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1 Introduction

Most programs start up in situations where there is a high premium on early delivery, or where they are already perceived as "behind schedule". These programs are quickly staffed, then jump into requirements analysis and design, continually trying to "catch up". This leaves little time to explore options and look for innovative solutions. As a result, many organizations tend to minimize risk and protect profits by providing "yesterday's solutions" that use known technologies and approaches. However, there can be limits to how far known technologies and approaches can scale and meet the demand for new capabilities and associated attributes such as performance and security.

Many of today's problems are in search of rapidly-developed, innovative solutions. So, the question is, what do projects need to do to encourage the rapid development of innovative solutions? Over the past few years, efforts have been initiated to explore critical success factors for rapid development [1, 2, 3, 4], or for innovation [5, 6]. However, these generally did not explore how these could be achieved together. We have done a mix of interviews and visits with a set of organizations known for providing innovative solutions while reducing development time, in order to determine these critical success factors and how they were employed. The scope of this effort included technical, managerial, people, and cultural aspects of the innovative environment. This paper discusses the details of these explorations.

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Section 2 provides background information on recent research that has been done in the area of innovation. Section 3 describes the approach used for the identification and analysis of critical success factors for innovation. Section 4 presents the findings that resulted from the analysis of the data collected from interviews and site visits. Section 5 summarizes the analysis into a set of conclusions.

2 Background

Much has been written about innovation in the commercial product development environment. For example, Brown and Eisenhardt [7] talk about competing on the edge by using structured chaos as a strategy. However, attempts to make software and system development processes repeatable and manageable are based upon concepts such as Max Weber's bureaucratic organizational concepts and Fredrick Taylor's scientific management concepts which focus on compartmentalization and division of labor [8]. Kreitman [8] refers to this as the Weber/Taylor bureaucracy and its influence can be seen in software and system engineering process guidance such as the Software Engineering Institute's Capability Maturity Model [9] and the International Organization for Standardization (ISO) and Electronic Industries Alliance (EIA) systems engineering standards [10, 11]. Those that are focusing on innovation and rapid development of software-intensive systems are writing about working on the edge of chaos [12, 13, 14] (much like Brown and Eisenhardt [7]) and the associated need for flexible, adaptable, agile development processes to deal with rapid change and to facilitate innovative solutions in ultra-large solution spaces [15, 8]. In addition, teams must be able to experiment and have self-adapting processes that don't require process committee approvals and documentation [12, 8].

Chaos theory explains and helps identify underlying order in apparently random data or events. Behaviors thought to be random may have natural boundaries or patterns. Once these boundaries or patterns are determined, the order becomes apparent. This order is sometimes referred to as "emergent order" [16, 17, 12] and can lead to focused innovative solutions. Key principles in this environment include:

- Self-organization as the root of order [16]
- Teams allowed to continually re-organize to deal with new information [17]
- Learning and creative option generation encouraged [18]
- Mission/vision driven [12, 17]
- Technical flexibility with "just enough" process [12]

Faste [19] has shown that problem solving across a group of people exhibits a Gaussian distribution. When a group of people are asked to individually come up with a solution, most will produce an OK solution (within the norm), a few will produce "really good" solutions, and a few will produce "really bad" solutions. It is also interesting that for every solution that someone might rate as "really good", someone else may perceive it as "really bad". Therefore, it can take some additional work (exploration) to determine if something is "really good" or "really bad".

This need to explore before deciding if something is "really good" or "really bad" suggests the use of responsible, leveraged "play" in order to evaluate the feasibility of candidate solutions. It is also well-known that people can't "play" when they are stressed which implies that innovative ideas must be identified before the team becomes stressed over a solution.

To better understand and further elaborate on these concepts, we contacted organizations that have been successful in developing and maturing processes to support the development of innovative technologies and systems that can be rapidly fielded when needed.

3 Identification and Analysis Approach for Critical Success Factors

The organizations targeted for this research are ones that are high-performance United States organizations known for successful and sometimes innovative development in a rapidly changing environment. Most of these organizations are involved in both traditional and rapid response system development. The organizations that provided inputs for this research are:

- The Aerospace Corporation's Concept Design Center (www.aero.org)
- Institute for Creative Technologies, University of Southern California (http://ict.usc.edu/about)
- Lockheed Martin Corporation's Skunk Works (http://www.lockheedmartin.com/aeronautics/skunkworks/SkunkWorksToday.html)
- Northrop Grumman's Futures Lab, a joint venture with Applied Minds (http://appliedminds.com/)
- Commercial rapid-development company that requested anonymity.

Representatives from each of these organizations were contacted and in several cases, visits scheduled to their innovation labs or centers. Questions in several areas were used to guide discussions, but no rigorous attempt was made to obtain a written response from each organization. However, several of the organizations did provide written responses or elaborated on notes captured by the visiting researchers.

The approach used to guide the interviews started with a set of questions shown in Figure 1. These questions were used to define the business domain for innovative projects, how projects are scoped, and the types of products that are developed. Next, the types of processes, methods, and tools employed in the innovation labs or centers were explored as well as the characteristics of typical engineer and engineering teams working in this environment and the characteristics of the associated workplace. Lastly discussions were held to elicit the organization's perspective on critical success factors for rapid innovation, and to validate draft summaries of the results. The following sections describe in more detail the questions used to guide discussions in each category.

Table 1. Critical Success Factors Questions

Category	Question
Scope of Project	1. What is your "home-ground" for projects?
	2. What areas are you most effective/least effective?
	3. What triggers a new project?
	4. How are projects initially defined/scoped?
	5. Do clients participate in the process and if so, how?
Processes	6. How structured is the work environment?
	7. Are formal processes used?
	8. What is the business model for projects?
	9. How are efforts funded (investment vs. outside funding)?
	10. What is the typical duration for a project?
	11. How do you set project time horizons?
	12. How much reuse is there across projects?
	13. Do you support "process improvement initiatives"?
	14. How do you deal with classified or proprietary information?
Methods	15. What methods/methodologies (if any) are used? (e.g., formally defined agile method, quality/evaluation checks)
	16. What percentage of the total process uses these methods/methodologies?
	17. What percentage of projects use these methods/methodologies?
Product	18. What are goals of projects? (potential examples: commercial product, technology to support future system development work, proof of concept for existing project)
	19. What % of a system/system aspect is modeled before proceeding into total system design/development?
	20. How much of model/prototype can be used "as is" vs. re-developed for actual use/integration?
	21. What is the mix of projects in your portfolio? (E.g., commercial, military, space, other government)
Tools	22. What types of development tools support your environment? (Commercial? Internally developed?)
	23. What types of project management tools support your environment?
	24. Do you use any type of prototyping or simulation frameworks?
People	25. What is the typical project size in terms of number of people?
	26. Are these people dedicated full time to each project?
	27. If not full time, how many projects is a typical person supporting?
	28. How would you characterize engineers working in this environment with respect to skills, experiences, work processes?
Work Space	29. How are workspaces organized to support collaboration and innovation?
	30. How controlled is the workspace with respect to clients, potential clients, or other visitors that may participate in collaboration?
Key Success Factors	31. What are critical success factors with respect to people, business practices, intellectual property, and facilities?
	32. What are typical metrics you use to assess the success of your projects?
	33. What aspects of your organization are critical to the success of your projects?
	34. How much of success depends upon innovation? If a significant part, what is done to encourage innovation?

3.1 Scope of Projects

The questions in this category captured information about the business domains or "home-ground" for the organization's innovation-related projects, what triggers a new project, how projects are initially defined/scoped, and how much outside participation there is by actual or potential clients. The goal of these questions was to discern how new innovation projects are selected and how tightly coupled they are to business values and goals.

3.2 Product

These questions probed the types of products that are produced in the innovation environment. They ask about the goals of the projects, whether they are more oriented towards a commercial product, technology to support future system development work, or proof of concepts for existing projects. The questions also probed the role of modeling, simulation, and prototyping; if they are employed, what percentage of the system is typically modeled, simulated, or prototyped; and whether models and prototypes can be used "as is" for an actual system or whether they need to be redeveloped for actual use or integration. The final set of questions asks about the mix of projects in the innovation portfolio.

3.3 Processes

The process questions investigate the business model for innovation projects, the formality of the innovation environment (and if there are formal processes, how are process improvement initiatives managed), how structured the work environment is, as well as funding sources for the projects (internal investment versus outside/sponsor funding). In addition, questions probed typical project duration, how these durations are set, and how classified or proprietary information is handled. Lastly, questions were asked about reuse (components, patterns, etc.) across projects and the role this typically has in innovation projects.

3.4 Methods

Methods can span development methods such as agile to quality methods such as inspections and testing. They can also include "go/no-go" business reviews that monitor results to date to determine where future investments should be made. The questions in this category probed the types of methods used, the percentage of the total process covered by specific methods, and the percentage of projects that use the methods.

3.5 Tools

Typically there are both management and development tools that support project activities. These questions probed the types of development and management tools typically used and whether they were primarily commercial or internally developed tools. Particular attention was paid to any types of prototyping or simulation frameworks that were used.

3.6 People

As pointed out by [12] and others, one can have the greatest development environment, processes, and tools, but it is having the right people that make the most difference. These questions probed both team and individual characteristics. The questions included team size, whether or not individuals worked full time or part time on innovation activities, and if not full time, how many projects each person worked concurrently. Questions were also asked to understand engineer backgrounds with respect to skill types, experience, and personal work processes.

3.7 Workspace

In addition to having the right people, the workspace must be "structured" to support both collaboration and experimentation. In addition, outsiders (clients, potential clients, venture capitalists, etc.) may want to participate in the process or view in-progress activities. This category of questions probed these areas and focused on how the workspaces are organized to support collaboration and innovation as well as the extent of control or access with respect to clients, potential clients, and other visitors. This can be a particular challenge with respect to outsiders since organizations participating in joint ventures may find themselves competitors on related projects.

3.8 Key Success Factors

The final set of questions asked the organization representatives to comment on their perceived critical success factors. These questions covered critical success factors with respect to people, business practices, intellectual property, and facilities. They also probed metrics used to assess success of projects and the aspects of the larger organization that are critical to the success of projects. Finally, the organization was asked to indicate how much of their success depends upon innovation and if a significant part, what is done to encourage innovation.

4 Findings

To encourage candid responses and to protect the proprietary nature of some of the organizations' responses, actual responses captured are not provided. Rather, this section describes critical success factors that were common at several sites, if not all sites, while providing some context in distinguishing classes of solutions.

4.1 Early Concept Exploration and Feasibility Assessment

All of the organizations that provided inputs indicated the importance of early concept exploration and feasibility assessment that often required considerable modeling and prototyping. The level of modeling and prototyping varied, typically based upon perceived risks of the technical approach or the technologies to be integrated into the solution. In order to encourage innovation, organizations think that it is important to establish a supportive culture and environment. The length of the "rapid innovation" period also reflected different balances of the risks of delay versus the risks of system malfunction.

One organization's objectives were to reduce the concept exploration time from 1-2 years to 60 days. This time was used to explore several approaches for major systems with few options for fixes once they were deployed.

The commercial company's strategy was to produce a quick prototype on Day 2, and iterate it into an initial operational capability in 16-24 weeks. This company developed supply-chain domain applications that had lower risks of malfunctioning, as they could be rapidly adjusted in a pilot operation.

4.1.1 Investment in Innovation Environment

Several organizations pointed out the importance in investing in innovation and technology maturation ahead of an identified need, especially when customers may need rapid responses to changing needs, missions, and threats. Innovation is very difficult to achieve in stressful situations. Starting with a clean sheet of paper and designing a solution quickly may produce a useful solution given the right engineering expertise, but it will probably not reach the level of innovation. To enable innovation, organizations:

- **Include Responsible Play:** Organize work to include responsible play with new concepts and ideas in a supported lab environment. Some have found ways to reduce stress and create time for responsible play by promising a customer a solution that is within the "norm", implementing that solution within half the planned time, saving it, then spending the rest of the time trying to build a "really good" solution within the remaining time (reclaimed play time).
- **Focus on Team Rewards:** Set up a collaborative environment that rewards team work rather than individual work. This leads to sharing and collaborating without fear that their personal rewards (e.g., promotions, raises, bonuses) will suffer when someone else gets the credit.
- **Use Both Science and Art:** Learn to balance the engineering focus between science and art. This means that the team looks for ways to make the familiar strange (art) and make the strange familiar (science). Another way to look at this is breaking models (art) and making models (science). This type of exploration follows a basic three-step process: build a model, test the model, reflect and break the model, leading to the building of a new model.
- **Make it OK to Fail:** It is often through failures that people learn and adapt ideas.
- **Leapfrog:** It should also be not-OK to not-fail. Keep teams from trying for 20% improvements. Go for at least a factor-of-2.
- **Multi-sourcing:** If it's OK to fail, you want to have several teams trying different approaches. This also stimulates the competitive juices, often even within a single organization. Some commercial companies have two to four design shops that compete for the next version of their product.

4.1.2 Root Cause Analysis of Customer Problem

Most of the organizations interviewed focused on finding solutions for a specific problem or set of problems. The first step in developing a "solution" is to understand the problem. Spending time up front to investigate the root cause of a customer's problem can result in significant payoffs. Sometimes the best solutions focus on eliminating the root cause of the problem rather than developing something to deal with the problem once it occurs.

4.1.3 Reality Confrontation

Early prototypes are invaluable in both understanding the requirements through iterative feedback from customer and understanding the capabilities and limits of new technologies or existing technologies used in new ways.

Much is learned from taking a design on paper and translating it into a prototype that designers, customers, and potential users can interact with. Have a working prototype on Day 2, and have real users ready to exercise and comment on it. A combination with Leapfrogging is to do a factor-of-1.5 solution, get some quick experience with it, and then try for a factor-of-4 solution. If you have to back off to a factor-of-3, you're still ahead.

4.1.4 Customer or Sponsor Commitment and Participation

For those cases where efforts are applied to a specific customer need, customer/sponsor commitment and participation are extremely important. In fact, at some sites, if the customer/sponsor does not provide the needed level of commitment and participation in developing and assessing the feasibility of the requested solution, work is deferred. The customer/sponsor participation is required to provide insights into the requirements/user needs as well as to interact with models and prototypes to give feedback to the concept developers. Note that innovative design may have no identified customer or sponsor. For example, when the organization is attempting to develop a breakthrough commercial product for a totally new market, they may rely on market surveys and trends rather that a specific customer or sponsor.

4.2 Value-Adding Tools

Tools are required to succeed in this environment. However, the tools must be the right (value-adding) tools and the users must be experienced with those tools. The wrong tool or the right tool with no team expertise is not of value. For those organizations that periodically tap their key corporate resources (i.e. super-stars) to work on special innovative, rapid response projects or to conduct feasibility assessments of concept designs, it is important that the project work environment include the tools that those team members use in their day-to-day work. Another key theme is that tools don't need to be the best or the most sophisticated. Sometimes it is the simple, stable tools that work best.

4.3 The Right People

Most agree that you can have the best tools and the best processes, but without the best people, success is difficult. To achieve the desired results in an innovative, rapid development environment, organizations need to enable the best to achieve the desired task.

4.3.1 Empower the Best

For the rapid response and up-front innovation, prototyping, and feasibility assessment work, the organizations typically focus on their super-stars and experts in the domain(s) of interest. (Some experiences indicate that super-stars can be as much as 10 times more productive than the average performers.) These people work together as a small, lean team, collaborating almost continuously and developing frequent iterations and refinements of concepts until the desired solution is identified and adequately understood.

Managers of these teams typically have full authority and responsibility for them and the technical members are empowered to make the technical decisions. Because of the relatively small size of many of these teams, the project organization is often flat. For larger projects (e.g., new aircraft design and development), teams are still relatively small when compared to the traditional team size, but there are typically not enough super-stars to fully staff the project. However, some super-stars mixed with committed and very experienced team members are still the norm.

4.3.2 Enable Holistic Concurrency

Have experts on tap who cover the key fielding considerations and their tradeoffs (for example performance, reliability, usability, producibility, evolvability, cost), who participate concurrently rather than sequentially, and who pro-actively keep up with the state of the art in their respective domains.

4.3.3 Identify a Keeper of the "Holy Vision" [20]

The strongest successes come when the team has someone with enough range of expertise and experience to understand and synthesize the components of solutions, and to bring the right people together when problems come up (e.g., Kelly Johnson's principles for Boeing's Skunk Works).

4.4 Supportive Work Environment

Whether or not the work is classified or proprietary, the innovative, rapid development teams tend to work in their own large, relatively unstructured open space (sometimes with cubicles) to encourage collaboration and experimentation. When the same key people are being used frequently for intense rapid-response projects, it is important for the organization to provide additional resources and rewards that will help these people with their outside lives (e.g., family, external commitments). If people on the teams are overly stressed, innovation and creativity will suffer. They could easily end up reverting to a 9-to-5 work mode that is counter-productive to the innovation and rapid-response goals.

5 Conclusions

This research work was motivated by the fact that certain organizations are able to innovate consistently. In this paper, we present our investigation of such organizations and our key findings. Successful innovative organizations share certain characteristics. They are all driven by business value and they are all prepared to make the needed investments. They exploit opportunities by taking calculated risks. They follow concurrent engineering practices to accelerate cycle times. They focus on their core business areas and continually look for solution patterns that they can reuse and can reuse in different and novel ways. They have proactive management that believes in small agile teams. As a result, they provide a culture and environment that supports innovation and arrange time for team members to investigate, play with, and learn from candidate solutions. These findings provide considerable guidance to organizations that are striving to rapidly develop innovative solutions and will continue to grow and evolve as more organizations employ these approaches.

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