future goals within their firm. If both responses are roles as a System Engineer/Architect (including senior positions), then we classify the respondent as a system engineer. However, if they are currently a System Engineer/Architect, but hope to be in a different role in 2 years, we classify them as someone looking to move "Beyond System Engineering". Conversely, a respondent who was previously not a System Engineer/Architect, but would like to within the next two years is classified as someone hoping to "Become System Engineer". Lastly, respondents that are not currently, and do not wish to have a title of System Engineer/Architect is classified as a "Non-System Engineer". Figure 3-2 illustrates the distribution of respondents by goal.

Using this categorization of goals, combined with the respondents years of experience (Question 4), we identified three primary categories of participant. We believe most respondents fall into one of these three primary groups. Figure 3-3 illustrates the distribution and clustering of the participants.

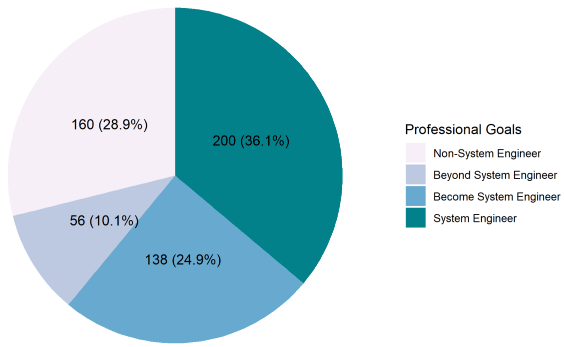

Figure 3-2: Respondents by Goal Category

One group consists of relatively junior system engineers, with 1-6 years experience. We speculate that this group is looking to hone their skills in order to advance their career in system engineering. Another group appears to consist of the senior engineers (15+) and engineering leaders. Finally, we have a group of non-engineers (or past engineers) from a wide range of overall work experience. We believe this group consists of employees looking to improve their understanding of system engineering in order to better support or interact with their engineering teams.

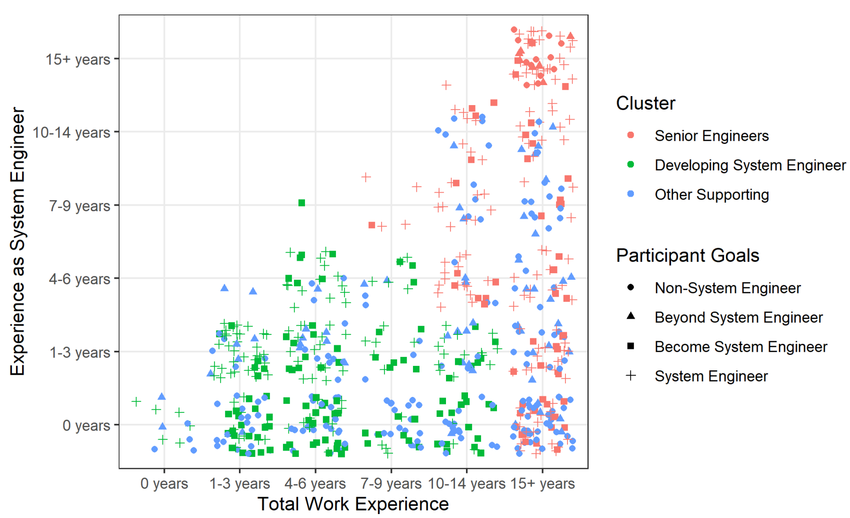

Figure 3-3: Clustering of Participant by Role and Experience

Architecture "Experts"

In order to aid with our analysis, we wanted to identify a subgroup of participants whom we could consider to be the most knowledgeable about system architecture in general, so-called "experts". However, determining architecture expertise and knowledge based on the survey responses is no trivial task.

Question 4 of the survey asked respondents how many years of experience as a System Engineering they have. This self-reported value is a tempting option to gauge experience. Unfortunately, years of experience is often not a reliable indicator of skill or expertise [20].

Furthermore, we believe that years of experience could even have an inverse correlation with expertise in our case, due to selection bias. Although the course targets engineering professionals, it is designed to provide an overview of system architecture. This introductory level course may not be as appropriate for an engineer with 10+ years of experience in architecture design/development. Therefore, a system engineer with 10+ years of experience, with an expertise in architecture, may not be as drawn to the course, or they may have already taken something similar.

Instead, Ericsson and Smith argue that "the dimension along which expertise is most appropriately evaluated should represent some measure of actual competence, rather than a possible correlate of competence such as amount of experience" [20]. With this in mind, we chose to use a combination of several questions in the survey as a means to measure expertise.

First, we asked respondents to identify the interfaces they were able to find in a particular system (Question 18). We believe the ability to identify interface points is a good indicator for architecture experience. We eliminated any respondents who did not identify 8 or more of the interfaces.

Next, we used the response provided to the question "Systems thinking is:" (Question 20) to see if they had a general understanding of system thinking. This question was a basic multiple choice question with four options, and one answer that was most correct.

Lastly, Question 32 directly asked respondents how many architectural decisions they have made in their career. We used this self-reported experience to eliminating any respondent who feel they have never made any architectural decisions in their career.

In order to keep the analysis simple, we constrained our assessment to a single discrete classification of expert, or non-expert. Figure 3-4 shows the distribution of respondents who meet the criteria for each individual metric, and how many respondents satisfied all three criteria. We label the respondents who satisfied all three of the criteria as our "experts". This calcification identified a subset of 151 respondents from our original population.

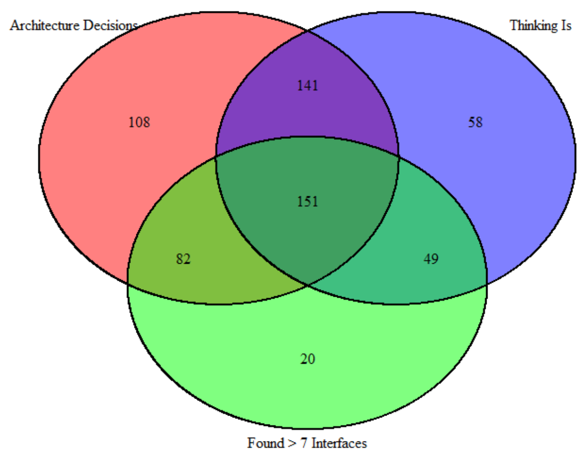

Figure 3-4: Venn diagram of respondents who satisfy the "expert" benchmark.

By no means is this metric a perfect assessment of expertise. However, we believe it provides a useful approximation to aid in our analysis. In order to validate our choice of metrics, we compare the result with the participants years of engineering experience (Question 4).

Figure 3-5 illustrates the correlation between experience and expertise. For engineers with 0-6 years of experience we observe a positive correlation between experience and expertise. Despite the fact that years of experience isn't a good indicator of expertise, it's definitely correlated [20]. Therefore, we feel this result is inline with the theory of expertise [20].

Interestingly, we observe that there is a non-negligible contingent of "experts" who are reported to have zero years of system engineering experience. This can be explained by the fact that Question 4 specifically refers to the title of "System Engineer", and many other roles and positions perform similar functions and gain similar experience.

For system engineers with 7+ years of experience, we observe that the correlation with expertise begins to breaks down. As previously mentioned, we believe this is attributed to selection bias based on which engineers are most likely to sign up and attend the related course.

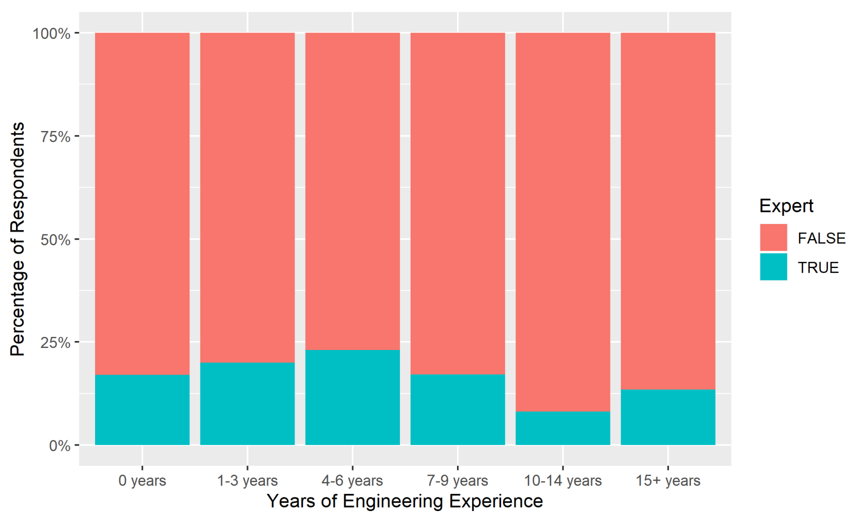

Figure 3-5: Percentage of Experts by Years of Engineering Experience

3.1.2 The Companies

The survey respondents came from over 177 different companies and organizations. However, a large portion of respondents come from a small handful of organizations. A total of 23.0% of respondents all work for one large organization in particular, while the top 10 companies combined account for just over 50% of the total respondents.

Market Position

Figure 3-6 shows the distribution of the market position of each respondent's company within their respective markets. Most notably, we see that very few respondents come from companies in the bottom half of their respective markets.

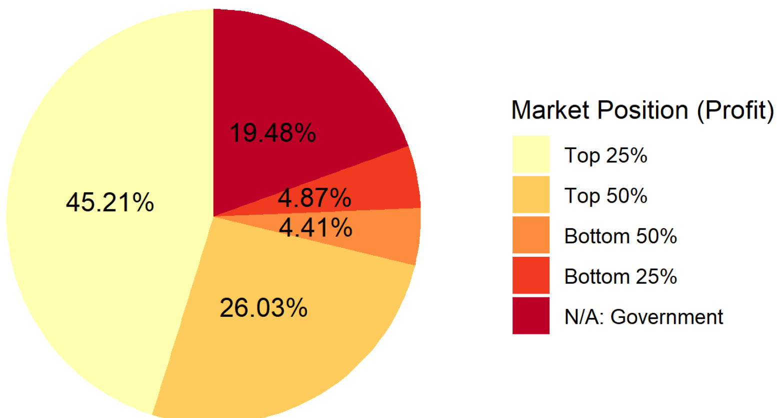

Figure 3-6: Company Market Position of Respondents

This bias within our data is not entirely unexpected. We believe several factors may account for this disproportionate representation.

First off, companies in a stronger position within their market are likely to be in a better position to provide employees with the time and flexibility to pursue learning and professional development opportunities.

Similarly, this course could be considered a premium learning opportunity. Even if an organization does prioritize time and flexibility for their engineers to pursue learning opportunities, they may be less inclined to cover the high price-tag that accompanies the course. Therefore, if an organization is struggling, they may seek out cheaper alternatives.

Alternatively, employees may have an inflated perception of their organization's performance. Whether through internal indoctrination, or the above-average effect, employees may believe their organization is in a stronger position than it really is.

Lastly, if we could even consider causation. Extensive research has shown that investing in professional development programs for employees can have significant benefits to overall organizational growth and success [4]. Therefore, organizations already predisposed to invest in their employee's professional development are also more likely to succeed within their markets.

3.1.3 The Industries

Respondents came from a range of industries. The survey asked respondents to self report their industry from a list of 40 potential industries. However, the majority of companies could be categorized into 6 primary industries. Figure 3-7 shows the distribution of respondent's general industries. The automotive industry is the largest industry in our sample, followed by Space and Defense.

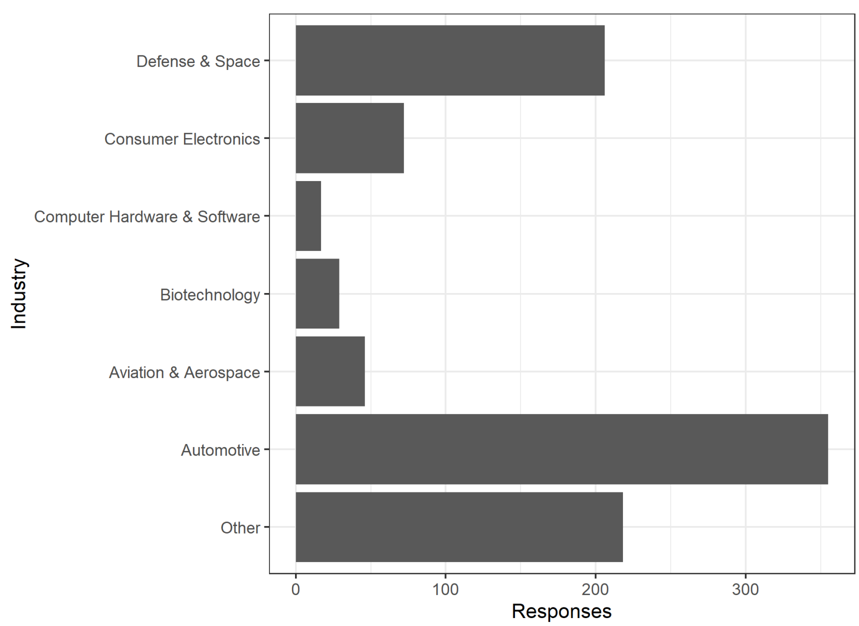

Figure 3-7: Industry Responses

3.2 The Questions

The survey was broken up into multiple sections, which were given to the course participants to fill out at various stages throughout the 5-week-long course. Table A.1 includes a full list of survey questions used in this paper.

3.2.1 Missing Data

When the survey was presented to the participants, none of the sections or specific questions were required to be answered. Therefore, not all questions were fully answered by all participants, and gaps exist in each respondent's data set.

That being said, we do not observe any strong correlation between participants and which questions were left unanswered. Therefore, in order to perform our analysis, we remove any entries that are missing one or multiple of the relevant variables during each analysis.

For example, when doing the expertise analysis related to Section 3.1.1, we ignored any respondents who did not answer Question 18, Question 20, or Question 32. Figure 3-8 shows the total number of participants that answered all three questions.

We believe this is a reasonable approach, because we do not observer any noticeable correlation between participants answers to any questions and the individual questions left unanswered. Therefore, we are confident that unanswered sections/questions are primarily due to participants random availability and circumstance, rather than a symptom of the questions or the survey itself.

3.2.2 Duplicate Data

In some instances, respondents completed individual sections of the survey multiple times. This results in multiple answers from the same participant to one or more questions within our dataset. In order to avoid double counting any respondents, we only include the most recent response for each specific question per respondent. We do not perform any further analysis into where, what, or why respondents answers may have changed between multiple submissions.

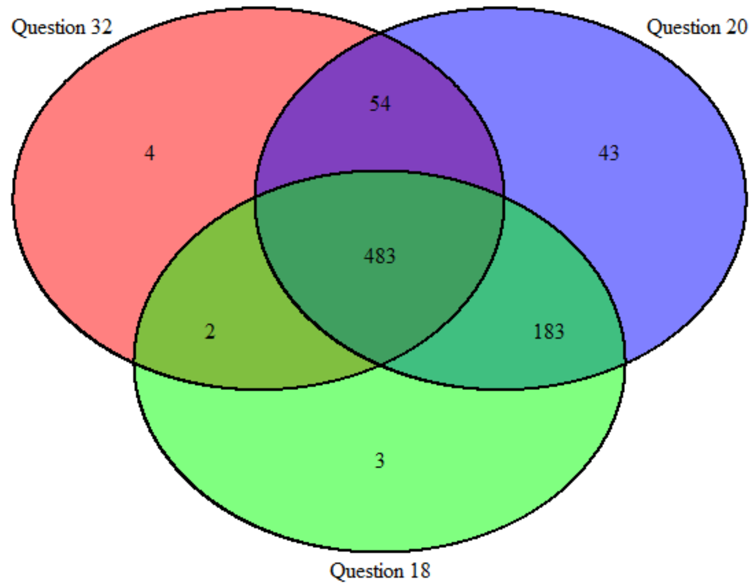

Figure 3-8: Total Respondents Considered in Expertise Analysis

3.2.3 Numerical Ranges

Many questions in this survey are asking for numeric responses via multiple choice. Some of these multiple choice options represent discrete values, while others represent a range of numbers. To perform numerical analysis on these types of questions, we needed to convert the ranged values to a discrete value that we can compute on.

A natural option is to simply convert any range values to the mean. However, due to some ranges being open-ended with no upper bound (ex: "50+"), we instead chose to treat all ranges as their lower bound. Table 3.1 provides some examples of how responses were converted to numeric values.

Table 3.1: Survey response numeric conversions.

Type	**Example**	**Value**
Interval Range	"4-6 years"	4
Open Ended	"50+ years"	50
Percentage	50%	50

3.3 Reliability of Data

Understanding the reliability of respondents answers the survey questions is paramount. We applied two main techniques to quantify the reliability of respondents answers using various questions. In some cases, we intentionally asked participants the same, or similar, questions multiple times. For example, Question 27 and Question 33 both ask the respondents: "what percentage of total product development manpower should be dedicated to architecture?". This allows us to measure how much a participants answer varies entirely on their own.

We also use known cross-participant relationships to compare how respondents varied when provide answers for the same information. For example, we compare how "Company Age" differs between the responses provided by employees within the same company.

3.3.1 Within Company Data Variance

A natural starting point to determine a baseline variance was to look at the responses provided for company age (Question 8). Age of company is a good starting point because the question itself is unambiguous, and we believe it should be a relatively knowable answer for any employee; irrespective of position, experience, department, or seniority.

Org	**Average Age**	**Standard Deviation**	**Percentage of Mean**
A	49.2	4.80	±9.8%
B	49.7	3.48	±7.0%
C	47.7	8.15	±17.1%
D	33.6	17.4	±51.8%
E	35	16.0	±45.7%
F	20	0	±0%
G	50	0	±0%
H	50	0	±0%
Avg		**5.46**	**13.1%**

Table 3.2: Average and Standard Deviation of company age responses by organization, for organizations with over 5 responses.

According to the responses, we observe that employees have a good general sense of how old their company is. In Table 3.2 we list the response variations for company age across several organizations. We divide the standard deviation by the mean age of each company in order to normalize the standard deviation for easier comparison. From there, we find that the average normalized standard deviation for company age (Question 8) is ±13.1%. We feel this represents that respondents have a relatively consistent understanding of their organizations age. Additionally, we did not find any specific group or subcategory of participant that noticeably out performing any other.

Next, we looked at Question 7 to quantify respondents consistency/understanding regarding the age of their company's core technology. Unlike company age, we see a much larger discrepancy in responses coming from employees of the same organization. In fact, we found that the average normalized standard deviation for Question 7 was ±50.1%.

We repeated this exercise for a range of questions in our survey. See Table 3.3 for a more extensive list of employee response variations for different questions in our survey.

Number	**Question**	**Deviation from Mean**
Question 7	How long has your company's core technology existed?	±50.1%
Question 8	How old is your company?	±13.1%
Question 14	What is the part count of your organization's typical product?	±1.29%
Question 26	What percentage of total product development time do you think your company spends on concept exploration and concept selection? (exploration)	±57.1%
Question 28	What percentage of your total product development manpower is dedicated to architecture? (manpower is)	±71.3%
Question 30	What percentage of your total product development time has been spent on getting the concept right?	±60.3%

Table 3.3: Standard deviation of responses by employees within the same organization

3.3.2 Biases and Sentiment

Some questions specifically ask the respondent what they think or how they feel. For example, were asked “What percentage of total product development time do you think is appropriate to spend on concept exploration and concept selection?” (Question 29). However, the majority of questions are presented as more factual in nature. For example: “What percentage of your total product development manpower is dedicated to architecture?” (Question 28).

Despite this, both sets of answers are extremely subjective and highly susceptible to bias and sentiment. Therefore, the data collected here speaks more highly of the individuals mental models and feelings, rather than the actual manpower dedicated in product development.

For example, a respondent that is frustrated with how much time is being spent on concept exploration, may overestimate/exaggerate their estimate of current concept exploration time, or conversely they may exaggerate how little time they think should be spent.

Irrespective of bias in the absolute responses provided, the employee’s sentiment is useful in its own right. By comparing the amount of time/effort they would prefer, against the amount of time they think is currently spent, we can derive a simple metric of whether the participant feels their company currently spends too much, not enough, or about the right amount of time on concept exploration. Similarly, if we compare the spread between the preferred and perceived time spent as an indicator of overall frustration levels.

Chapter 4

Findings

With our survey data, we test three hypotheses to examine how industry, disruption, and market potential relate to organizational impact on early stage concept development. Our questions in the survey around this activity used the term "concept exploration" and "architecture design", and we did not expect respondents to distinguish whether their activity was exploration or exploitation in the academic sense.

As such, our data does not distinguish between exploration and exploitation explicitly, instead we lump both of these efforts together at the engineering level as system design innovation in the following discussion.

- H1: Organizations anticipating high market growth will spend more time on system design innovation to exploit the growth.
- H2: Organizations anticipating a decline in their market will emphasize system design innovation to explore new ways to expand their market prospects.
- H3: Engineers don't know how much time to dedicate to early stage design innovation.

4.1 Hypotheses

4.1.1 H1: Organizations anticipating high market growth will spend more time on system design innovation to exploit the growth.

First, we look to understand how organizations with different market expectations spend their time. Literature has theorized that market growth encourages managers to find ways to capture the additional business before their competitors do [33].

We test this theory with engineering teams, and their focus on system design innovation. Specifically, we test whether higher market growth effects engineering focus by encouraging engineering teams to spend more time on early stage product development in order to exploit the market growth.

In Figure 4-1, we observe that organizations anticipating a steeper rise in market growth appear to dedicate more time and resources towards concept exploration in engineering product development compared to periods of stagnant or steady rising market growth.

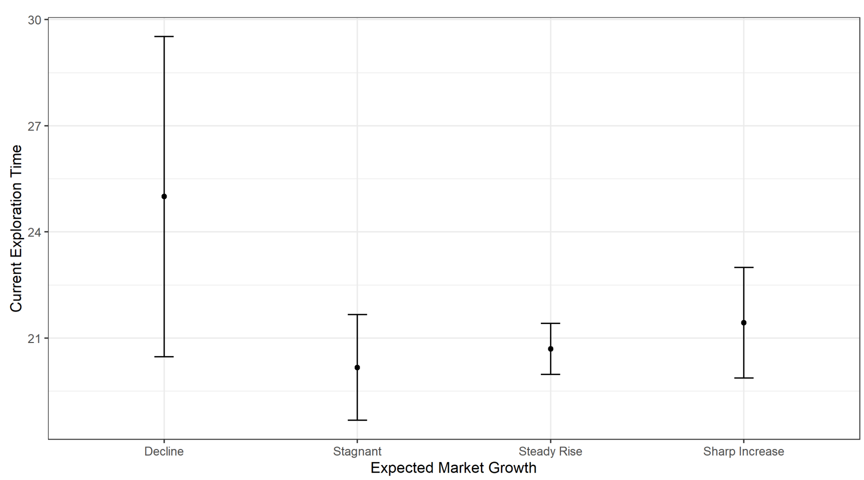

Figure 4-1: Reported Concept Exploration Time by Anticipated Market Growth

To validate this visual inspection, we construct a null hypothesis that claims anticipation of "Sharp Increase" in market growth does not affect whether how much time and effort organizations spend on early stage development. Testing this hypothesis on our dataset, we find a p-value of 0.053, which therefore suggest (with a confidence level of 94.7%) that a "Sharp Increase" in anticipated market growth does impact early stage development.

4.1.2 H2: Organizations anticipating a decline in their market will emphasize early stage development to explore new ways to expand their market prospects.

Our second hypothesis attempts to understand how organizations handle the pressure and risk of potential decline in market growth, and how it affects engineering teams. Some literature theorizes that shrinking markets drive the motivation for change, by inducing managers to explore new ways to compete [33]. We hypothesize that this pressure results in engineering teams spending more time on early stage concept development.

Looking at the difference between stagnant and declining market growth, shown in Figure 4-1, we notice a sharp up-tick in concept exploration time spent by organizations in a declining market. On average, a company anticipating a market decline are reported to spend 35.4% of development time on concept exploration, while stagnant organizations are reported to only spend 24.0% on average. An increase of almost 50%. In other terms, it could be the equivalent of spending an extra half-day per week on concept exploration.

This supports the hypothesis that managers are motivated to spend more time exploring product innovation when they feel more certain that their market is declining and not just stagnant.

Again we test our confidence using a null hypothesis that a market in "Decline" does not affect how much time and effort organizations spend on early stage development. We get a p-value of 0.0006474, therefore we confirm the effects of a Declining market on early stage development with a confidence level of 99.94%.

It is human nature to resist change and when market growth is stagnant, managers and employees may not be ready to act until they are convinced that the company will decline unless something is done.

To further support this theory, we also look at the respondents sentiment and frustration (as discussed in Chapter 2). Question 29 of the survey asked participants how much time their organizations should be spending on concept exploration, irrespective of how much time is currently spent. Figure 4-2 illustrates the difference between current and desired exploration time based on market growth expectations.

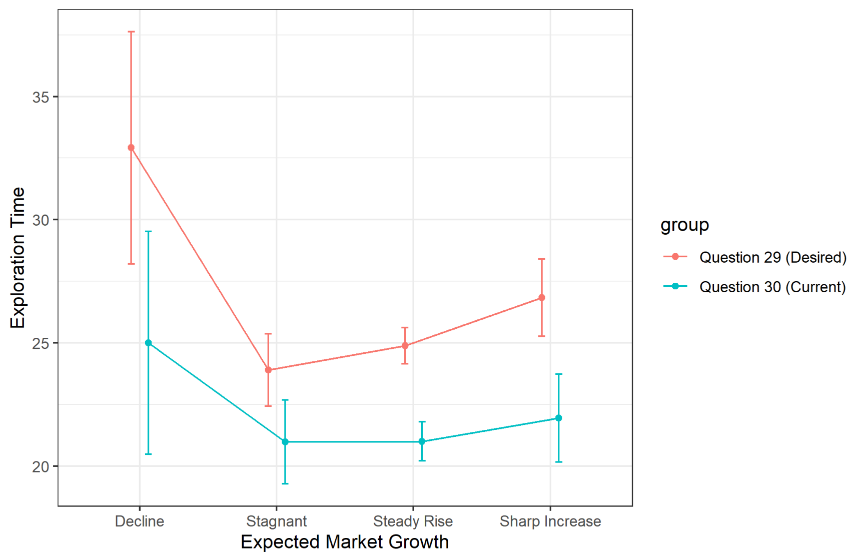

Figure 4-2: Desired Concept Exploration Time by Anticipated Market Growth

Immediately, we see that on average, employees typically want to spend more time on exploration. However, if we look at the delta between the current and desired exploration time responses, we observe that there is even a more pronounced desire from within engineering to spend even more time on concept exploration as the market prospects are looking grim.

In Figure 4-3, we calculate the delta between engineers desired exploration time versus reported current exploration time. With this data, we quantify the degree of urgency employees feel about changing their current focus and resource allocation. As shown, despite the fact that declining markets already have the highest average time spent on concept exploration, they also continue to have the greatest desire to spend even more time.

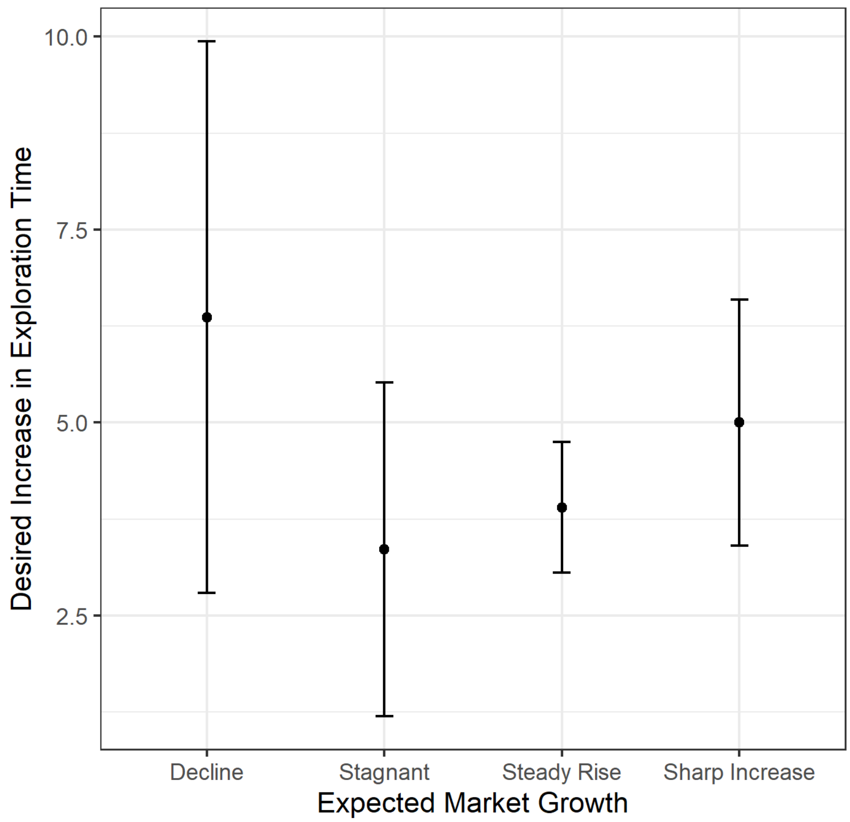

Figure 4-3: Concept Exploration Time Delta by Market Growth with Error Bar

4.1.3 H3: Engineers don't know how much time to dedicate to system design innovation.

Our third hypothesis is an attempt to quantify how well engineering teams understand and can articulate their innovation efforts. We hypothesize that engineering teams do not have a solid understanding of how much time and effort is, and should be, dedicated to system design innovation.

Figure 4-4 compares how respondents differed when asked the exact same question concerning their opinion of how much effort should be dedicated towards early stage development. Question 27 and Questions 33 of the survey are word for word the exact same question, but asked at two different stages during the course. We expected most participants to answer the same thing between both questions, however, only 26.6% of our respondents actually provided the same answer. Furthermore, 37.0% of those to answer differently, changed their answers by over 10%.

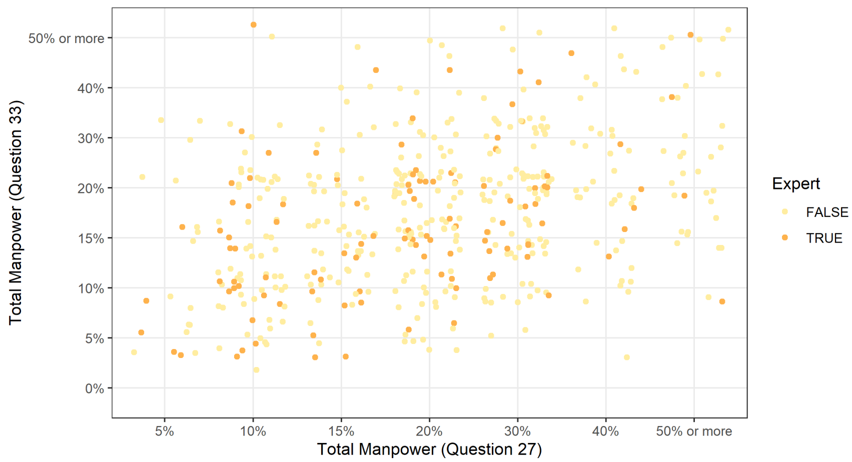

Figure 4-4: Relationship between the answers provided to two identical questions on architecture planning manpower.

We also asked respondents how much time their current organization spends on exploring new concepts (Question 30) compared to the responses from other employees within their organization.

We found that the responses from employees within the same organization varied wildly. On average, the normalized standard deviation was ±60.3%. Table 4.1 shows how six different organization differed in average exploration time, standard deviation of the responses, and normalized standard deviation (standard deviation divided by the mean). See Table 3.3 for a list of response variations of other questions from the survey.

Lastly, we wanted to make sure that our findings weren't just a symptom of selection bias. Our data set comes from a population of engineers and managers taking a course to learn more about system architecture. It's possible the respondents simply lack the experience or knowledge to reliably recognize and articulate their effort and firms focus on early stage development. Moreover, junior engineers may have less exposure to the full engineering process at their organizations.

Org	**Average Age**	**Standard Deviation**	**Percentage of Mean**
A	20.6%	12.6	±61.2%
B	23.3%	14.5	±66.1%
C	22.3%	11.7	±52.5%
D	21.0%	13.4	±63.8%
E	19.2%	14.1	±73.4%
F	25.6%	13.8	±53.9%
Avg	**23.0**	**13.9**	±60.3%

Table 4.1: Exploration Time responses by organization

In order to test this, we investigated how the more experienced respondents in our dataset perform compared with the rest of the population. In section 3.1.1, we identified a subpopulation of "experts". Using this population, we repeat the same analysis as above, except we only considered the experts in our calculation this time.

If the issue were caused solely due to a lack of knowledge, skill, or experience, we would expect to see slightly more reliable responses from this group of experts. However, we see the same inconsistent behaviour with the experts as we did with the rest of the dataset. Therefore, we are confident that knowledge and experience are not a driving factor for the wildly inconsistent responses we observe.

Chapter 5

Discussion

In this chapter, we discuss the implications of our findings and what they might mean to different industries. The main finding in our survey regarding design innovation is that the engineers surveyed didn't have a clear understanding of how much time to spend on concept exploration. Because of this, we can conclude that the engineers didn't have a clear strategy for exploration time versus exploration time. We discuss this in more detail and provide some possible reasons for our observations. We end our discussion with some thoughts on how we can apply this knowledge combined with past research to help organizations and managers improve.

5.1 Lack of Clear Strategy

In our findings, we observe two seemingly contradictory relationships. On the one hand, engineering focus on early design and architecture appears to be positively correlated with market growth. That is, the more market growth an industry is expecting, the more product development is incentivized to explore concepts to best capture the growth. On the other hand, we observe that organizations only seem to refocus on design and architecture efforts once they begin to feel the pressures of anticipated market decline rather than perceiving the pressure earlier during the stagnant phase. On average, we observed a 20% increase in exploration time when compared to organizations that consider their market growth relatively stagnant.

This reversal in trend suggests that there is not a consistent behaviour driving the development strategy.

Furthermore, in our findings we observe the striking result that engineers struggle to consistently quantify their views on early stage development. Respondents do not appear to have a clear understanding or mental model of how much effort and time their organizations should be spending on early stage development. We argue that this is a strong signal that the engineers surveyed lack a clear strategy for how to balance their efforts in early stage development.

We can think of several reasons as to why this may occur. There are many possible explanations for why we observe this behaviour, and it is hard to pinpoint the exact cause for this behaviour is. Having said that, we suggest the following possible reasons and discuss below how likely we believe they are:

- Lack of experience or exposure
- No strategy to begin with
- Communication and alignment gap
- Challenges translating strategy into action

5.1.1 Lack of Experience or Exposure

The simplest explanation is that our respondents are new or less experienced with the concepts of design and architecture, and therefore struggle to reliably answer the questions concerning the amount of effort spent on early stage development because they don't necessarily recognize the differences. The respondents are taking a course to learn more about system architecture, after all.

Similarly, one might expect that junior engineers could have less exposure to the full engineering process at their organizations. This could mean they are simply unaware of their organizations focus across the entire processes.

However, we performed the same analysis on a subpopulation of respondents who we previously identified as "experts" (as defined in Section 3.4). If the issue were caused solely by a lack of knowledge, skill, or experience, we would expect to see slightly more reliable responses from this group of experts. Unfortunately, there was no strong indication that the more experienced respondents were able to more reliably respond to questions about their early stage development efforts. For this reason, we do not believe that knowledge and experience is a primary reason for the behaviour we see.

5.1.2 No Strategy to Begin With

Another possibility is that there is no innovation strategy at the company level and not just at the engineering function level. This would help explain why responses were so varied and inconsistent, and could also explain why organizations appear to decrease focus on early efforts when markets prospects decrease. Much of the literature correlates having a strong strategic message as key to keeping everyone in the organization on course. As pressure increases, people tend to favour easier less-risky options, so may be deterred from dedicating more time towards design exploration.

However, we observed how once the market prospects appear particularly dire, engineering teams undergo a drastic shift in focus. Engineering teams hit a breaking point where they redirect efforts back towards early stage development. The re-emphasis on early stage design and architecture shows that, at some level, there was a strategic shift within the engineering team (and likely the entire organization) to instigate this change.

Moreover, many of the organizations in our study are large established organizations. Organizations of their size are likely to have at least some level of corporate strategy and innovation planning. Therefore, we find it unlikely that there is a complete lack of planning. Though, it very likely could indicate a weak or misaligned strategy.

5.1.3 Communication and Alignment Gap

Alternatively, engineering may lack a clear strategy because the strategy has not been clearly communicated to engineering. A communication gap between the corporate strategy and innovation planning could cause confusion and uncertainty. Which may be why we see engineering struggle to adequately articulate and implemented at the engineering level.

5.1.4 Translating Strategy into Action

Lastly, even with a clear message, engineering managers may not know how to apply the strategy to their everyday decision-making and engineering processes.

5.2 Suggestions for Organizations and Managers

Improvements can occur at the corporate level and engineering management levels. We propose a few actionable items that corporate leaders and engineering managers could do to improve their engineering operations.

5.2.1 Have a Clear Corporate Innovation Strategy

Without strong strategic direction or guidance, people naturally gravitate towards easier and less risky choices [11]. Rather than exploring a wide range of concepts, it can be far more appealing to instead exploit existing concepts and apply incremental changes and improvements. Which means organizations may only pursue a very narrow focus to their concept exploration [37], despite strong evidence suggesting that a broader more thorough exploration of the solution space leads to higher quality results [19].

To counteract this, [30] showed that having a clear written vision with attention to exploration and exploitation efforts is fundamental to implementing an effective innovation strategy [30].

5.2.2 Power Through The Turn

Making drastic changes in an organization can be very challenging and painful. Going through large strategic change is often fatal to an organization as it can be immense disruption, met with resistance, and often comes too late.

However, based on the findings, it appears there is a clear and substantial shift in product development focus at the point in which organizations begin to feel their market may be in decline. Even more troubling is the fact that firms appear to decrease their early stage development efforts as the market growth slowed down.

To avoid the jarring reversal in trend, we believe organizations should be powering through market slow downs with more (or at least the same) level of exploration.

5.2.3 Align Engineering with Innovation Strategy

Even with a clearly communicated innovation strategy, it's not of much use if engineering teams and managers do not adjust their development processes to align with the strategy. Burton et al. emphasized this when they showed how the alignment/misalignment of management systems strongly impacts the outcome of exploration projects [6].

However, Translating an innovation strategy to real world actions and processes is not necessarily easy. Every organization and engineering team is vastly different, so there is no hard and fast rules for how to best align an engineering teams development processes with a corporate innovation strategy. That being said, pretty much every development methodology includes guidelines and recommendations for how to consider and adjust focus on innovation.

Rather than prescribing or suggesting specific tactics, or processes, we feel the most important aspect for managers to improve is awareness and attention.

Managers need to be aware of the corporate level strategies. Particularly how the strategy relates to innovation. As already discussed in Section 5.2.1, a clear corporate level innovation strategy that can be written down and shared across the organization is vital to an effective innovation strategy. If managers are still unclear about the high-level strategy, then it's important to raise this issue and open a communication channel to get this resolved.

From there, managers first and foremost need to keep the strategy top of mind and ensure that they continually consider how their decisions and actions align with the strategy. Koryak et al. highlighted just how importance managerial attention is to the development of explorative and exploitative capabilities [30].

Additionally, adopting a portfolio approach as a means to prioritize and accept active projects can be an effective way to balance the engineering efforts and ensure they are inline with the innovation strategy [43].

5.2.4 Managers: Identify Misalignment

In order for managers and leaders to ensure they stay on tack, we discuss several signals and indicators that managers can be on the lookout for to assess how well they are aligning with the overall strategy or if they are starting to veer off course.

Team Sentiment

One indicator we see from our survey data is that engineering sentiment towards early stage development could be an indicator that more time and effort is required. The absolute metric of how much effort and time employees feel should be budgeted towards early stage development may be quite noisy.

However, a Goldilocks approach of just measuring employee sentiment towards the current processes (too much, not enough, or it's just right) could be used to assess if engineers feel they should be spending more time. In our data, we see that this sentiment analysis showed a noticeable increase in "not enough" category as markets prospects began to stagnate.

Project Timeline and Budgeting

Both retrospective and prospective assessment of time allocation and budgets of various stages of the development process can be used as a simple quantitative measure of innovation focus. This can be used as a simple smoke test for managers. Additionally, if, over time, the focus changes, managers can reconsider if the shift is inline with the innovation strategy.

Compare Incoming Project Proposals

Incoming project proposals can be a good indicator of engineering focus. Each proposal could be classified as exploration or exploitation, and then compare the balance of project proposals.

For example, if the majority of project proposals are related to optimizing various components, but the innovation strategy suggests higher emphasis on exploration efforts, then this could be an indication that the engineering team is out of alignment.

A classic example of this is how PreQuip managed to get its development efforts under control and properly aligned with its corporate strategy by developing, tracking, and maintaining an aggregate project plan [51].

5.3 Suggestions for Research

Additional research could be done to identify where the potential root causes for lack of coherent innovation strategy comes from. We also believe that more work can be done to better connect the principles of the broader innovation strategy to the units involved in product development.

5.3.1 Lack of Clarity

First off, additional research can be done to better understand the root causes for the apparent confusion within engineering with regard to time and effort in early stage development. Above we already outlined some potential causes, but more data would be needed to better understand the behaviour we observed.

5.3.2 Parallels with Engineering

There are clear similarities between existing research done on disruptive technology and organizational learning that can be leveraged and applied in the context of an engineering team and product development processes. We believe further research in these areas could help to provide engineers and managers with clearer understanding and better tools to tackle the challenges of balancing their product development lifecycle, specifically with regard to early stage development focus.

It's safe to say that the concerns and benefits discussed by all these profound researchers on the topics of organization learning and corporate strategy, are relevant and applicable to product development efforts.

Therefore, much of the learnings from these other disciplines could be used to help guide engineering teams to rationalize and guide their relationship with the paradoxes of innovation strategy.

Risk Aversion

Clayton Christensen formed the basis for his Innovators Dilemma after observing the relentless pressure executives face from investors to continually improve, outperform, and grow [10]. This is all too familiar at the product development level as well. Engineering teams and managers are constantly under pressure to decrease costs, improve performance, and deliver faster.

Just like how these pressures can affect business decisions, engineering teams and managers are also susceptible to the same pitfalls of short-sighted solutions and risk aversion.

Further research could build on the recommendations and learnings for organization structures, and apply them more specifically towards product development structures.

Learning

March's 1991 paper discusses two sides to organizational learning through the lens of exploration and exploitation [31]. Using this dichotomy, the field of organizational learning has made leaps and bounds towards how organizations can learn and adapt in changing environments.

However, the same trade off between exploration and exploitation is very applicable to engineering ability to improve their technical capabilities and core competencies.

Innovation Strategy

Both March and Christensen's seminal papers have spurred extensive research into the broader discussion of innovation strategy. The concepts have the been applied to countless other fields and disciplines. Unfortunately, very little research has directly applied these concepts to engineering and engineering management. We find this particularly fascinating because product and engineering breakthroughs are a fundamental source for disruptive technology innovations.

It's safe to say that the concerns and benefits discussed by all these profound researchers on the topics of organization learning and innovation strategy, are immensely relevant and applicable to product development and engineering. Therefore, we believe there is ample room for further research to extend the learnings from these other disciplines more directly towards engineering management. We believe this could help guide engineering teams to rationalize and guide their relationship with the paradoxes of innovation strategy.

Chapter 6

Conclusion

Successfully delivering on engineering projects can be very hard to get right. There are countless sources of risks and uncertainties, ranging all the way from development time/costs and performance to customer needs and technical uncertainties. Not to mention it's a constantly moving target. Change in markets, customer needs, new technology, and other disruptions, means that what was the right decision today, may not be the best choice for tomorrow. Therefore, an organization's ongoing ability to innovate and adapt to changing environments is absolutely crucial to its long-term survival.

Without strong strategic direction or guidance, people naturally gravitate towards easier and less risky decisions. In product development this can be seen by a strong tendency to exploit existing designs by applying incremental changes/improvements rather than exploring a wider range of new designs when selecting concepts for new products.

This interplay of exploration and exploitation has been around for ages. It is commonly used to distinguish the needs of exploring new innovation/creating new markets versus exploiting existing capabilities/markets. For decades, this concept has been studied in organizational learning and innovation strategy literature. However, very little literature correlates these learnings with product development lifecycle and engineering processes. Our study addresses part of the gap by examining how exploration and exploitation manifest themselves at the engineering level.

In this thesis, I argue that engineering teams also internally trade-off between exploration and exploitation during development and would benefit with more intentional and explicit consideration of their strategy.

Using survey data collected during an online system engineering course, we find that engineering departments struggle to adopt and follow effective innovation strategies. We cannot be sure of the exact cause in these cases. It could be that there was no fleshed out innovation strategy to begin with or because the strategy was not communicated effectively to the engineering department or because the engineering department failed to follow it.

What we did find was that as an organization's market growth decreases, attention to architecture and design innovation within engineering also decreases. This trend continues until the organization hits a tipping point where the development teams appear to undergo a drastic shift back towards design innovation. We argue that this behaviour is best explained by risk aversion and internal inertia rather than an intentional strategic decision. A more effective strategy should include a more intentional response to market change that considers the overall innovation and corporate strategy. For example, as the markets begin to stagnate, a stronger strategy may be to consider shifting priorities towards additional exploration efforts, rather than simply decreasing exploitation.

Furthermore, we demonstrate that development teams often do not articulate an appropriate strategy for each of the product development phases, and engineers struggle to maintain a consistent mental model of how much time and effort their organization currently wants to (or should) spend exploring the design space. So, although the organizational level may have developed a more intentioned innovation strategies, it is clear that this fails to disseminate down to the development level.

We suggest engineering teams and strategy teams pay more attention to how their focus and efforts align in the context of innovation management. It is critical that innovation be clearly written and communicated across the organization so that engineers can understand the implications of the innovation strategy. Early stage development phases need to be reasoned and budgeted in a manner consistent with the innovation strategy. Finally, management needs to ensure that the correct motivations are in place to ensure that the strategy is followed.

Following these results, we hope this paper will spur additional research in the area of product development and innovation strategy. First and foremost, additional research could be done to identify where the potential root causes for lack of coherent innovation strategy comes from. We also believe that more work can be done to better connect the principles of the broader innovation strategy to the units involved in developing the products. For example, such work could dig deeper into how engineering approaches and balances efforts of exploration with exploitation.

Appendix A

Tables

Table A.1: Survey Question

#	**Question**	**Answers**
Q1	What industry are you in?	List of 40 potential industries.
Q2	What is your current job title?	Systems Engineer Senior Systems Engineer Systems Architect Senior Systems Architect Other
Q3	How many years of work experience do you have?	0 years 1-3 years 4-6 years 7-9 years 10-14 years 15+ years

Continued on next page

Table A.1 – continued from previous page

#	Question	Answers
Q4	How many years, if any, with the title or duties of a system ENGINEER?	0 years 1-3 years 4-6 years 7-9 years 10-14 years 15+ years
Q5	How many years, if any, with the title or duties of a system ARCHITECT?	0 years 1-3 years 4-6 years 7-9 years 10-14 years 15+ years
Q6	What job title would you like to have 2 years after completing this course / certificate program?	Systems Engineer Senior Systems Engineer Systems Architect Senior Systems Architect Other
Q7	How long has your company's core technology existed?	$<$ 5 Years 5 Years 10 Years 20 Years 100+ Years

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Table A.1 – continued from previous page

#	Question	Answers
Q8	How old is your company?	0-5 Years 6-10 Years 10-20 Years 20-50 Years 50+ Years N/A: Government
Q9	How much growth do you foresee in your market (e.g. the whole industry, not just your company) in the next decade?	Decline Stagnant Steady Rise Sharp Increase N/A: Government
Q10	Where is your company ranked within your industry on total profit dollars?	Top 25% Top 50% Bottom 50% Bottom 25% N/A: Government
Q11	Where is your company ranked within your industry on revenue growth?	Top 25% Top 50% Bottom 50% Bottom 25% N/A: Government

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Table A.1 – continued from previous page

#	Question	Answers
Q12	What is the magnitude of your organization's typical unit cost?	$1-100
		$100-1,000
		$1,000-10,000
		$10,000-100,000
		$100,000-1,000,000
		$1,000,000-10,000,000
		> $10,000,000
		Unknown to me
Q13	How long is your organization's typical development cycle time in months?	< 1
		1-6
		6-18
		18-36
		36-60
		50-120
		> 120
		Unknown to me
Q14	What is the part count of your organization's typical product?	0
		1-10
		10-100
		100-1,000
		1,000-10,000
		10,000-100,000
		100,000-1,000,000
		> 1,000,000
		Unknown to me

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Table A.1 – continued from previous page

#	Question	Answers
Q15	What is the approximate number of full and part time employees involved in a typical product development project of your organization?	1-10 10-50 50-100 100-500 500-1,000 > 1,000 Unknown to me
Q16	How many source lines of software code are there in your organization's typical product?	0 1-10 10-100 100-1,000 1,000-10,000 10,000-100,000 100,000-1,000,000 > 1,000,000 Unknown to me
Q17	Have you ever taken an online course before?	Yes No Not sure

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Table A.1 – continued from previous page

#	Question	Answers
Q18	Which external interfaces did you find? (Select all that apply)	Outflow fluid Output pipe coupling Input pipe coupling Inflow fluid Pump mount points Shaft lubrication input Shaft coupling mount points Shaft guard mount points Electric motor mounts Vibration transfer Thermal management User control management External power input None of the above Other

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Table A.1 – continued from previous page

#	Question	Answers
Q19	Select 3 design decisions you deem necessary to the successful development of the centrifugal pump.	Open, semi-open or closed impeller Open, semi-open or closed impeller Type of shaft coupling lubricant Motor voltage, AC (220v, 110v, etc) or DC (12v, 24v, etc) Motor type, single or three phase, DC brushless, etc. Impeller material Motor cooling design Highly modular motor/pump vs single module design Definition of standard interfaces for pump coupling, mounting and motor vs non-standard Operable fluid types, i.e. water only, solids, gas, etc. Mean time between failure Bearings material definition Failsafe integrated valve into external interfaces

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Table A.1 – continued from previous page

#	Question	Answers
Q20	Systems thinking is:	An examination of the parts of a complex system Adopting a systematic process to thinking about a problem Considering a system as an interconnected, holistic entity Adopting different systems to try to solve a problem Not sure, that's why I'm here None of the above
Q21	How many architectural decisions have you made in your career?	None A few Tens Hundreds
Q22	How many discrete architectures does your company have for sale today?	1-2 3-9 10-20 20+
Q23	How many discrete architectures has your company built products on since the company's founding?	1-2 3-9 10-20 20-100 100+
Q24	How many disruptive technologies has your industry experienced since inception? (For example, digital CCD chips were a disruptive technology to film cameras)	None 1-2 3-9 10+

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Table A.1 – continued from previous page

#	Question	Answers
Q25	We should analyze whether to change the architecture for each new product we develop.	Strongly disagree Somewhat disagree Neutral Somewhat agree Strongly agree
Q26	What percentage of total product development time do you think your company spends on concept exploration and concept selection?	0% 5% 10% 15% 20% 30% 40% 50% or more
Q27	What percentage of total product development manpower should be dedicated to architecture?	0% 5% 10% 15% 20% 30% 40% 50% or more

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Table A.1 – continued from previous page

#	Question	Answers
Q28	What percentage of your total product development manpower is dedicated to architecture?	0% 5% 10% 15% 20% 30% 40% 50% or more
Q29	What percentage of total product development time do you think is appropriate to spend on concept exploration and concept selection?	0% 5% 10% 15% 20% 30% 40% 50% or more
Q30	What percentage of your total product development time has been spent on getting the concept right?	0% 5% 10% 15% 20% 30% 40% 50% or more

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Table A.1 – continued from previous page

#	Question	Answers
Q31	What percentage of your total product development time has been spent on getting the concept right?	0% 5% 10% 15% 20% 30% 40% 50% or more
Q32	How many architectural decisions have you made in your career?	None A few Tens Hundreds
Q33	What percentage of total product development manpower should be dedicated to architecture?	0% 5% 10% 15% 20% 30% 40% 50% or more

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