Value Creation in the Product Development Process

by

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Written in the shadow of the September 11th terrorist attacks, this thesis is dedicated to the victims in the hope that the knowledge herein will contribute, in its fashion, to lasting peace and security.

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ABSTRACT

A framework for value creation in the product development process is proposed as an aid for visualizing and understanding value in complex processes and thus guiding resource allocation, process measurement, and process improvement. The framework is based on information received from a variety of industry site visits and stresses process value. It defines process value in product development as the approach of the enterprise in creating a desired product for the customer, continuing profit for the shareholder, and lifetime satisfaction for the employee. The four principal elements of the framework include tasks, resources, environment, and management. These elements are further divided into several levels of value attributes, affording a constructive view of value creation.

Several sets of data provide observations on portions of the framework. An analysis of industry work breakdown structures revealed (i) tasks contribute markedly different types of value among programs, implying that no single definition of "the product development process" exists at a detailed level, (ii) lower level tasks contain more enabling activities, supporting the notion that improvement efforts should focus at a detailed level of the process, and (iii) programs transitioning to lean include more tasks emphasizing cost/schedule, advocating that companies should recognize cost/schedule more explicitly. A survey showed that engineers spend over 70% of their time on communication-related activities, suggesting that achieving effective communication should be a priority of process improvement efforts. Finally, programs using earned value management had greater consistency and fewer delayed tasks than programs which tracked task completion dates only.

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I expect to pass through life but once, if therefore there be any kindness I can show, or any good thing I can do to any fellow being, let me do it now, and not defer or neglect it, as I shall not pass this way again.

– William Penn

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As suggested later in the thesis, graduate research is similar to the product development process. The core areas of tasks, resources, environment, and management were as critical in my research as they are in the product development process. This analogy helps to recognize the importance of others in the success of research. Resources, environment, and management are linked with faculty advisors, industry members, colleagues, friends, family and faith. Thus, the successful completion of this work is a testament to the many hours that others have contributed. I am grateful for these contributions and consider myself fortunate for having the opportunity to work with those listed here.

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Chapter 1: Introduction and Executive Summary

In 1996, Womack and Jones published *Lean Thinking*, which has become a primary guide for the transition to lean within the aerospace industry. Their book suggested five lean principles that enable corporations to reduce cost and time, while increasing quality. Aerospace organizations have successfully responded to these recommendations in their manufacturing operations. However, design, development, and testing activities have not yet achieved the same level of success in implementing lean principles. Despite a number of lean initiatives in "above the shop floor" activities, only a few improvements have been realized (McManus & Harmon, 2001).

The Lean Aerospace Initiative product development team has addressed several research projects that explore the application of lean to complex system product development. For example, Slack (1998) initially demonstrated that lean principles are applicable to product development, Browning (1998) provided a useful approach for modeling cost, schedule, and performance, and the 1998 LAI summer workshop identified seven types of information waste. These research projects pointed out the need for an understanding of what value means in product development, which is the subject of the thesis.

This chapter serves as an introduction and executive summary for value in product development. The research motivation in the next section leads to a problem statement and set of key questions that are addressed. The principal result of the thesis is a framework for value creation in the product development process. In addition to the framework, some lessons are drawn from the data collected and several insights are discussed.

1.1 Motivation and Problem Statement

The first principle of lean is specifying the value. During the product development process, however, value is difficult to understand. The complexity of the process, distance from the final customer, shifting market conditions, and uncertainties of technical performance, cost, and schedule, all make a simple definition of value based on customer needs unworkable for process improvement. Alternatively, concentrating on the cost of the product development process, which makes up only a small fraction of the lifecycle cost, does not focus attention on the appropriate aspects. Hence, a framework for understanding the nature of value in product development is desired. Such a framework should allow the decomposition of the complexities of value and give insight into how various aspects of product development value might be measured and improved. The framework should be supported by both qualitative understanding of industry practices and quantitative data on the aspects of value defined in the framework.

1.2 Key Questions

Key questions to be addressed include:

- How is value defined during product development? How can value be quantified before the beginning of the use life?
- Given the definition of value, how can one understand the product development process, in order to find out how to best create this value? Are the existing tools adequate to do the job, or are more advanced models needed?
- What metrics can be established to measure value during product development, and can they be used in real circumstances?

1.3 Research Overview

The thesis structure is shown in Figure 1.1. The initial chapters explore the lean philosophy (Chapter 2), the product development process (Chapter 3), and value (Chapter 4). These chapters define the principal considerations for developing a framework of value creation.

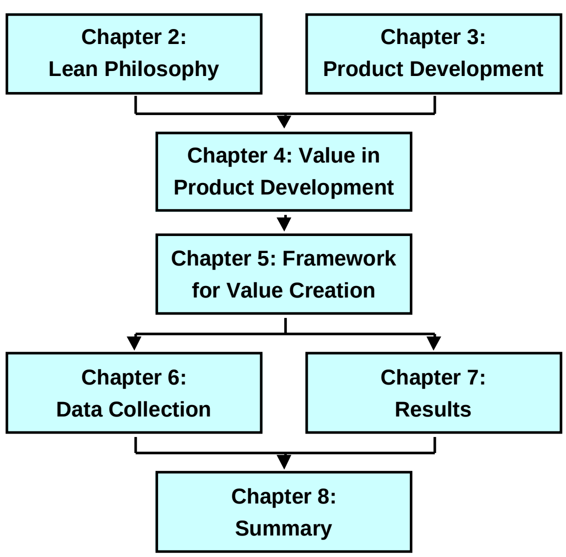

Figure 1.1: Structure for "Value Creation in the Product Development Process"

The insight gained from the background material is then combined with a series of industry site visits to produce the conceptual framework shown in Figure 1.2 and discussed in Chapter 5. This framework, and its associated breakdown of value attributes, is a principal outcome of the thesis. The four elements of the larger framework, explained in Section 5.4, include tasks, resources, environment, and management. Although its validation is beyond the scope of the research, several sets of data were acquired that provide insight on specific areas of the framework.

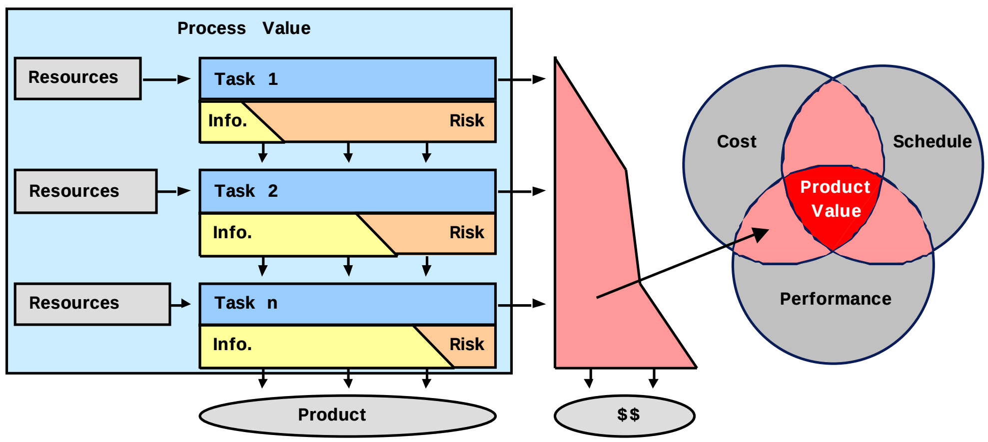

Figure 1.2: Conceptual Framework of the Product Development Process

The scope and methodology of the data collection is presented in Chapter 6, which included more than eighty interviews, four types of surveys, 15 work breakdown structures, and four sets of task completion data. Its analysis, presented in Chapter 7, provides several observations summarized in the next section on thesis contributions.

1.4 Summary of Thesis Contributions

1) The recognition of *process value* apart from *product value*. In manufacturing, value is typically defined as a product meeting performance, cost, and schedule specifications. However, in product development, it may be more useful to consider process value. Process value can be defined as the ability to perform with maximum quality at minimum cost. Intuitively, this can be thought of as the effectiveness of the process in reducing performance, cost, and schedule uncertainty (Browning, 1998; Browning, 2001; Deyst, 2001). In product

development, considering process value allows improvement even when the ultimate impact on product value cannot be determined.

2) The value creation framework of Chapter 5. Its decomposition of the process into the elements of *tasks*, *resources*, *environment*, and *management* aids the visualizing and understanding value in complex processes. This understanding can in turn be used to assist in resource allocation, process measurement, and process improvement.

3) Analysis of industry work breakdown structures (WBS's). This analysis reveals that 85% of tasks, as specified by the WBS, contribute to customer value via design, development, and risk reduction activities. The WBS's show great variety in product development processes, illustrating the difficulty of defining a product development process at any but the highest level. Most of the tasks in high-level WBS's appear to contribute value directly to the product; however, low-level (process) WBS's show more supporting tasks. This supports the idea (Browning, 1999) of analyzing product development at the lowest practical level.

4) A survey on communication. A high percentage of time in product development is spent on communication-related activities (in comparison to isolated activities). This emphasizes the importance of communication, particularly as it relates to process improvement. The survey also showed that face-to-face or small group discussion is still the most effective means of communication.

5) An analysis of four sets of task completion data. This showed that a rigorous approach to managing the schedule (that is, earned value management) can reduce the number of tasks behind schedule. This result suggests that it is possible to manage the timely completion of product development tasks, leading to the realization of product value through an emphasis on process value.

Chapter 2: The Lean Philosophy

This chapter introduces the lean philosophy, including its origin, its five basic principles, and several results from implementation efforts. Companies have historically pursued many activities to increase corporate profits, including process changes such as standardizing workflow and reengineering initiatives. The common theme among these activities was usually cost reduction. In the last two decades, however, a new concept, *lean,* has been introduced to the industrialized world. Unlike previous attempts directed at cutting costs, lean is directed at *maximizing* value (Browning, 2001). It is the philosophy of continuous improvement of corporate processes to maximize value given limited resources. This perspective emphasizes delivering customer satisfaction. Although lean applies to all processes, most implementation efforts have been directed at manufacturing. More recently, these efforts have broadened to include other areas, such as product development. This chapter presents a brief review of lean that includes several insights that apply to the study of value in product development.

2.1 Origins of Lean

Two decades ago, the U.S. automobile industry faced a crisis due to Japanese competition. Japanese cars typically required half the effort to design and manufacture, yet contained fewer than half the number of defects. U.S. executives maintained that this quality was specific to the Japanese culture and could not be replicated in the U.S. However, a comprehensive survey of automobile firms by Womack, Jones, and Roos (1990) changed that belief. Their book, *The Machine that Changed the World,* brought to light a new method for product design and manufacturing. This philosophy, later termed *lean production*, emphasizes flexibility and customer value, rather than the batch and queue process of mass production. The method originates at the heart of the Toyota Production System, which continues to be "hailed as the source of Toyota's outstanding performance as a manufacturer" (Spear and Bowen, 1999).

The crisis of high costs and poor performance of U.S. automakers in the early 1980s led directly to their desire to adopt lean practices. A few years later, the aerospace industry faced a crisis with the end of the cold war and similarly pursued lean practices. As these two sectors of the economy strove to develop lean practices, it was quickly realized that the Toyota Production System was not easily duplicated (Spear and Bowen, 1999). The system was not just composed of tools and practices, but of a fundamental philosophy that made it enormously flexible and adaptable. Womack and Jones (1996) explored this philosophy in their second book, *Lean Thinking*, which discussed five key principles.

2.2 Lean Principles

In *Lean Thinking*, Womack and Jones (1996) proposed five central ideas to describe lean. These principles are (i) specify value, (ii) identify the value stream, (iii) create continuous flow, (iv) organize customer pull, and (v) pursue perfection. These principles are central to establishing a lean enterprise and, in several instances, have been adopted verbatim by leading aerospace firms as tactics for implementing lean.

2.2.1 Specify Value

The first lean principle is to precisely specify value. Womack and Jones (1996) define value as "a capability provided to a customer at the right time at an appropriate price, as defined in each case by the customer." This definition is useful for applications where the final product is explicitly defined, such as manufacturing. For product development, however, it is less helpful. In practice, lean assessments of product development tend to fall back on ad hoc characterizations concerning which activities add value. Although simple applications of this lean principle can often root out obvious wastes found in most product development processes, optimization of the processes cannot be achieved without a more specific definition of value. This idea is a primary motivation for this research on value in product development.

As applied to product development, the first principle highlights an important conclusion. An innovative environment requires two types of value: *product value* as described by Womack and Jones (1996) and *process value*, which is largely untouched in value literature. The difference between these types of value is illustrated in Figure 2.1.

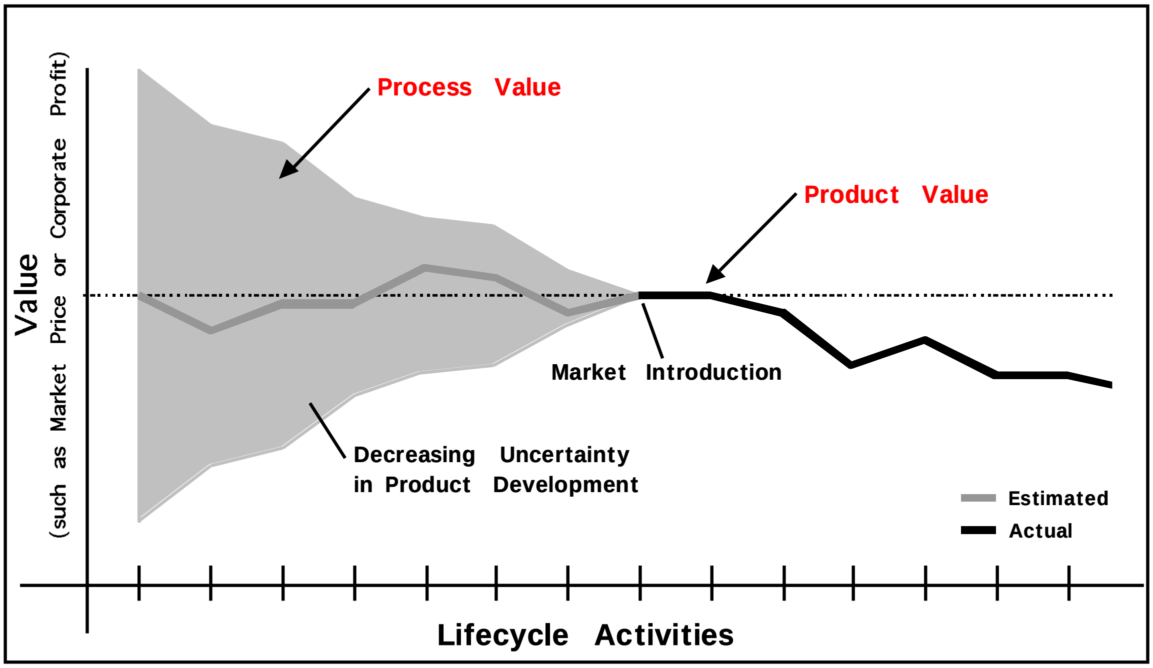

Figure 2.1: Product versus Process Value in Product Development

Figure 2.1 shows product value as the estimated and later actual value of the product as it progresses through product development and into production. When Womack and Jones define value as "a capability," they are defining the value of the physical product. In production, this is an appropriate definition as little doubt exists. In contrast, product development (as discussed in Chapter 3) embodies enormous uncertainty.[1] The product development process decreases this uncertainty, which leads to a definition of process value as the decreasing uncertainty that activities provide.

Process value and product value are thus not necessarily correlated. A good process that efficiently reduces uncertainty will not always achieve the program objectives. An example of this is the Iridium satellite constellation. Despite using modern processes and arriving on schedule and under budget, it drove its parent company into bankruptcy due to an insufficient customer base. This uncertainty in product value has prompted some industry experts (e.g., Reinertsen, 1997) to caution against a specific set of best practices.

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[1] Uncertainty, as defined here, is the variance in performance, cost, and schedule of the expected product.

2.2.2 Identify the Value Stream

The value of a product is determined through a sequence of actions that eventually delivers the product to the customer. This sequence forms the value stream, which the Lean Aerospace Initiative (1999) has characterized as "the sum of the specific actions performed on a product to carry it from raw material state into the hands of the customer." Womack and Jones (1996) point out that the concept of a value stream is slightly different than the value chain, originally introduced by Porter (1980), who emphasizes shorter sequences of activities designed to fulfill near-term objectives. Identifying and evaluating the value stream has proven useful to industry (Millard, 2001). Millard describes value stream analysis and mapping (VSA/M) as the understanding and improvement of business processes using illustrations to show the product flow towards a final outcome.

The primary benefit of VSA/M lies in its ability to arrange the process into specific, sequential actions that can be analyzed and improved. Since an understanding of value creation is at the heart of this improvement, it follows that the creation of value must also be decomposed to the level of actions.

2.2.3 Create Continuous Flow

Once the value stream has been identified, the process of continuous flow can be introduced. Continuous flow, as characterized by one industry site, is "the progressive achievement of tasks that transform (with no stoppages, backflows, or unnecessary work) relatively raw material or information into a customer desired product or service." Henry Ford introduced this idea in 1913, when he switched to continuous flow for the Model T and successfully reduced the assembly effort by 90% (Womack and Jones, 1996). Womack and Jones use Ford's example to state that "tasks can almost always be accomplished much more efficiently and accurately when the product is worked on continuously." Moreover, they suggest that getting value to flow faster "exposes hidden waste in the value stream." The concept of continuous flow may be applied in all phases of the product lifecycle. Unfortunately, this concept has not yet been introduced in many areas of industry. For example, McManus and Harmon (2001) have reported that 62% of the product development tasks they examined were found to be idle at any given time in a detailed member study. This statistic is in line with their other findings from kaizen events that show 50 to 90% idle time.

Continuous flow is probably the most important aspect of value creation. Assuming that product development follows the historical path of production, continuous flow represents the next major leap in process improvement. Organizations that successfully implement continuous flow in design, development, and testing activities will obtain large reductions in time and cost. Thus, an effective definition of value should embrace the concept of continuous flow.

2.2.4 Organize Customer Pull

The fourth principle is pull, which "is a system of cascading instructions from a downstream customer to upstream in which *nothing* is produced by the upstream supplier *until* the downstream customer signals a need" (Womack and Jones, 1996). Sales forecasts do not drive production and instead products are produced as customers signal their desire. This lets customers pull what they need rather than providers pushing unwanted products.

To apply pull, Toyota created an information and production control system (Cochran, 2000). At the heart of the system are kanban cards that signal what to produce and when to produce it. These cards control the pace and level of production, eliminating run size delay in manufacturing. In product development, the cards are sometimes used to signal the need for specific information. This concept has not generally been applied in the aerospace industry, where product development is far from achieving the level of customer pull found in Toyota (McManus and Harmon, 2001).

2.2.5 Pursue Perfection

The final step in achieving a lean enterprise is pursuing perfection. Pursuing perfection implies process improvement is never done and increases in efficiency can be achieved repeatedly. For example, industry has successfully increased efficiency in some processes by upwards of 30% each time they revisit a process (Womack and Jones, 1996). Womack and Jones also argue that transparency, or unrestrained access to data, is the most important aid to perfection and that it creates an environment where it is easy to discover better ways to create value.

2.3 Examples of Lean Implementation

Womack, Jones, and Roos (1990) originally presented a few illustrations of lean implementation from a small number of industry sectors. Since then, there have been many successful applications of lean, particularly in the production of durable goods. The results of these efforts have rippled through the economy, motivating Postrel (2001) to write that lean is responsible "for most of the dampening of the business cycle" experienced in the last decade.

Examples in manufacturing include the Ford Motor Company, which is realizing "major improvements to culture, cost and order to delivery time" at its Chicago assembly plant by using new infrastructure and value stream mapping tools (Fowler, 2001). The Department of Defense invested $96 million in several lean projects and has documented a two to one return (LAI, 1999). The improvements have included a 50% reduction in microwave power module (MPM) costs, 40% reduction in AMRAAM missile cycle time, and an $18 million price reduction on the C-17 main landing gear pod and cargo door. Other examples include a turnaround of a Lockheed Martin facility in Georgia that was credited, in part, to the use of lean initiatives (Squeo, 2000), and a European plant in Augsburg that has now been designated a DASA Centre of Excellence, following the implementation of lean engineering (Cook, 2000). The F-16 program also experienced substantial savings, including 50% less floor space and 60-80% less cycle time with the use of lean (Lewis, Norris, & Warwick, 2000). These savings have even expanded beyond the prime contractors. At Boeing, Wichita, a web-based customer pull system "saved hundreds of millions of dollars" in reduced inventory ("Informed Innovation," 1999).

The success of lean manufacturing techniques has spurred the industry to introduce lean to the product development phase as well. For example, Northrop Grumman has organized 24 lean initiatives above the shop floor (Cool, 2001), which made a direct impact on "enhanced competitiveness and financial performance." Perhaps one of the best examples is the F/A-18 E/F aircraft (winner of the Collier Trophy), which was produced below cost, on-schedule, and with comparatively superior performance (Cool, 2001). Although lean was not formally implemented, Stanke (2001) has suggested that the program incorporated many aspects of a lean enterprise in its development phase.

Despite these improvements, lean is not fully implemented. The Lean Aerospace Initiative (1999) surveyed industry leaders regarding the extent of lean implementation in the aerospace industry. The result showed that less than 50% of the activities in each business area had participated in improvement efforts. In particular, lean implementation efforts had been attempted in less than 20% of product development activities. Moreover, the majority of sites interviewed believed that this improvement is only the tip of the iceberg. One reason for the delayed application of lean is the difficulty in translating lean from the manufacturing environment to the product development process.

2.4 Summary

The lean philosophy is not just a single-use "solution" to fix current corporate problems. Rather, lean is a lifelong philosophy of increasing customer, employee, and shareholder value by more efficiently producing products desired by the customer. At the heart of lean is an understanding of the creation of value, which serves as a primary motivation for this research. Value is traditionally considered to be the value of the product, but in product development, it is more fruitful to consider the value of the process. Another insight into value creation comes from VSA/M, where decomposition of the process into specific actions suggests that an effective value methodology will similarly partition the process. There is also potential for continuous flow to improve the product development process. Finally, this chapter illustrated that most of lean success has been in production techniques, in contrast to product development where the lean principles have been found difficult to implement.

Chapter 3: Product Development Overview

In considering value creation in product development, it is necessary to explore the product development process in a rigorous fashion. This chapter is thus devoted to the product development process, consisting of the preliminary design, detailed design, and test & evaluation phases of the product lifecycle. The influence of product development on lifecycle cost is discussed, and lean theory is found to be a useful process improvement framework. A primary challenge in implementing lean is seen to be the difficulty in understanding value in the complex environment of aerospace product development. This complexity exists on three levels (product, process, and organization), which must be addressed simultaneously.

3.1 Introduction to the Product Lifecycle

The product lifecycle is the identification, development, and production of new products to fulfill changing customer needs. The lifecycle is described in Table 3.1 from several academic and industry sources. The table illustrates the three primary elements. Concept development is the identification of customer needs and working with the customer to produce suitable design requirements. Product development consists of the design and testing phases. Production is the manufacturing of the product for delivery and support to the customer. Although these elements are shared by most of the industry, some products are created in such limited quantities that the production phase is unnecessary. In an organization visited, where this occurred, the use of lean terminology was non-existent, demonstrating how lean has flowed from production into product development.

Table 3.1 illustrates the definition of product development used in this research, which emphasizes the preliminary design, detailed design, and test & evaluation phases of the product lifecycle. This characterization was chosen because it highlights the period between the contract with the customer and resulting build-to package. Since it is assumed that the most appropriate product requirements have been chosen, this research addresses the challenge of satisfying the specified requirements via the product development process.

Table 3.1: Definitions of the Product Lifecycle Process

	Rosenau, 2000	Ulrich et al, 1995	LAI, 1998	Site A, 2000[2]	Site D, 2000[2]	Site E, 2000[2]	This Research
Concept Development	Fuzzy Front End	Concept Development	System Definition	Customer Needs	Customer Needs Analysis	Advanced Studies	Concept Development
					Define Mission Requirements	Preliminary Analysis	
					Define Concepts		
					Develop Concept		
Product Development	Stages & Gates	System Level Design	Preliminary Design	Preliminary Design	Perform Preliminary Definition	[Product] Definition	Preliminary Design
		Detailed Design	Detailed Design	Product Development	Perform Detailed Definition	Design	Detailed Design
		Testing and Refinement	Fabrication, Assembly, Integration, & Testing		Build First Test Article	Development	Test and Evaluation
Production	Pre-profit Sales	Production Ramp-up	Production	Production	Production	Operations	Production
	Continued Sales				Support		Support and Operations

An organization (E) visited in the course of this research has described the product lifecycle as the "categorization of everything that should be done to accomplish a project into distinct phases, separated by control gates. Phase boundaries are defined so that they provide more-or-less natural points for go/no-go decisions." Typically, at the end of each phase there is a review by the organization to ensure the program is meeting performance, cost, and schedule objectives. These reviews establish intermediate checkpoints through which all new products must proceed.

The Lean Aerospace Initiative (1998) further refined their framework as shown in Figure 3.1. The pyramid is illustrative of the increasing information generated from the program. The information flow is tracked, with each step using internal inputs (the outputs of previous steps) and external inputs (constraints, common practices and standards, etc.) to produce a set of products passed to the next level. Risks are also considered at each step in this model. Only the

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[2] The organizations visited are labeled A-F (see Chapter 6), and are not identified pursuant with LAI guidelines.

highest level of the model is shown, and its expanded version includes additional detail not depicted here (LAI, 1998).

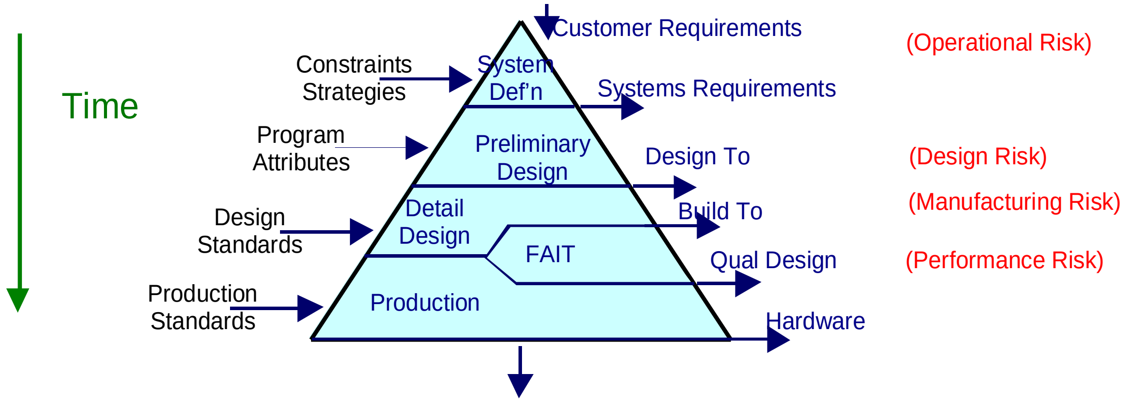

Figure 3.1: Product Lifecycle Process (LAI, 1998)

For this research, six phases in the product lifecycle are considered, as described in the following subsections. The phases selected are not a unique definition of the process. Rather, their selection is intended to provide the greatest clarity to the reader. The lifecycle phases are (i) concept development, (ii) preliminary design, (iii) detailed design, (iv) test & evaluation, (v) production, and (vi) operations & support.

3.1.1 Concept Development

Concept development includes the initial identification of the customer needs and the conversion of those needs into product requirements and specifications. For example, one organization (F) that participated in this research is heavily involved in the conceptual development of military aircraft and unmanned vehicles. They initiate the development effort by translating the needs of the military into product specifications that can be used for design.

This phase of the product lifecycle process initiates the architecture of the "technical baseline." The resolution of the technical baseline is increased throughout the development process to include functional and performance specifications for hardware, software, information items, and processes; interface requirements; specialty engineering requirements; verification requirements; data packages, documentation and drawing trees; and application of engineering standards (NASA, 1995). This structure provides the initial guidance for preliminary design.

3.1.2 Preliminary Design

In this phase, an assessment is made regarding the development and production of the product. Some activities include the search for commercial-off-the-shelf (COTS) components, inclusion of company standards, determination of make/buy decisions, acceptance and test strategy, and use of trade studies. These activities, combined with the system requirements from the previous phase, form the basis for several outputs, such as the systems requirements document, cost targets, subsystem specifications, system interfaces, test plans, system concepts (mock-up layouts), manufacturing concepts, and producibility assessment. These outputs are discussed at the preliminary design review, before a "go/no-go" decision to continue on to the detailed design phase (LAI, 1998).

3.1.3 Detailed Design

In the detailed design phase, the emphasis shifts from the decomposition of the product (as evidenced by the numerous requirements documents of preliminary design) to creating the final design. The primary elements of this phase include design, analysis, and simulations. These activities result in a "build-to package", or BTP, which is presented at the critical design review. The BTP typically includes the product definition, the manufacturing processes, and the logistics plan, including safety, support, hazards, and maintainability (LAI, 1998). As illustrated in Figure 3.1, fabrication, assembly, integration and testing (FAIT) is initiated concurrently with this phase and runs as a parallel activity into production.

3.1.4 Test & Evaluation

The objective of this phase is to eliminate technical and manufacturing risks prior to high-rate production. Test and evaluation involves the construction and evaluation of multiple pre-production versions, or prototypes, of the product. Typically, there are two classes of prototypes. Early (alpha) prototypes are designed using the intended materials, but flexible manufacturing processes, and later (beta) prototypes are created using the correct materials and processes, but with a different assembly scheme than the final product. The beta prototypes are generally used to answer questions regarding performance and reliability (Ulrich and Eppinger, 1995).

Performance and reliability are major components of the development process. Industry personnel have suggested that this phase accounts for "two thirds of the development cost." For example, to qualify for extended twin-engine operations, the Boeing 777 flight-test program was "the most extensive in Boeing history, a total of 7,400 hours" (Condit, 1996). Similarly, the software code for a successful military aircraft had "2,140 requirements in the test plan and spent nearly four years in testing," as described by an industry manager. In satellite development, the system test and evaluation phase often surfaces major problems that require the developers to change "fixed" parameters at a high cost and time delay. Once this phase is complete, the product is ready for production.

3.1.5 Production

In the production phase, the product is manufactured and delivered. Depending on the complexity of the production process, the delivery of products can increase continuously or via a step function. For example, aircraft are typically produced in two stages: low-rate initial production (LRIP) and high-rate production (HRP).

This phase realizes corporate and customer value, as production generates cash flow to sustain operations. Rosenau (2000) emphasizes two phases of production separated by the break-even point: pre-profit sales and continued sales. He proposes that the objective of new product development is to advance as quickly as possible to the point of profitability.

3.1.6 Support and Operations

Involvement of the company rarely ends with product delivery, and there is usually a lengthy period of time that involves the support and operation of the product. The product may require rework, additional upgrades, or service as a result of operational wear. Given its extensive product knowledge, the original equipment manufacturer (OEM) is generally involved in providing these services to the customer. The additional commitment may continue for years, or possibly decades. For instance, the B-52 has been operational for nearly fifty years, requiring numerous service modifications (Hernandez, 1999). This period of support is generally the most profitable for aerospace companies. For example, the Pratt & Whitney division of United Technologies discounts its jet engines heavily, relying on the profits generated by providing support and spare parts (Womack & Jones, 1996).

3.2 Importance of Product Development

The study of value in product development requires a clear definition of the product development process. However, little consensus exists in current literature for a single definition. Ulrich and Eppinger (1996) describe product development as "the set of activities beginning with the perception of a market opportunity and ending in the production, sale and delivery of a product." Other authors (see Table 3.1) regard product development separate from concept development or production. NASA (1995) further refines this definition, as distinct from preliminary design activities. This research will define product development as the preliminary design, detailed design, and test & evaluation phases of the product lifecycle.

The product development process is fixed between two critical points: the product requirements document at the end of conceptual development and the "build-to package" that has completed the test & evaluation phase. This period is the transformation of customer requirements into a set of instructions that allows for the production of the desired product. Figure 3.2 uses the uncertainty[3] in technical performance measures (TPMs) to illustrate this process. TPMs are introduced with the program requirements document (A), and the uncertainty of their outcome is eliminated with the finalized build-to package (B). This reduction in uncertainty may be considered equivalent to value (Browning, 1998; Browning, 2001; Deyst, 2001).

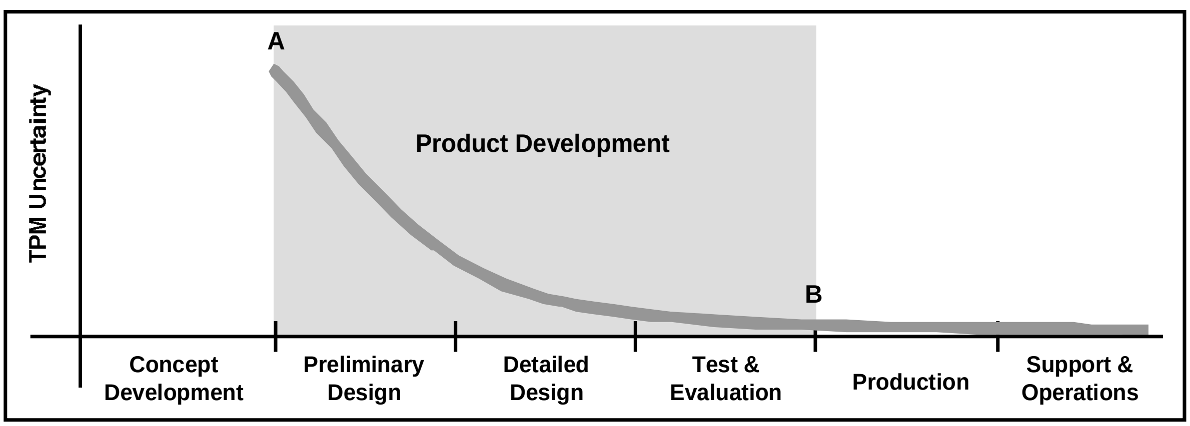

Figure 3.2: TPM Uncertainty in the Lifecycle Process

[3] TPM uncertainty is the variance, or range, associated with the expected performance of the product.

The responsibility of product development to determine TPMs indicates its unique disposition within the entire lifecycle. The reduction of uncertainty shown in Figure 3.2 corresponds with the remaining leverage that management can exert. In other words, as the TPMs are defined, management no longer has the ability to change them without incurring considerable increases in cost and schedule. Furthermore, the definition of the TPMs commits nearly 80% of the lifecycle cost, while incurring less than 15% of the cost (Fabrycky and Blanchard, 1991). This relationship, illustrated in Figure 3.3, highlights the importance of product development.

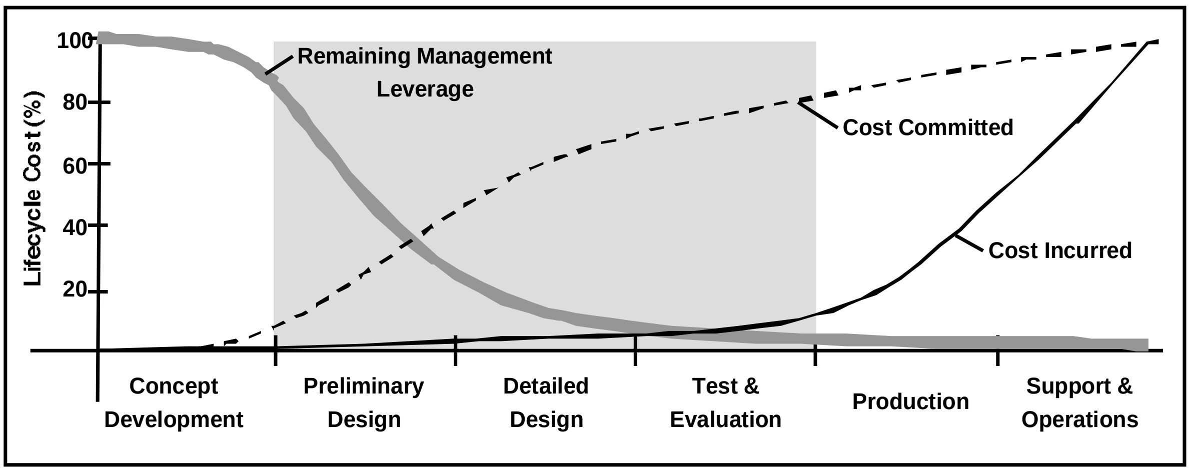

Figure 3.3: Lifecycle Cost Committed (adapted from Fabrycky and Blanchard, 1999)

The significance of Figure 3.3 is that value in product development must be examined as it affects the entire lifecycle. Otherwise, a danger exists in sub-optimizing the process, leading to undesired consequences in production where redesign is difficult. This observation suggests that lean must be applied with an emphasis on downstream value, rather than immediate cost cutting.

In production, lean emphasizes the value of the product, as it is transformed from raw materials into a finished good. The focus is on manufacturing, where lean principles such as flow, pull, and perfection can be applied to a production-orientated value stream. This environment reduces the need for communication beyond related manufacturing activities, which may explain why communication is not explicitly included in the five principles of lean. When multiple phases are considered, as in product development, it will be shown (in Section 3.4) that communication is critical to the delivery of lifecycle value.

3.3 Complexity and the Three Dimensions of Product Development

The complexity of product development has been the greatest hurdle of most process improvement methodologies. This complexity is based on the three dimensions of product development: the product, process, and organizational architectures.[4] For example, the development of a modern aircraft involves tens of thousands of parts, thousands of tasks, and thousands of individuals interrelated across different functional and corporate organizations (Eppinger & Ulrich, 1995; Condit, 1996). Managing this complexity occurs through system decomposition, as illustrated in Figure 3.4. "Complex systems are successively divided into pieces that are less complex, until they are simple enough to be conquered" (NASA, 1995).

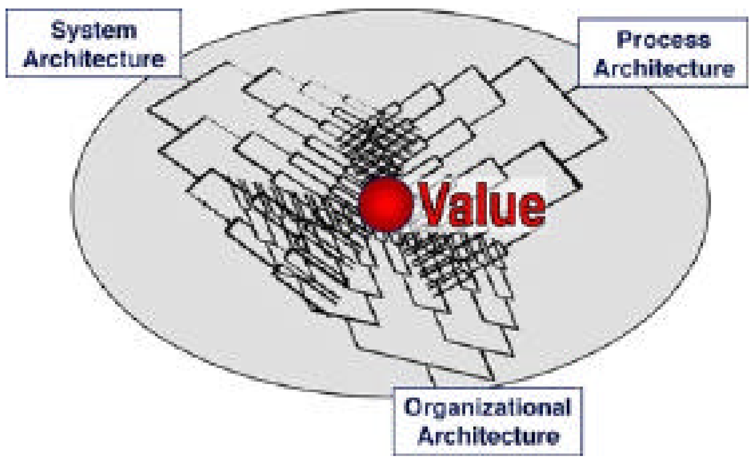

Figure 3.4: Managing Complexity to Create Value

In Section 2.2.1, the relationship between product and process value was discussed with the suggestion that process value, not product value, should be the focus of improvement in product development. This section adds a third dimension, organization, to the discussion of complexity and value in product development.

[4] Product, process, and organizational dimensions are based the "fundamental triangle of society problem solving" by Warfield (1976) and the research of Browning (2001) and Eppinger (2001),

3.3.1 The Product

Product decomposition results in the product architecture, which is established during the preliminary design phase. The method for categorizing the components varies with each organization. A general portrayal is, respectively, system, subsystem, and component (Eppinger, 2001), although further categories are available, such as the system, segment, element, subsystem, assembly, subassembly, and part (NASA, 1995). Selecting a specific product architecture for a given product has far-reaching implications, affecting product performance, product change, product variety, component standardization, and manufacturability (Ulrich and Eppinger, 1996).

The problem of determining product architecture illustrates the conflict of product value versus process value. Selecting the best product architecture represents product value. However, the results of the decision will not be known until it is too late to select a different architecture. Thus, process value, or selecting the best process, is emphasized in product development. The difference between these methods occurs in the measurement of the results. In manufacturing, the product is measured (following Six Sigma methodology), whereas in product development, the process should be the basis for measuring value. This hypothesis contributes to the framework of value creation in Chapter 5.

3.3.2 The Process

Process decomposition commonly leads to the work breakdown structure (WBS) that separates into team-level *activities* and individual-level *tasks*. The WBS is similar to the product architecture, except that it contains pieces of work necessary for program completion. Typically, several related documents are linked to the WBS, such as the cost account structure, the schedule, and the product requirements (NASA, 1995). The association of process architecture with cost and schedule creates an ideal environment for measuring value. Thus, most lean implementation efforts are directed towards development processes (McManus and Harmon, 2001), rather than the product or organization. Malone (2001) concurs with this proposition and argues that "processes…are the key building blocks for inventing new organizations. We need to give as much attention to managing the process as we have in the past to managing the products." He goes on to suggest the creation of "process knowledge repositories" that are consistent, user-friendly collections of knowledge about activities, their variations, and their interrelationships. This idea is being pursued by several sites visited in the course of this research.

3.3.3 The Organization

Until recently, aerospace companies were usually functional organizations, where employees spent the majority of their time with coworkers who shared their engineering discipline. Problems encountered included weak product teams and poor communication across disciplines. A modern approach of product teams eliminates these problems, yet sacrifices the increased knowledge shared by the entire discipline (Allen, 1977). This dilemma prompted the use of matrix organizations (Trott, 1998) that characterize most of the aerospace industry. In matrix organizations, employees divide their responsibility between their functional groups (such as structures, aerodynamics, or quality assurance) and integrated product teams (IPTs). On a complex program, such as the Boeing 777, there might be over 200 teams, involving multiple phases of the product lifecycle (Condit, 1996).

IPTs are important to the study of value, because they represent the environment where distinct functional groups agree on the product design and manufacturing plan. This agreement increases the likelihood of reducing the uncertainty, or variance, of technical performance measures. Thus, an effective process improvement methodology will most likely be applied within the environment of the integrated product team.

3.4 Pervasive Communication in Product Development

"Effective communication is vital" was the phrase echoed unequivocally by all of the product development sites visited. Clark and Fujimoto (1991) show that intense, bilateral communication is critical for problem solving. Individuals must be able to effectively communicate within their IPTs, their functional disciplines, across the organization, and with other organizations. Matrix organizational structures and concurrent development require an even greater level of communication. Allen (1977) and Bernstein (2000) studied this area extensively and recommended a variety of methods to increase verbal communication as a means for enhancing performance. The relationship Allen documented, between communication and performance, suggests that increased communication will lead to increased value in product development.

3.4.1 Communication Architecture

Despite the need for communication, it is not easily integrated into the organizational community, and it is probably the most rapidly changing area of product development and the study of value. The advance of technology has made it possible to create high quality information channels that contribute to increased value. Ulrich and Eppinger (1996) have emphasized that these information channels are critical to fully understanding the design constraints and the customer needs. For example, Ford Motor Company interactively links designers in Turin, Italy and Dearborn, Michigan before expensive models must be constructed, thus saving a great deal of time and money (Suris, 1996). Advances such as these have promoted planned communication networks that link suppliers, developers, and customers, providing clear value to the process. However, these networks are not always successful.

One industry site (A) studied communication flow across a product team and found broken communication links (where only one person felt they were communicating with another) in 32% of the cases. In other instances, overly formalized communication architectures can become so burdensome "that members of the team may try to circumvent the process" (NASA, 1995). This circumvention leads to emergent communication pathways, an otherwise helpful phenomenon that increases with the co-location of IPTs (Allen, 1977).

3.4.2 Collaborative Design and Development

This research builds on the current lean principles and suggests that collaborative design and development activity, augmented by co-location, is the heart of value creation in product development. A number of researchers have extolled the benefits of collaborative teamwork. Paulus and Yang (2000) have shown evidence that it enhances creativity and innovation. Their result is consistent with the finding from the Lean Aerospace Initiative (1999) that "teaming across multiple tiers of the supply chain early in the design process fostered innovation in product architecture, resulting in significant quality improvements, 40-60% cost avoidance, and 25% reduction in cycle time." Similarly, Iansiti (1998) found the same result in the computer industry that "in the most effective workstation and server projects, critical decisions were made rapidly and jointly by a dedicated core business team…who met daily."

Collaboration involves the exchange of information, ideas, experiences, and insights, and it occurs when the exchange is jointly undertaken and purposeful, with the expectation of mutually beneficial results (Miles, 2000). An example of collaboration involves the design of the Boeing 777, as recounted by Boeing CEO Philip Condit:

> An airline member of one team that was designing an electronics bay pointed out that the light was positioned directly overhead. That seemed like a logical place for a light, to our engineers. But the airline rep explained that when a maintenance person is actually working in the bay, his head and shoulders block most of the light, making it very difficult to see. So, we changed the design, and put two lights on the sides of the bay. A small thing perhaps, but that kind of valuable customer insight was reflected in more than 1,000 design modifications to the 777. (Condit, 1996)

The result is that a great deal of communication is necessary to create the collaborative environment illustrated above. Thus, communication must be a pervasive part of product development, leading to the conclusion that it is an integral component of value.

3.5 Fundamental Metrics of the Product Development Process

The objective of aerospace firms is to create profits by delivering products desired by customers at the right time and at an appropriate price. The success of product development is best measured by shareholder return on investment (ROI), which may be considered equivalent to shareholder value. As the final outcome measure, however, ROI responds very slowly to current business strengths and weaknesses. For this reason, it is useful to have other, more timely metrics, such as cost, cycle time, revenue, performance, resource utilization, etc. There are four general types of metrics that are most recognized in product development: performance, cost, schedule, and risk. Value in product development has historically been regarded as the appropriate balance of these metrics. The majority of industry personnel interviewed identified the first three of these metrics, and many included risk as well. This corresponds directly to public and proprietary literature, which also addresses these metrics. For example, NASA (1995) states that the objective of systems engineering is "to see to it that the system is designed, built, and operated so that it accomplishes its purpose in the most cost-effective way possible, considering cost, schedule, and risk."

3.5.1 Performance

For most of the 20th century, performance was the number one driver in aerospace product development (Condit, 1996; Womack and Jones, 1996). Designs consistently attempted to fly higher, faster, or farther. However, the time and cost necessary to achieve these performance gains meant that other aspects of the product were compromised. For instance, the space shuttle main engine is still rebuilt after each mission at a high cost and time delay. In the last decade, the emphasis on performance has shifted to include more balance between performance, schedule, and cost.

Performance is usually measured using technical performance measures (TPMs), also known as product parameters. These parameters (such as weight, range, and lift-to-drag) should attempt to completely describe the product, so that design alternatives may be objectively compared (NASA, 1995). The data collected from TPMs are additionally tracked in a "requirements watch-list," where the risk of not meeting the specifications is determined. Performance is generally a difficult metric to use for value due to the variety and ambiguity of most TPMs. Although a few deterministic cases exist (where an objective function can be applied), most efforts at combining TPMs result in subjective, weighted ratios that lack the confidence of program managers. Nevertheless, Figure 3.5 provides a notional view of performance value that has been found useful in product development.

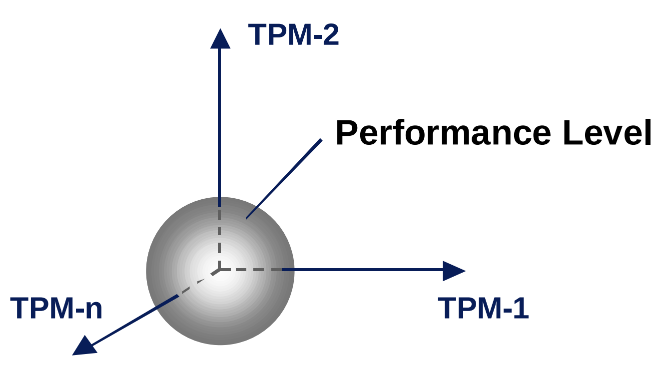

Figure 3.5: Product Performance via Technical Performance Measures

3.5.2 Cost

Performance may have been predominant in the past, but cost is now the decisive factor in most development programs. For example, airlines have stated, "their number one priority is for airplanes that are less expensive to own and operate" (Condit, 1996). Similarly, other programs, such as the F-22, are experiencing "a war on costs" (Mushala, 2001). A criterion for long-term success is becoming affordability, and industry is, as described by one program manager, "actively searching for cost-cutting opportunities."

Cost is not a simple metric. NASA (1995) describes the system lifecycle cost as "the total direct, indirect, recurring, nonrecurring, and other related costs incurred, or estimated to be incurred in the design, development, production, operation, maintenance, support, and retirement over the planned life span of a project." This definition spans multiple years and organizations, leading to difficulty in its use to optimize lifecycle value. Furthermore, the large overhead costs that accompany most aerospace firms preclude the use of cost as an effective measure for process improvement. Instead, the program schedule has been found more practical, as it can be associated more easily with individual tasks.

3.5.3 Schedule

The schedule (in the form of a work breakdown structure or integrated master schedule) is typically required for product development, because activities need time for completion in a way that respects their underlying time-precedence relationships (NASA, 1995). A schedule is created by the program manager, who (i) identifies program objectives, (ii) constructs initial plan, (iii) gathers additional opinions, (iv) revises, and (v) finalizes the plan. The program manager rarely uses historical data, relying, instead, on the previous experience of the team. Since the manager is responsible for the execution of the schedule, their objective is to include sufficient schedule margin to ensure a predicted completion date. This objective is usually balanced by a competitive interest or contract deadline introduced by the customer.

The schedule is also employed to monitor and control the product development process. The duration of each task is compared against the schedule as a means for managing the process. This methodology was imported from manufacturing, where value is equated to the control of quality, cost, and time. Also from manufacturing, cycle time (or the time for a single product to run through a process) is being used with greater frequency to manage process improvement. On several site visits, it was common for corporate management to initiate a process improvement activity by starting with an objective of a 20 to 50% reduction in cycle time.

3.5.4 Risk

Risk is not generally regarded in the same category as the previous metrics. Since risk is the unknown variability of an expected outcome, it is considered to be a property of performance, cost, and schedule. However, because of the primary role it plays in product development, it is usually segregated. In the product development context, risk denotes a combination of the likelihood and consequence of an undesired event (NASA, 1995), and it generally exists in the forms of technical, cost, schedule, technology, market, and business risk (Browning, 1998; Browning, 1999).

Either formally or informally, risk is considered in some fashion on a product development program. In a formal process, there is risk identification, analysis, mitigation, and tracking. This process may require extensive resources and contingency plans. An informal process uses significantly fewer resources, and it places more responsibility on engineers to recognize potential pitfalls. In the study of value, risk has not been introduced until recently. Browning (1998 and 2001) and Deyst (2001) have proposed that the reduction of risk can be used to manage the product development program. They suggest an approach of tracking uncertainty to evaluate product development success. For example, Figure 3.6 shows a high-level illustration of how uncertainty may be used to illustrate failure and success. The objective is to determine the likelihood of failure and eliminate the odds of it occurring through resource allocation.

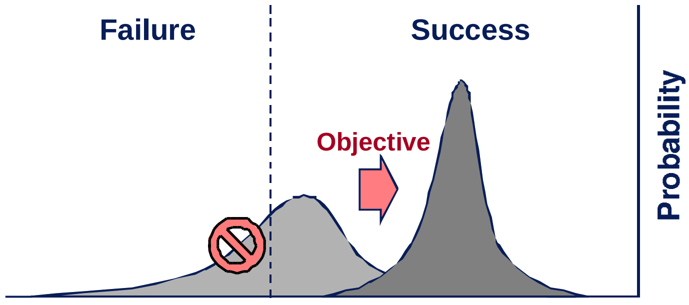

Figure 3.6: Managing Performance, Cost, and Schedule Uncertainty

3.5.5 Balancing Performance, Cost, Schedule, and Risk

Best lifecycle value is achieved through a balance of performance, cost, schedule, and risk. This statement was found to be the prevailing industry theory, from a series of site visits. The idea is similar to the System Engineer's Dilemma:

> To reduce cost at constant risk, performance must be reduced. To reduce risk at constant cost, performance must be reduced. To reduce cost at constant performance, higher risks must be accepted, and to reduce risk at constant performance, higher costs must be accepted. (NASA, 1995)

However, findings by Iansiti (1998) in computer hardware development and Womack, Jones, and Roos (1990) in the automobile industry conflict with this perception. Iansiti discovered that "the speed of development is inversely proportional to the resources allocated." In other words, hiring more engineers increases, rather than decreases, development time. Furthermore, Womack, Jones, and Roos (1990), demonstrated, using Toyota versus General Motors as an example, that performance, cost, schedule, and risk may be simultaneously improved in product development. Thus, this research suggests that the industry perception of balance is incorrect and could potentially hinder process improvement efforts.

3.6 Summary

The product development process is defined for this research as the preliminary design, detailed design, and test & evaluation phases of the product lifecycle. It exerts considerable influence on the lifecycle, since it commits 80% of the expected cost, while only incurring 15% (Fabrycky and Blanchard, 1999). Thus, value creation in the product development process must be studied in the context of the entire lifecycle. Rather than focusing on the individual steps of a value stream, such as in manufacturing, value in product development rests on a complex web of communication across functional and corporate organizations. This communication contributes to value creation and leads to the collaborative design environment of the integrated product team (Allen, 1977). Finally, the four fundamental metrics of value (performance, cost, schedule, and risk) are considered (NASA, 1995).

Chapter 4: Value in Product Development

The previous chapters discussed the lean philosophy and product development. This chapter pursues a more rigorous understanding of value. It presents some of the history on value in philosophy, economics, and product development, and it discusses the many definitions and some specific tools that, in a sense, quantify value. The objective is to present a suitable foundation for value that is used in the conceptual framework of Chapter 5.

4.1 Why is Value Important?

Many researchers have explored the topic of value because of its importance across many fields. In engineering, a primary objective is to improve on the current state, or create additional value. To add value, it is first necessary to understand it, which is why Womack and Jones (1996) list the specification of value as the first principle of lean engineering. This principle has proven beneficial in manufacturing, where it has been helpful in identifying the overall effectiveness and efficiency of activities (Deyst, 2001). In product development, value is similarly sought after, although the search has been more difficult. The Lean Aerospace Initiative (1998) has stated that "to properly measure the effectiveness of the product development process we must address the 'value' associated with product development activity at each step of the process." Similarly in industry, managers from nearly all of the sites interviewed stated the need for some measure of value. Industry members maintain that the identification and measurement of value serves three main purposes in product development: resource allocation, process measurement, and process improvement.

4.1.1 Resource Allocation

Resource allocation is the critical executive challenge (Rosenau, 2000). Currently, the process of allocating limited resources typically occurs through verbal discussion, as seen during the majority site visits. Team leads present their needs to a program board, which then decides where to allocate remaining resources. Often, there is no follow-up of this process. Rather, a "corporate memory" exists that tracks past performance. A precise definition of value would allow for more objective decisions.

4.1.2 Process Measurement

Manufacturing often defines value as reduced cycle time and fewer defects. Using this approach, manufacturers have had success in measuring current process performance. For example, a baseline process measurement is usually obtained by determining the cycle time and the number of defects produced. Unfortunately, product development lacks a similar understanding of value. Measuring the baseline often reduces to measuring the cycle time, with little consideration given to the quality of the process.

4.1.3 Process Improvement

Once a process has been measured, it is a candidate for process improvement. A precise understanding of value would allow the comparison of several processes to determine where the greatest potential for improvement lies. Once a process is identified, it can be given new tools or reengineered to provide greater value. Thus, an understanding of value not only provides the baseline for process improvement, but also the results.

4.2 What is Value?

The *Oxford English Dictionary* (1989) gives eight high-level definitions for value, each with more specific definitions, providing a total of 22 distinct meanings. In the first of these definitions, value is the "amount of some commodity, medium of exchange, etc., which is considered to be an equivalent for something else; a fair or adequate equivalent or return." And, the last definition given is in regards to painting, "due to proper effect or importance; relative tone of color in each distinct section of a picture." These multiple definitions forewarn of the complexity and subjectivity that obstruct a firm understanding of value. Loosely speaking, however, value is a measure of worth or importance of something, with a more useful definition being the topic of considerable debate.

Lloyd (1993) studied value extensively in a paper on government contracting. He found value to be an ambiguous and "weak criterion by which to judge acquisition policy." His work provides insight to the discussion of value in product development, along the themes of axiology[5] and economics. In axiology, Lloyd looked at value from classical until modern times (citing philosophers such as Aristotle, Rescher, Mudge, Edel, Pareto, and Gauthier) and concluded that:

> The results of axiology have…failed to produce a consistent, meaningful standard of value on which to judge policy. To base policy on personal preferences (as much value theory amounts to), is to continue regulating contracts as we have in the past, without any change in substance. (Lloyd, 1993)

In economics, Lloyd considered the classical view based on utility value, a Marxist approach of labor value, and the neoclassical perspective of market value. In particular, he emphasized the idea from the Austrian school of economics that value is both subjective and objective. Subjective value depends upon the possession of some good "to satisfy a want, provide some gratification, afford some pleasure, or spare some pain." And, objective value signifies "the capacity of a good to bring about some definite extrinsic result." His conclusion centered on the value definitions of marginal utility and cost-benefit analyses, as shown below.

> If marginal utility determines value, though, this naturally means that it all boils down to whose perception, personal preferences, or utility are at stake, which is hardly a meaningful standard for the development of acquisition policy…Measurement decisions in cost-benefit analysis may clearly reflect subjective or ideological determinations. Further, to include externalities and intangibles in the analysis means that their assessment "may tend to have the status of highly subjective guesses." Our hope for objective criteria in value theory in the form of cost-benefit analysis has thus proved fruitless. (Lloyd, 1993)

As Smart (1966) noted, history "is strewn with wrecks of theories of value," leading to Lloyd's final conclusion directed at acquisition policy that "one would be hard pressed to choose a less helpful standard than value." Although this conclusion warns of the difficulty associated with choosing a standard for value in product development, some success has been found in the study of corporate value.

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[5] Axiology is the field of philosophical study that deals with the general theory of value. It has sought a unified philosophy of value, but is generally regarded as unsuccessful (Lloyd, 1993).

Corporate value is important because it has promoted the measurement of value for individual company products. Using general accounting practices, products are described by three economic indicators: net present value (NPV), internal rate of return (IRR), and the break-even point (B/E). These three concepts are illustrated using a cumulative cash flow chart (see Figure 4.1). The NPV is the sum of all of the discounted cash flows over a specified period. The IRR is the expected rate of return from the investment. And, the B/E is the period of time required to recoup the investment.

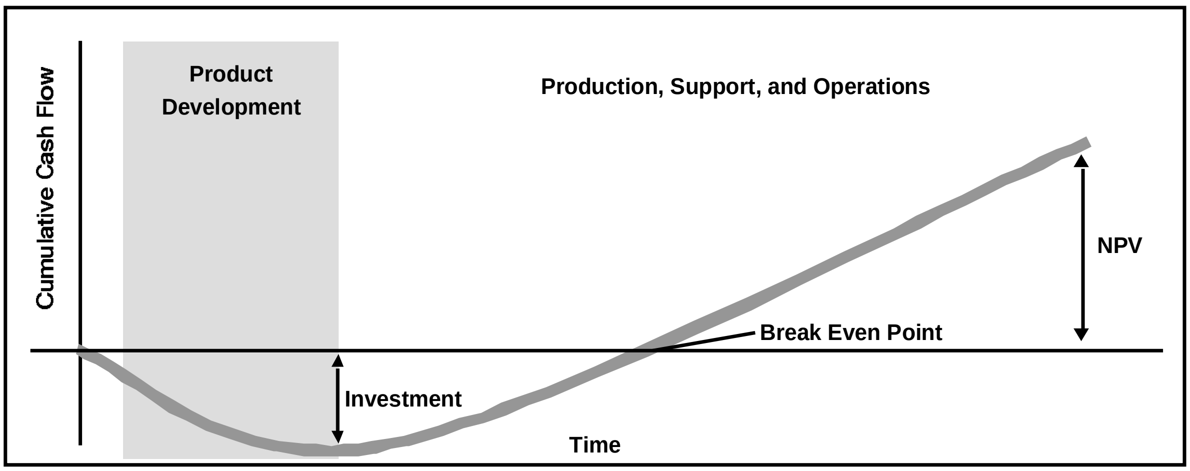

Figure 4.1: Cumulative Cash Flow of the Product Lifecycle

Figure 4.1 illustrates two aspects of the product development process. Although it directly affects the shape of the entire lifecycle curve, it appears here as a liability. This chart might suggest the reduction or containment of the initial investment because short-term realities are often considered more important than long-term objectives.

In sum, the concept of value, at a detailed level, has eluded a useful definition, beyond that proposed by Millard (2001) when he advised, "do what is good." Its prevailing subjectivity has led to multiple definitions that rely primarily on the observer, rather than some objective criterion. Still, some success has been found in economics, where the laws of supply and demand have effectively determined corporate value. Corporate value has led to a type of product value, where the measures of NPV, IRR, and B/E characterize the value of new products. These measures generally consider product development to be a cost rather than a value-added activity. Executives, however, recognize the importance of product development, and their view has led to alternative characterizations of value in product development.

4.3 Value in Product Development

Previous sections have highlighted the challenge of value in product development. It is critical to the lifecycle process, yet it is generally treated as a liability via general accounting practices. This conflict has given rise to several alternative definitions for value in product development. Table 4.1 lists definitions for value that have been proposed by academics and industry experts.

The value definitions span two primary movements: value engineering & analysis and lean engineering. This is observed from the definitions as they originate with performance and cost, grow to include schedule, and finally consider risk as the fundamental elements of value. Additionally, the value definitions raise the issue of product versus process value. This difference is best shown using the 1998 definitions given by Slack (a LAI research assistant) and the LAI product development team. The former emphasizes the utility, importance, availability, and cost of the product, whereas the latter stresses the process capability in contributing to the form, fit, or function of the product. In the innovative environment of product development, process value is deemed more useful.

4.3.1 Value Engineering and Value Analysis (VE/VA)

Several decades ago, the movement of value engineering and value analysis swept through the product development process. The founder of value engineering, Larry Miles (1961), defined value as the appropriate performance and cost. His insight was the result of working for General Electric in World War II, where material shortages required the partial redesign of many products. Miles found that the redesign effort forced developers to consider function, rather than a priori beliefs on what was needed for the product. This change of emphasis surprisingly improved the performance, at a lower cost, and prompted the rise of value engineering.

Kaufman (1985) advanced value engineering when he defined value as function divided by cost. He noted that value as viewed by the producer equals function divided by cost, but as viewed by the buyer means perceived benefits divided by price. Unfortunately, Kaufman was unable to quantify function (Lloyd, 1993). In this regard, Keeney and Raiffa (1976) provided some help with the multi-attribute utility theory (MAUT). MAUT decomposes a product into descriptive, yet quantifiable attributes and uses utility theory to combine these attributes into a single descriptive function of performance (NASA, 1995). Generally, however, MAUT has been difficult to apply and suffers from a lack of confidence in the product development community.

Table 4.1: Value Definitions for Product Development

Source	Value Definition
Miles, 1961	Value is the appropriate performance and cost.
Kaufman, 1985	Value is function divided by cost.
Shillito & DeMarle, 1992	Value is the potential energy function representing the desire between people and products.
Womack & Jones, 1996	Value is a capability provided to a customer at the right time at an appropriate price, as defined in each case by the customer.
Slack, 1998	Value is a measurement of the worth of a specific product or service by a customer and is a function of: (1) Product's usefulness in satisfying customer need (2) Relative importance of the need being satisfied (3) Availability of the product relative to when it is needed (4) Cost of ownership to the customer
LAI, 1998	Value is anything that directly contributes to the "form, fit, or function" of the build-to package or the buy-to Package · Form: Information must be in concrete format, explicitly stored · Fit: Information must be (seamlessly) useful to downstream processes · Function: Information must satisfy end-user and downstream process needs with an acceptable probability of working (risk)
Browning, 1998	[Value is] balancing performance, cost, and schedule appropriately through planning and control.
Deyst, 2001	Value is the amount by which risk is reduced per resource expended.
Stanke, 2001	[Value is] a system introduced at the right time and right price which delivers best value in mission effectiveness, performance, affordability and sustainability and retains these advantages throughout its life.
Site A	Value is anything that enhances performance (form, fit, & function) as measured by cost, schedule, and risk from the perspective of the customer, be they external and internal.
Site A	"Value is a balance between performance, schedule, and cost."
Site C	Value is a product design and manufacturing plan that enable the building and delivery to the customer of a product that meets the form, fit, and function requirements that the customer wants.
Site D	Value is the knowledge that adds form, fit, or function to the "design-to" package.
Site D	"Value happens when all of the stakeholders agree."
Site F	"Value is in the eye of the beholder. It must be tied to who is making that judgment and what the alternative is."

A more recent work on value that arose from the value engineering movement is *Value: Its Measurement, Design, and Management*, by Shillito and DeMarle (1992). In their book, they compile a number of methods for using value in process improvement. They contend that:

> The basis of value measurement is the ability to gauge the value of elements in a system using subjective measurements of relative importance and costs...Assigning numerical weights to the value of components in a product or service establishes their value and uncovers areas where improvements are needed. (Shillito and DeMarle, 1992)

Once numerical values for importance and cost have been obtained, they are graphed in the format of Figure 4.2. The relative importance is plotted against the relative cost. Shillito and DeMarle, citing their earlier work, suggest the products (or product features) should have an importance over cost ratio of one (such as B). Points lying above the line (A) should be considered for additional resources, whereas points lying below the line (D) are targets for process improvement initiatives. Tanaka (1973) extended the theory with the *Optimum Value Zone*, shown in Figure 4.2. He proposes that activities close to the origin (C) are also areas of considerable value.

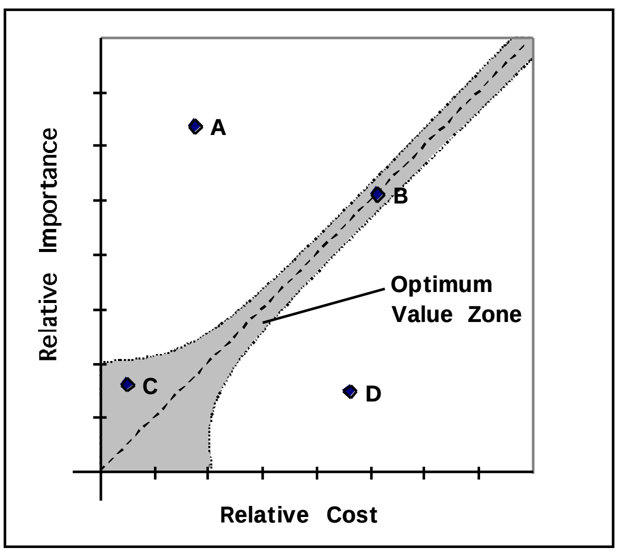

Figure 4.2: Measuring Value (Shillito and DeMarle, 1992; Tanaka, 1973)

Although Shillito and DeMarle emphasize this approach for measuring product value (consistent with value engineering), the method is sufficiently general that the value of development tasks or activities may also be ascertained in this fashion. This adaptation summarizes much of the value engineering and value analysis movement. Its emphasis on product value generated several useful methodologies and benefited specific areas of manufacturing, yet contributed less effectively to the improvement of the product development process.

4.3.2 Lean Product Development

More recently, lean has been applied to product development in the aerospace industry. The five principles of lean have previously been discussed, and this section will focus on the definition of value within lean. Womack and Jones (1996) defined value as "a capability provided to a customer at the right time at an appropriate price, as defined in each case by the customer." This definition is product-centered and is more suitable for manufacturing than product development. A better definition, for product development, is that value is "anything that directly contributes to the 'form, fit, or function' of the build-to package or the buy-to package" (LAI, 1998). This definition is useful because it provides a method for judging the value of the process. Another process-centered definition is from Deyst (2001) that defines value as "the amount by which risk is reduced per resource expended." These definitions have only been recently proposed, yet industry has begun to use them in kaizens (or lean events).

4.4 Tools for Quantifying Value in Product Development

If value encompasses the elements of performance, cost, schedule, and risk, as suggested in Section 3.5, then the quantification of value can be found in dozens of process- or management-related tools. The significance of this idea is that all tools, regardless of their explicit association with value, measure value in one form or another. For example, scheduling, risk mitigation, or relational tools may all be identified with value. The product development process uses a considerable number of such tools, of which over 30 were reviewed for this research. From this list, eight were chosen as particularly relevant for the quantification of value (see Table 4.2). The primary consideration in the selection of these tools was their ability to measure specific intervals of the process, as this partitioning of the process is critical to the study of value (Sobelman, 1958; Womack & Jones, 1996).

Table 4.2: Tools for Quantifying Value in Product Development

Reference[6]	Name	Value Definition	Metric(s)
Ulrich and Eppinger, 1995	Gantt Chart	Schedule	Program completion (time)
Thompson and Strickland, 1998	Critical Path Management (CPM)	Schedule	Duration of critical path (time)
Thompson and Strickland, 1998	Activity Based Costing (ABC)	Cost	Cost of activity ($)
Department of the Air Force, 2000	Earned Value Management System (EVMS)	Cost and schedule performance to plan	Cost performance index & schedule performance index (ratios)
Steward, 1981	Design Structure Matrix (DSM)	Structured communication	Number and pattern of interactions (#)
Davis, 2001	Balanced Scorecard	Operational plan, customer satisfaction, quality, people, etc.	Subjective indices (1-5 or 1-10)
Womack and Jones, 1996; Millard, 2001	Value Stream Analysis & Mapping (VSA/M)	Direct value added to the customer	Subjective (value-added, required non-value-added, or non-value-added
Browning, 2001; Deyst, 2001	Risk Value Method or Risk Value Model	Performance risk	TPM uncertainty (ratio)

Probably the oldest and most commonly used process tool is the *Gantt chart* that aids in scheduling multiple activities and tasks. Value is implicitly associated with a timely and predictable schedule, usually measured in hours or days. If all other factors are assumed constant, value increases as scheduling time decreases. This is usually a poor assumption, however, as illustrated by the Systems Engineer's Dilemma discussed earlier (NASA, 1995).

The second methodology is a *critical path management (CPM)*. It is similar to a Gantt chart, although it emphasizes the sequence of activities "whose combined required times define the minimum possible completion time for the entire set of tasks" (Ulrich & Eppinger, 1995). The critical path associates value with the reduction of this minimum completion time. The benefit of this tool is that it may often lead to immediate, short-term improvements in the process.

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[6] In the case of the Gantt chart, CPM, ABC, EVMS, and the balanced scorecard, the reference is not the original source of the management tool.

Another common technique is *activity based costing (ABC)*. This is an accounting practice used to associate expenses with specific activities or tasks. Rather than divide costs between personnel, software, overhead, etc., ABC links individual costs with the activities that created them. Value, in this context, is correlated with cost, where the objective is to reduce the cost associated with each activity.

The *earned value management system (EVMS)*, as the fourth tool, has gained recently in industry popularity. Programs such as the F/A-18 E/F, B-2, and THAAD have used EVMS for program management. EVMS tracks cost and schedule performance to plan. Increasing value is correlated with reaching milestones under the planned budget. The benefit of EVMS is that, through rigorous control of the process, it surfaces problems before they lead to lengthy delays.

The next methodology is the *Design Structure Matrix (DSM)* (Steward, 1981). It maps the relationships or channels of communication between tasks. DSM methodology describes the product development process in an iterative manner. Browning (1998) extended DSM methodology in his doctoral thesis to model the iteration of program schedule and cost. One advantage of using DSMs is that they identify productive and non-productive communication between system elements, tasks, and people, contributing to process improvement.

The sixth tool is the *balanced scorecard* that subjectively rates processes to ensure a balanced approach to value. Scorecards are often used with slightly different sets of enterprise attributes. For example, a division at Boeing uses the enterprise attributes of operational plan, customer satisfaction, quality, and people (Davis, 2001). Each are rated subjectively on a 1-10 scale. The result is a system that approximates value across a host of different tasks and functional disciplines. The benefit of using the balanced scorecard is that it can successfully identify diverse types of value.

Another methodology that uses a subjective approach is value stream analysis and mapping (VSA/M). Womack and Jones (1996) proposed the idea that tasks may be categorized as value-added (VA), required non-value-added (RNVA), or non-value-added (NVA). Using these labels, VSA/M visually depicts the flow of information in product development, allowing the restructuring of the process to facilitate the value contribution from tasks. Millard (2001) found

VSA/M to be an effective method for process improvement in product development. A principal benefit of VSA/M is that it emphasizes direct value added to the customer.

Finally, the *risk value method* and *risk value model* are similar tools proposed, respectfully, by Browning (2001) and Deyst (2001). The methods emphasize measuring value through the reduction of risk. Essentially, successful product development is the procedure by which the uncertainty (or the variance) of technical performance measures is eliminated in a planned and systematic way (Browning, 1998; Browning, 2001; Deyst, 2001). The methods are ideal for activities such as testing, where performance remains unchanged, but risk is significantly reduced.

This research suggests that these methodologies provide a foundation for the quantification of value. However, none capture the full complexity of value in product development, and few express value in a fashion explicit enough to be used in process improvement efforts.

4.5 Summary

A review of value in the product development process suggests that a process-centered definition of value is needed. For example, two useful definitions include "anything that directly contributes to 'form, fit, or function' of the build-to package" (LAI, 1998) or "the amount by which risk is reduced per resource expended" (Deyst, 2001). Additionally, it is important to address value through detailed increments of the development process. Each increment of the process (such as a task or subtask) should be considered as it affects communication, performance, cost, schedule, and risk throughout the lifecycle. Although no current management tool includes all of these traits, there are several tools that help forge a complete picture. Of these, eight were examined in greater detail for their relationship to product development value. A successful approach to maximizing value will include elements from each of these tools, while maintaining an emphasis on delivering lifecycle value. These insights contribute to the value creation framework of Chapter 5.

Chapter 5: Delivering Value in Product Development

This chapter integrates the ideas presented in the previous chapters into a conceptual framework for the creation and delivery of value in product development, which is supported in the remaining chapters.

5.1 Initial Observations

In this section, several observations are surfaced that are relevant to product development value. Section 5.1.1 combines earlier insights into three principal themes and Section 5.1.2 considers the best perspective for assessing value.

5.1.1 Considerations of Value

Chapters 2-4 surfaced the eight elements of value outlined in Table 5.1. They are related to three distinct areas of product development, as shown in the table. Process value and decomposition suggest focusing on the *process architecture*. Continuous flow, lifecycle perspective, and communication advocate a *collaborative environment*. The use of management tools, particularly those that treat schedule and technical risk, indicate that a *management approach* must be part of a framework for value creation.

Table 5.1: Proposed Elements of Value

	Value Should Consider the…	Section(s)	Themes
Process-	Process, rather than the product	2.2.1, 3.3.1, 4.3.2, 5.1.2	Process Architecture
Decomposition-	Individual task level of the process architecture	2.2.2, 3.3.2	
Continuous Flow-	Continuous flow of information to produce the product	2.2.3	Collaborative Environment
Lifecycle Perspective-	Perspectives of all stakeholders and lifecycle phases	3.2	
Communication-	Role of communication in product development	3.4	
Schedule-	Task duration as a measure of value	3.5.3	Management Approach
Technical Risk-	Reduction of uncertainty as a measure of value	3.5.4	
Management-	Capability of management tools to quantify value	4.4	

5.1.2 Perspective of Value

An important question regarding value is *"who determines value?"* Value is different in the eyes of each stakeholder. Customers measure value through the performance and cost of the products they receive. The shareholder considers value as the combined profits from all company products. The government requires regulatory compliance, as a subset of the greater environmental need for safety. Employees request fulfillment and stability. Finally, the enterprise seeks to balance each of these perspectives, while maximizing shareholder value.

The idea of a process-centered value definition is helpful in this discussion. The pursuit of process value suggests that the product (or customer value) is not the sole objective, and a larger corporate perspective is needed. Value should be considered as it affects the product line, or even all products, in contrast to one-time applications for specific products. Browning (2000) presents a useful illustration:

> The first version of a new, commercial aircraft does not maximize value to the customer. The initial design contains many sub-optimal characteristics, including over-designed elements such as the wings. However, the initial product can provide good enterprise value by meeting customers' near-term expectations while providing a platform upon which to base product upgrades, such as stretched fuselage versions, etc. These upgrades do a better job of maximizing value to particular customers. (Browning, 2000)

To expand this idea, maximizing value should maintain the perspective of enterprise value. For example, selecting necessary software, building knowledge repositories, or allocating critical resources should be done in context of the corporation rather than specific products. This idea supports a process-centered definition of value, and it encourages a more helpful perspective of value than is usually found at a detailed level of product development.

5.2 Conceptual Framework for Value Creation and Delivery

The ideas presented in Section 5.1 may be incorporated into a description of value creation. Here, a conceptual framework is presented that illustrates the delivery of value in product development (see Figure 5.1). It includes many of the principles previously discussed, including the representation of process versus product value.

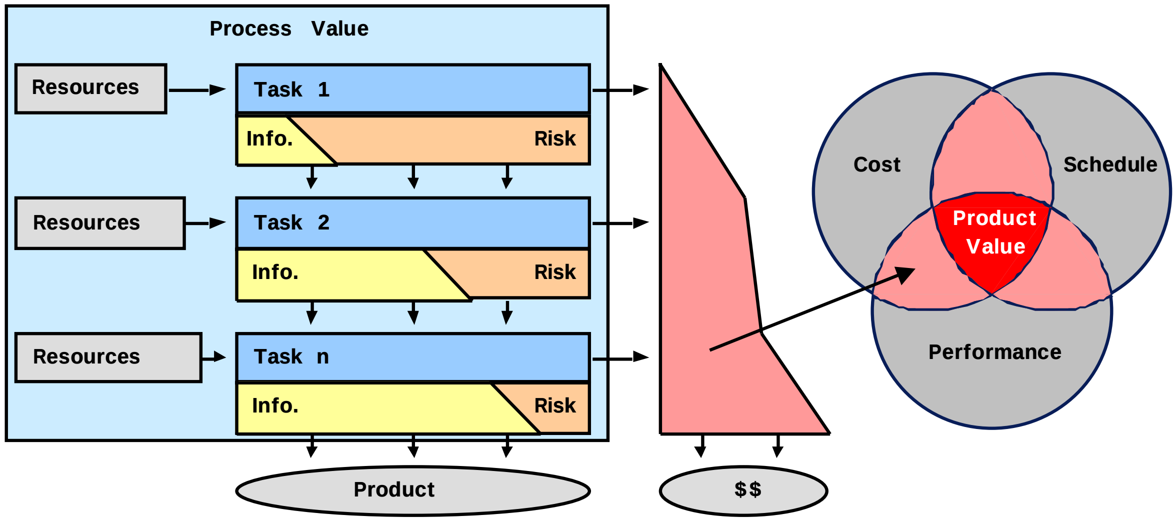

Figure 5.1: Conceptual Framework for Value Creation and Delivery

In Figure 5.1, product development tasks are shown creating information and reducing the risk of the product. These tasks need internal inputs (from previous tasks) and external resources (such as people and tools). The tasks contribute to the information package necessary to define the design and/or contribute to lowering the risk to an acceptable level. Finally, the tasks pass information to succeeding tasks.

This framework illustrates two types of value (also shown earlier in Figure 2.1). Process value is created from the selection and coordination of resources and tasks. Regardless of the specific product, an experienced, talented team is a valuable asset. Although this team may not always achieve the customer objectives (representing product value), they will reduce the risk for the enterprise and ascertain whether the objectives are attainable. In contrast, product value is a measure of the product created, often described as a balance of performance, cost, and schedule.

The challenge for lean practitioners lies in determining how to maximize process value throughout the development effort. Investigating process value, as mentioned earlier, requires the study of the process architecture, environment, and management approach. Additionally, *resources* should also be considered, given their contribution of preexisting value, flowing into the process architecture.

5.3 Research Propositions

The framework presented in Figure 5.1, combined with the previous chapters, allows three research propositions to be drawn. These propositions establish a structured approach for maximizing process value.

> (1) Value in product development is the approach of the enterprise in creating an effective product for the customer, continuing profit for the shareholder, and lifetime satisfaction for the employee. This view of value cannot be expressed by a single, quantitative metric. Rather, value is embodied in a structured approach (or template) that emphasizes a combination of qualitative and quantitative tools to maximize overall process value.

The evidence supporting this proposition has been found throughout the research. Sections 2.2.1, 3.3, 3.5, 4.2, and 5.1 illustrate the complexity of product development and the need to introduce a broader perspective. These sections also emphasize process value, which is composed of such diverse areas as resources, tasks, and communication. It is unreasonable to expect a single metric to measure each of these areas. However, Section 4.4 presents several methodologies that have successfully quantified value in subsets of the product development process. This success suggests that rather than the measurement of a single metric, value should be more flexible, such as an approach to the development process (or set of lean principles).

> (2) Despite the use of many tools for improving facets of the product development process, a framework, or set of guidelines, does not exist for the *creation* of lean design and development programs.

Until recently, most concerted efforts at process improvement were directed at the manufacturing sector. Thus, familiar methodologies such as Six Sigma, statistical process control, and even the lean principles were originally intended for preexisting, repetitive processes. These methodologies are now transitioning to the environment of the product development process. Often, the results are successful, as described in Section 2.3. For example, emphasis on value has increased coordination with the customer, value stream mapping has eliminated some of the waste, and continuous flow has increased concurrent development. However, the manufacturing roots of these tools continue to provide a subtle bias, emphasizing the improvement of old and repetitive processes. Furthermore, these tools often lack a direct association with communication and iteration, two critical elements of the product development process (see Sections 3.2, 3.3, and 3.4). For these reasons, a new set of guidelines is needed that provides the framework for lean product development.

> (3) A useful set of principles for product development includes four themes of value, including the "right" tasks, resources, environment, and management approach. These themes must be treated as distinct elements of value.

The proposed themes are suggested from the elements of value in Table 5.1 and the conceptual framework in Figure 5.1. Tasks and resources are explicitly labeled in the picture and are supported by sections describing process value (Sections 2.2.1, 3.3.1, 4.3, and 5.1.2). The "right" environment is surfaced from the need for continuous flow (Section 2.2.3), a lifecycle perspective (Section 3.2), and communication (Section 3.4). Finally, an effective management approach should be employed that measures the outcomes of performance, cost, and schedule.

5.4 Extending the Framework for Value

Given the propositions of the previous section, the objective of this thesis is the exploration of a framework for value creation, following the identification of tasks, resources, environment, and management approach as the principal elements of value. The result of this work is the proposal of a complete framework (see Figure 5.2), described in the remaining sections of this chapter, and partial evidence for its validation is presented in Chapters 6 and 7. The framework provides practitioners with a structure to pursue process improvement centered on process value, and the evidence serves as an initial inquiry that provides some insight, but more importantly, acts as a foundation on which to conduct further research.

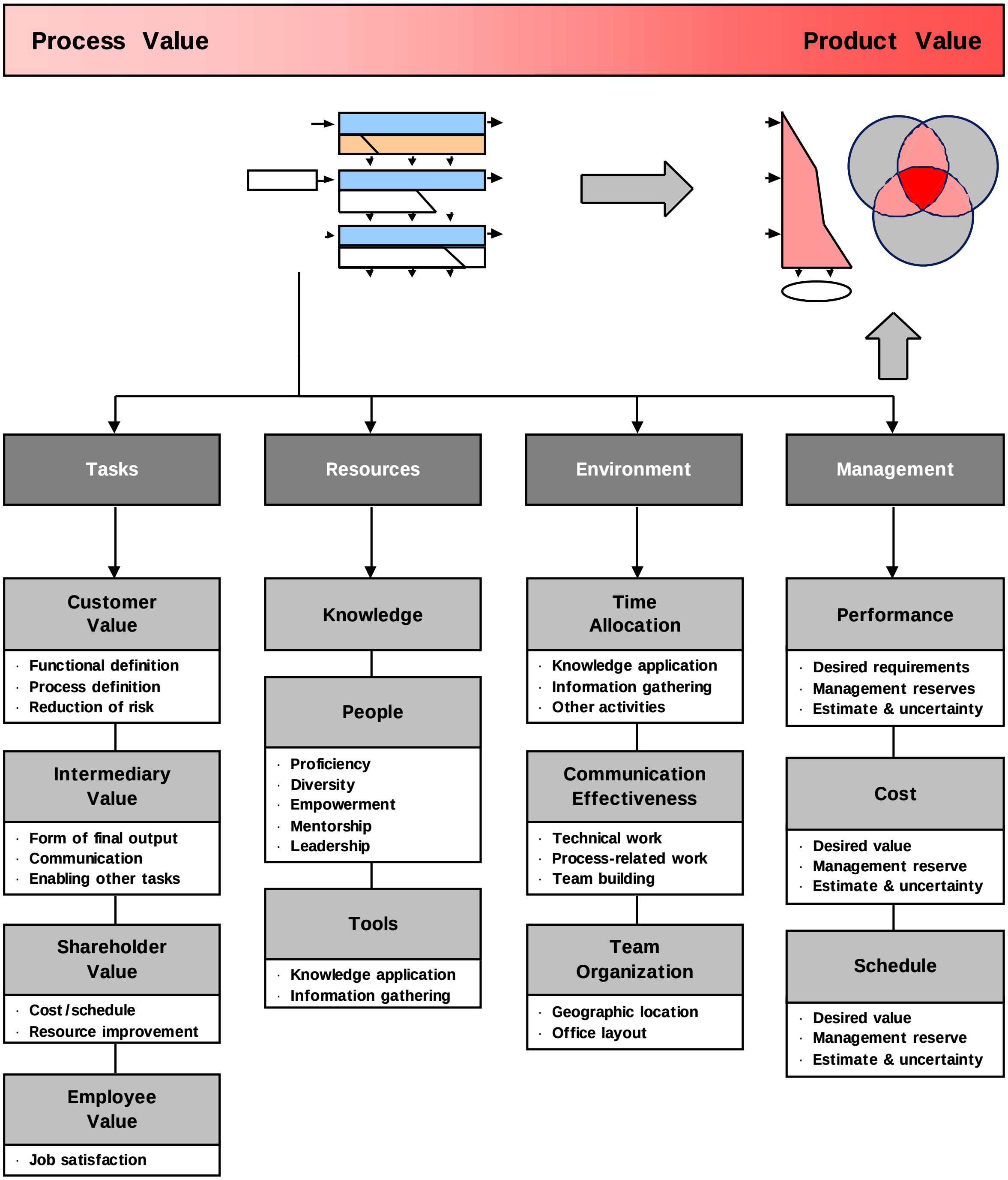

Figure 5.2: Framework for Delivering Value in Product Development

Three types of value are shown in the framework of Figure 5.2. The first column, under tasks, represents the principal building blocks of value, usually specified via the process architecture or work breakdown structure (WBS). Tasks contribute several types of value, as further explained in this research, building ultimately to enterprise value. The next two columns, resources and environment, facilitate the product development process. Although they do not, in the strictest sense, create value, the resources and environment have a direct influence on the process. Finally, the fourth column emphasizes the delivery of value. In other words, it is the successful management of cost, schedule, and performance that leads to the satisfaction of the relevant stakeholders.

The framework presented in Figure 5.2 is highly interdependent, as may be noticed by the similarity of the subheadings. A given activity in product development will include aspects across several categories. Thus, some themes consistently appear in the framework. For instance, knowledge application (or design, analysis, testing activities) and information gathering are common themes found in the framework. In the following subsections, the framework is described in greater detail, setting the stage for the data collection in the next chapter. It should also be mentioned that the framework evolved concurrently with the data collection and analysis.

5.4.1 Creating Value via the "Right" Tasks

An initial step of the product development process is the selection of the most appropriate tasks, usually described in a process architecture or work breakdown structure. Currently, program managers develop these documents based on their experience and consultation with a select group of engineers. Occasionally, they will use a template to select tasks, adjusting it as necessary for a particular program. This selection process provides an opportunity to instill the use of value, as a guide for the allocation of resources.

Measuring the value of tasks, however, generally proves difficult, since tasks add value from a variety of perspectives. Depending on the task, the customer, shareholder, employee or government may see it as value-added. Furthermore, there is rarely a single metric that describes the utility of the majority of tasks found in the work breakdown structure. Thus, the balanced scorecard approach was chosen as the means for evaluating the diverse types of value provided by product development tasks. Although the method is subjective (usually relying on a 1-5 or 1-

10 rating system), it has been used to successfully identify gaps in current programs. Following this method, a list of *value attributes* was created to describe the value provided by product development tasks (see Table 5.2). The attributes were chosen based on a perspective of value, in which the enterprise balances the needs of the customer, shareholder, employee, and government. In addition to these stakeholders, the *intermediary* was added as an important element. Intermediaries are the successive tasks and/or employees that lead to the completed objective (such as the build-to package). Their inclusion is necessary for studying value at a detailed level of product development.

Table 5.2: Value Contribution of Tasks to Enterprise Value

	Perspective	Description	Value Attribute: Task contributes to…
Enterprise Value	Customer	The customer considers the build-to package to be of primary importance. The BTP leads to the production of a product that meets the customer requirements at an affordable cost.	V1. Functional performance of end product
			V2. Definition of processes to deliver product
			V3. Reduction of risks and uncertainties
	Intermediary	Intermediaries need the right information in a useful format to enable the effective and efficient completion of tasks.	V4. Form of final output
			V5. Facilitating communication
			V6. Enabling other tasks
	Shareholder	Shareholders desire a high return on their investment. At the task level, this is accomplished via short-term cost/schedule savings or long-term infrastructure improvement.	V7. Cost and/or schedule emphasis
			V8. Learning or resource improvement
	Employee	Employees regard job satisfaction as their principal requirement.	V9. Employee job satisfaction
	Government, supplier, end-users, etc.	The government, suppliers, end-users etc. provide a host of additional needs that are often implicitly considered in the perspectives above.	V10. Other

The proposed list of value attributes is defined in Table 5.3. The definitions cover several classes of value, from direct contribution to the end product to employee satisfaction. The definitions also attempt to capture aspects of what in lean terminology might be called "necessary non-value-added" tasks, such as enabling tasks. Historically, the first three categories, representing customer value, are the most important.

Table 5.3: Value Attributes of Product Development Tasks

Task Contributes to…[7]
V1. Functional Performance of End Product
The task affects the functionality of the end product delivered to the customer. It should contribute directly to either the function or the form that affects the function. For example, related tasks include requirements specification, design decisions, material/part/subsystem specification, etc. This definition also includes all aspects of design from the initial draft to the final document.
V2. Definition of Processes to Deliver Product
The task directly affects the processes necessary to deliver the end product to the customer. It includes the design or procurement of the tools and processes necessary for manufacturing, testing, certification and/or other downstream processes, such as the creation of test procedures.
V3. Reduction of Risks and Uncertainties
The task contributes to eliminating the uncertainty in performance, cost, and/or schedule. Typically, tasks include the analysis, fabrication, and testing of the product. However, other areas might include the testing of tools/production processes, risk analysis, and cost/schedule management. Each of these areas helps to reduce uncertainty, leading to the success (or in some cases failure) of the product.
V4. Form of Final Output
The task directly contributes to the final documentation given to the customer or manufacturer. This typically includes the design of the materials, parts, subsystems, and systems. Additionally, the larger build-to package will include instructions for the manufacture of the product.
V5. Facilitating Communication
The task aids necessary communication. This is usually exemplified by reviews or meetings, but may also include discussion with other company or industry personnel. Related tasks pursue an objective of providing the necessary information to all team members for the efficient design and development of the product.
V6. Enabling Other Tasks
The task is necessary for other tasks to proceed, although it does not directly contribute to the design, production, or testing of the product. Examples include non-essential areas of management and documentation. For instance, approvals and documentation outside of the build-to-package add indirect value.
V7. Cost and/or Schedule Emphasis
The task emphasizes cost and/or schedule, usually associated with reducing the cost or labor of the product. For example, the use of Gantt charts, earned value management, or other management tools is applicable. Similarly, tasks that focus on manufacturing or support costs are also relevant.
V8. Learning or Resource Improvement
The task contributes to the skill base necessary to do future work. This definition includes developing greater knowledge, improving tools or processes, creating new technologies, and communicating this knowledge throughout the team.

[7] The definitions have been adapted from a set originally proposed by McManus (2000b).

V9. Employee Job Satisfaction
The task is interesting and enjoyable. It is considered a positive experience that increases the desire of the employee to do similar tasks. This criterion is highly subjective and may only be determined by the person responsible for completing the task.
V10. Other
Task performs a necessary or valuable function not covered in the above categories. Examples might include contributions to work environment or environmental impact reduction, satisfying of regulatory or contractual requirements, the following of existing processes, and other needs.

5.4.2 Facilitating Value Creation via the "Right" Resources

Once the necessary tasks have been selected, the next step is selecting the "right" resources to effectively carry out the program. The importance of resources surfaced from more than 80 interviews conducted with industry members.[8] In the majority of cases, engineers and managers spoke of specific resources (such as people or tools) as the primary ingredients for successful product development. The results from these interviews and a brief literature review are shown in Table 5.4. Additionally, knowledge is important but often overlaps with people and tools. For instance, tacit knowledge typically resides in people and explicit knowledge is found in tools.

Table 5.4: Value Contribution of Resources

		Attribute	Description
Knowledge	People	Proficiency	Adequate training should ensure proficiency, despite a technologically evolving workplace
		Diversity	Opportunities should exist to develop diverse backgrounds across the product lifecycle
		Empowerment	Employees should have responsibility, accountability, and authority (RAA)
		Mentorship	Collaboration and guidance should be a leadership priority
		Leadership	Key positions should have the most appropriate people
	Tools	Knowledge Application	Efficient tools should be employed to directly apply knowledge in the creation of value (such as CAD, CAM, etc.)
		Information Gathering	Efficient tools should allow the swift access of tacit and explicit knowledge across the extended enterprise

[8] The research interviews and site visits are discussed in Section 6.2.

5.4.3 Facilitating Value Creation via the "Right" Environment

The third step of successful product development is creating the "right" environment. The environment facilitates the delivery of value in product development by promoting effective communication. In studying the environment, it can be partitioned into three areas: time allocation, communication effectiveness, and team organization as shown in Table 5.5. Time allocation is the percentage of time spent on value-added, enabling, and other activities. In manufacturing, similar metrics have been kept where the time spent directly with the product has been measured. Communication effectiveness looks at the role of different types of communication to conduct technical, process-related, and team activities. Finally, the team organization is an important consideration. Co-location is considered the most effective, but it is sometimes difficult to employ in programs involving large numbers of people. Also important is the office layout, which can help promote communication (Allen, 1977).

Table 5.5: Value Contribution of the Environment

	Attribute	Description
Time Allocation	Knowledge Application	Knowledge application is the direct creation of value, such as in design, analysis, or testing activities
	Information Gathering	Information gathering is the enabling value that allows sufficient knowledge to develop before being applied
	Other Activities	Other activities are generally unrelated to the task at hand
Communication Effectiveness	Technical Work	Technical work is the primary function of a job, as outlined by the job description, and includes knowledge application and information gathering
	Process Related Work	Process related work is associated with the process side of a job, typically consisting of suggestions or mandated changes on how a job is performed
	Team Building	Team building relates to the social interaction necessary for a good working environment
Team Organization	Geographic Location	Geographic location is the distance separating the team members and the extended enterprise
	Office Layout	Office layout is the internal building configuration where the team is located, including cubicles, meeting rooms, and other facilitating rooms

5.4.4 Delivering Value via the "Right" Management Approach

The final step of successful product development is selecting the "right" management approach. This step, in particular, delivers the ultimate value to the customer through the management of performance, cost, and schedule. Earlier, Section 3.5 reviewed these elements, suggesting that the objective of the product development process is the successful reduction in uncertainty (or estimated variance) of each element. As shown in Table 5.6, the process of uncertainty reduction may be decomposed for each element into the (i) desired value, (ii) management reserve, and (iii) ongoing estimate and uncertainty. The desired value is the initial goal of the product development process, which will meet the cost, schedule, and performance requirements of the customer or marketplace. Associated with this goal, there is usually a budgeted reserve should the product fail a particular specification. This reserve allows greater flexibility to deliver a successful product. Finally, the management approach should provide continual awareness of the expected values (expressed as a range) of performance, cost, and schedule. By measuring the uncertainty (or variance) of the expected outcome, resources may be allocated to eliminate the risk of failure.

Table 5.6: Value Contribution of the Management Approach

	Attribute	Description
Performance	Desired Requirements	Desired performance requirements describe the performance envelope desired by the customer or marketplace
	Management Reserves	Management reserves for performance are the possible concessions that are considered acceptable by the customer or marketplace
	Estimates & Uncertainties	Performance estimates and uncertainties are the ongoing estimates and ranges of key parameters or technical performance measures (TPMs)
Cost	Desired Value	Desired value for cost is the initial price which the customer or marketplace finds acceptable
	Management Reserve	Management reserve for cost is the additional cost (beyond the desired value) that may be born by the customer or marketplace
	Estimate & Uncertainty	Cost estimate and uncertainty are the ongoing estimate and expected range of the final cost
Schedule	Desired Value	Desired value for schedule is the initial delivery date which the customer or marketplace finds acceptable
	Management Reserve	Management reserve for schedule is the additional time (beyond the desired value) that is still considered acceptable
	Estimate & Uncertainty	Schedule estimate and uncertainty are the ongoing estimate and expected range of the final product delivery

5.5 Summary

This chapter presented a framework that describes the elements that contribute to value creation in the product development process. It is suggested that tasks are the building blocks of value and contribute multiple types of value to the stakeholders. The resources and environment facilitate the creation and delivery of value by providing the knowledge, communication, and necessary time to the process. Finally, the management approach delivers a product desired by the customer with the right cost and at the right time. The traditional management metrics (that is, performance, cost, and schedule) bridge the boundary between process value and product value. The value framework presented in this chapter is used in the subsequent chapters as a foundation for investigating specific aspects of value creation and delivery.

Chapter 6: Data Collection

The framework in Chapter 5 presents a broad decomposition of value in product development. Fully testing and validating this framework is beyond the scope of the thesis. Instead, the framework is presented as a representation of value that aids in the visualization and understanding of value. This chapter illustrates the use of the framework as a guide for the collection and presentation of data, with the outcome of increased understanding in a few localized areas. The following sections review the scope of the data collected and the methodologies used to collect it.

6.1 Scope of Data Collection

Several aspects of the framework were examined using eight methods of collecting data, including a variety of interviews, surveys, and industry data (see Figure 6.1). With each set of data, a specific objective was addressed, providing insight on an aspect of the development process. For instance, the interviews with industry members surfaced the importance of resource value, which was not originally considered as part of the framework. Similarly, the three case studies (Appendix B) gathered anecdotal evidence on successful team environments. Several types of surveys were used to obtain descriptive information concerning industry tasks, academic tasks, communication, and technical uncertainty (Appendix D). The most detailed level of information was found in collections of work breakdown structures and task completion data.

The data represent a broad cross-section of the aerospace industry, as shown in Figure 6.1. Four aerospace companies (A-D) and two government organizations (E & F) contributed the majority of the data. Additionally, data were taken from the doctoral research of Browning (G) (1998), the previous experience of an advisor (H) (McManus, 2000a), and participating graduate students at the Massachusetts Institute of Technology (I). The data represent more than 120 people, 15 programs, and three case studies. This participation is described in detail in the following sections, where the notation followed is <*organization-program.trial*> for attributing the data. For example, A-1.2 signifies Organization A, Program 1, and Trial 2. The checkmarks in Table 6.1 denote participation via the specified methods of data collection.

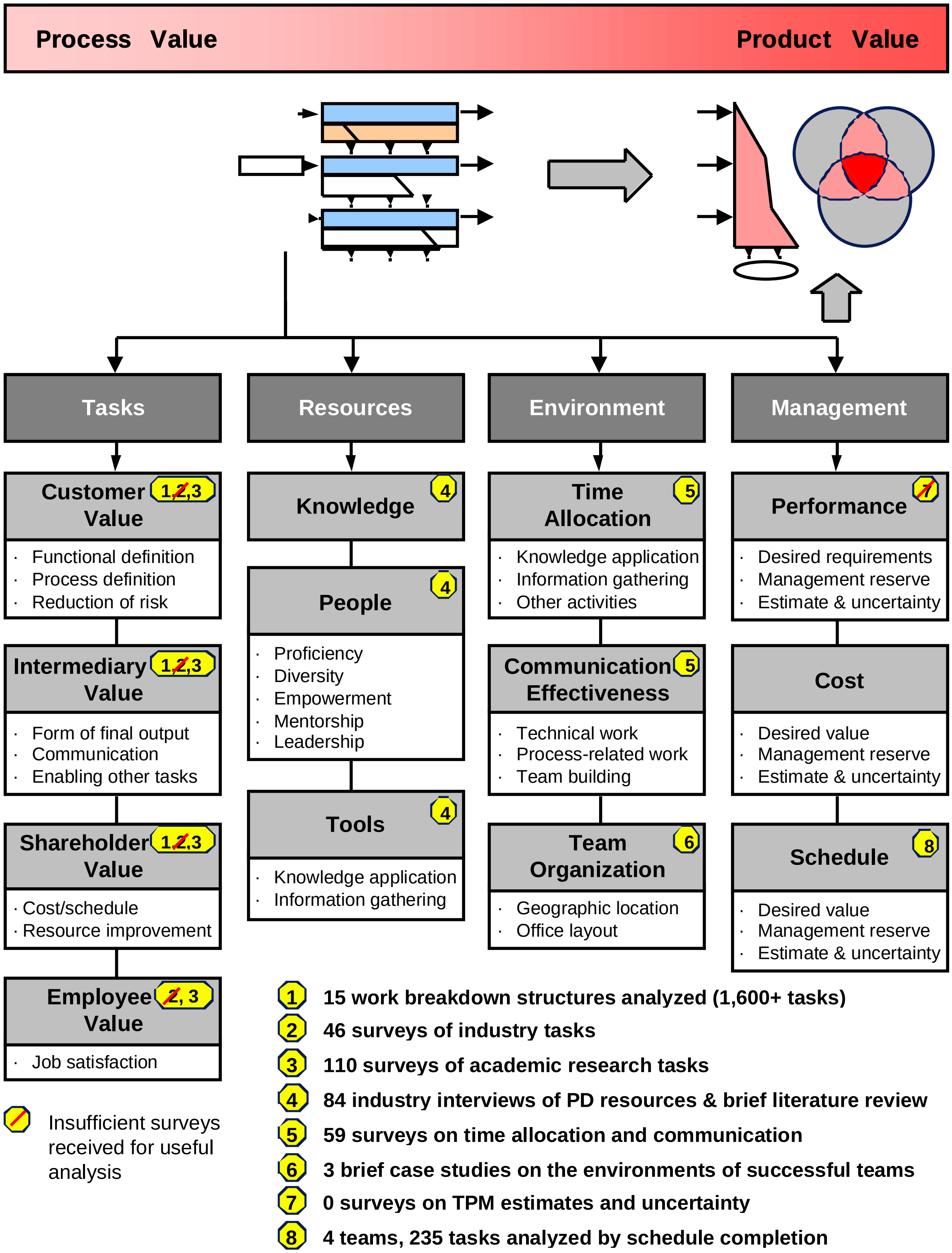

Figure 6.1: Data Collection Across the Framework

Table 6.1: Site Key for Data Collection

Org.	Type of Organization	Sites	Organization - Team.Trial	Description of Program or Detailed Process[9]	Method of Data Collection[10]							
					1	2	3	4	5	6	7	8
A	Commercial	1	A-1	Subsystem Development	√			√	√			
			A-2	Subsystem Development	√							√
			A-3	System Development	√							
			A-4	Test & Evaluation	√	√					√	
			A-5	Information Systems Support	√							√
B	Commercial	3	B-1	Engineering Change Process	√	√		√	√			
			B-2.1	Engineering Redesign Proposal	√	√						
			B-2.2	Engineering Redesign Proposal		√						
			B-2.3	Engineering Redesign Proposal		√						
			B-3	Software Development	√							
			B-4	Subsystem Development	√							
			B-5	Subsystem Development								√
			B-6	Subsystem Development								√
C	Commercial	3	C-1	Technology Development	√			√	√			
			C-2	Cost Estimation Process	√							
			C-3	Build-to Package Release Process	√							
D	Commercial	1	D	-				√	√			
E	Government	2	E-1	Avionics Development	√			√	√			
F	Government	2	F	-				√	√			
G	Commercial	-	G-1	System Development	√			√	√			
H	-	-	H-1	Structural Analysis Process	√	√		√	√			
I	MIT	1	I-1.1	Graduate Research on Lean			√					
			I-1.2	Graduate Research on Lean			√					
			I-1.3	Graduate Research on Lean			√					
			I-1.4	Graduate Research on Lean			√					
			I-1.5	Graduate Research on Lean			√					
			I-2	Technical Graduate Research			√					
"12 Days of August," F/A-18 E/F, Boeing								√		√		
Developing New Products, Jet Propulsion Laboratory, NASA								√		√		
Mission Control Center, Johnson Space Center, NASA								√		√		

[9] The sources of data are differentiated between programs and processes (that is, breakdowns of tasks into subtasks).

[10] Methods of data collection (1-8) follow the numbering of the previous page (Figure 6.1).

6.2 Methodology for Task Research

Within the proposed framework, tasks are considered the principal building blocks of value creation, since they represent the physical design and creation of the product. Given this proposition, the research addresses three key questions in regards to product development tasks. Table 6.2 lists the key questions and the methodology for analyzing the data collected. The results of this analysis are presented in Section 7.1.

Table 6.2: Methodology for Task Value

Key Questions Addressed[11]	Methodology	
Q1: What types of value do tasks contribute?	6.2.1	Initial work breakdown structures gathered from industry programs
	6.2.2	Tasks separated into categories
	6.2.3	Value attributes for tasks defined as part of the larger framework (**Q1**)
Q2: How do task lists (or work breakdown structures) differ among programs and levels of detail?	6.2.4	Programs assessed by lean penetration
	6.2.5	Relationships proposed between tasks, value attributes, and program assessment
	6.2.6	Data analyzed to differentiate program work breakdown structures (**Q2**)
Q3: Can task value be quantified in a useful fashion (and, if so, how)?	6.2.7	Surveys created to measure task value (see Appendix D)
	6.2.8	Resulting data from industry and academic teams analyzed (**Q3**)

6.2.1 Work Breakdown Structures Gathered

The work breakdown structures obtained from industry sites are listed in Table 6.3. The data shown include type of program, average task duration, number of tasks, levels of hierarchy, and lifecycle phase. In most cases, the programs include several hundred tasks, last from four months to several years, and span preliminary and detailed design phases. Several detailed processes are listed that have durations of only a few days. These processes add the most specific tasks, or subtasks, of product development. Additionally, the work breakdown structures provide the names (and sometimes descriptions) of hundreds of product development tasks. Thus, the analysis presented is limited by the detail of the work breakdown structures collected, which generally consist of one or two lines per task.

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[11] The questions addressed by the research were developed concurrently with the analysis of the data.

Table 6.3: List of Work Breakdown Structures Collected

Source		Average Program or Process Duration	Number of Tasks	Levels of Hierarchy	Lifecycle Phase (1-5)[12]	
					Start	End
Product Development Programs	A-1	-	304	3	~ 2.3	~ 5.0
	A-2	256 days	55	2	~ 2.5	~ 4.3
	A-3	889 days	1,603	5	~ 2.5	~ 5.0
	A-4	204 days	106	2	~ 4.2	~ 5.0
	A-5	101 days	51	2	-	-
	B-3	445 days	30	2	~ 1.7	~ 4.7
	B-4	611 days	647	6	~ 1.7	~ 4.3
	C-1	270 days	246	6	~ 1.4	~ 2.5
	E-1	1,907 days	125	3	~ 1.7	~ 5.0
	G-1	171 days	38	4	~ 1.7	~ 3.0
Detailed Processes	B-1	-	33	3	~ 4.90	~ 4.95
	B-2	-	14	2	~ 4.90	~ 4.95
	C-2	-	42	1	~ 1.40	~ 1.45
	C-3	22 hours	34	1	~ 3.90	~ 3.95
	H-1	-	13	1	~ 3.50	~ 3.55

6.2.2 Task Categories

Using the work breakdown structures, categories of tasks were created to represent the majority of product development tasks. Following functional analysis theory proposed by Miles (1961), verb-noun combinations were chosen to create a comprehensive set of categories for product development tasks, including ten verbs and eleven nouns (see Section 7.1.1). Nearly all of the tasks on the WBS's were mapped into the resulting 110 task types.

6.2.3 Value Attributes

As discussed in Section 5.4.1, the value attributes from the framework were incorporated into the analysis of product development tasks. The list of value attributes addresses the question of

[12] Lifecycle phases include concept development (1), preliminary design (2), detailed design (3), test & evaluation (4), and production (5).

"what types of value do tasks contribute?" It is proposed that tasks contribute ten possible types of value, as discussed in the previous chapter.

6.2.4 Lean Penetration Assessment

Lean penetration, or the corporate knowledge of lean practices, is generally easier to determine than whether an organization is lean. Since lean penetration often correlates with using lean practices, a comparison is desired between lean penetration and work breakdown structures. This comparison provides insight on how lean practices are reflected in WBS's. To accomplish this objective, the lean penetration of each program was rated as either high or low, based on (i) industry recognition such as awards, accomplishments, and contracts, (ii) LAI literature including theses and unpublished reports, and (iii) personal or advisor observations from visiting and interviewing program personnel.

6.2.5 Relationships Between Tasks and Value Attributes

Using the structure of the previous subsections, relationships were defined to connect the task categories and value attributes. The 110 types of tasks were then mapped to zero, one, or two of the value attributes. This transformation was used to suggest the types of value contributed by task descriptions in work breakdown structures.

6.2.6 Data Analysis

The resulting data (in Table 7.4) consist of a series of percentages, calculated using Equation 1, that give the relative percentage contributed to each type of value (per program).

$$\% = \frac{\text{\# of tasks with designated attribute}}{\text{\# of detailed tasks per program/process}} \tag{1}$$

This information was used to draw a number of comparisons regarding the differences between (i) programs and processes, (ii) levels of lean penetration, and (iii) aggregate levels of value (that is, customer, shareholder, etc. categories). The results address the second question posed.

6.2.7 Quantifying Task Value

To address the third question, additional data were collected via task surveys from industry and academic teams. The intent of the surveys was to determine whether the value generated by a given task value can be quantified in a useful fashion. For this purpose, surveys were fashioned in which employees or students rated the contribution to the various aspects of value made by each task. The surveys were available online and evolved slightly over the course of the study (see Appendix D). Using the surveys, employees could rate tasks according to the degree of value contributed. The rating scale was 1-5, where five is a significant contribution, one is little to no contribution, and N/A (or zero) signifies "not applicable." Additionally, the amount of direct effort (in hours) required by the task was collected, along with optional comments.

Twelve groups, listed in Table 6.4, participated in this segment of the research. These groups included a portion of an earlier program (A-4), three of the earlier processes (B-1, B-2, and H-1), a social science research group (I-1), and a technical research group (I-2).

Table 6.4: Survey Participants for Measuring Value of Tasks

<table>
<tr><th colspan="2" rowspan="2">Sources</th><th rowspan="2">Scheduled Tasks</th><th rowspan="2">Tasks Measured</th><th rowspan="2">Hours per Task</th><th colspan="2">Lifecycle Phase (1-5)</th></tr>
<tr><th>Start</th><th>End</th></tr>
<tr><td rowspan="6">Industry Processes</td><td>A-4</td><td>10</td><td>12</td><td>-</td><td>~ 4.2</td><td>~ 5.0</td></tr>
<tr><td>B-1</td><td>33</td><td>4[13]</td><td>0.6</td><td>~ 4.90</td><td>~ 4.95</td></tr>
<tr><td>B-2.1</td><td>14</td><td>7[13]</td><td>2.2</td><td>~ 4.90</td><td>~ 4.95</td></tr>
<tr><td>B-2.2</td><td>14</td><td>5[13]</td><td>1.7</td><td>~ 4.90</td><td>~ 4.95</td></tr>
<tr><td>B-2.3</td><td>14</td><td>5[13]</td><td>1.3</td><td>~ 4.90</td><td>~ 4.95</td></tr>
<tr><td>H-1</td><td>13</td><td>13</td><td>-</td><td>~ 3.50</td><td>~ 3.55</td></tr>
<tr><td rowspan="6">Academic Processes</td><td>I-1.1</td><td>-</td><td>34</td><td>2.3</td><td>~ 1.5</td><td>~ 2.1</td></tr>
<tr><td>I-1.2</td><td>-</td><td>26</td><td>6.5</td><td>~ 1.5</td><td>~ 2.1</td></tr>
<tr><td>I-1.3</td><td>-</td><td>10</td><td>4.7</td><td>~ 1.5</td><td>~ 2.1</td></tr>
<tr><td>I-1.4</td><td>-</td><td>20</td><td>8.3</td><td>~ 1.5</td><td>~ 2.1</td></tr>
<tr><td>I-1.5</td><td>-</td><td>15</td><td>5.5</td><td>~ 1.5</td><td>~ 2.1</td></tr>
<tr><td>I-2</td><td>-</td><td>20</td><td>2.5</td><td>~ 1.5</td><td>~ 2.1</td></tr>
</table>

The academic research groups were employed in this study as a pilot group (see Appendix C). Graduate student research is similar to product development, as a product (the thesis) is designed and delivered to a customer (the university). There are, however, some differences. Research

[13] Process subtasks cancelled midway through research study.

activity generally lacks a detailed structure, and a document similar to an industry WBS is unavailable. Success is more difficult to measure in graduate research. Also, the attributes of value are different. The attributes of Table 5.3 were replaced with a list of attributes relevant to the completion of a graduate thesis. Nevertheless, academic research offers useful information (specific to this study) for evaluating the product development process.

6.2.8 Data Analysis

The data from the industry and academic processes were analyzed following the work of Shillito and DeMarle (1992) and Tananka (1973). They proposed that value could be measured by graphing relative cost (or time in this case) against importance (measured using the attribute rankings). Graphs of the academic data, using their technique, are shown in Section 7.1.

6.3 Methodology for Resources Research

No quantitative data were collected on the value of resources. Insights regarding resources emerged from the site visits and literature review. Since resource value was a prevalent theme in the site visits, the site visit interviews are described here. In a majority of cases, industry members characterized specific people or software tools as critical elements for a successful program. Table 6.5 shows the key questions and relevant methodology.

Table 6.5: Methodology for Resource Value

Key Questions Addressed		Methodology	
Q1: From an industry perspective, what are the principal contributors of value in product development?		6.3.1	Interviews, indirectly related to resource value, were conducted across a broad cross-section of the aerospace industry
Q2: How might this value be quantified to enable process improvement?		6.3.2	Interview notes and literature search surfaced principal elements and suggestions for quantification (**Q1** and **Q2**)

6.3.1 Site Visits and Interviews

Table 6.6 summarizes the six organizations visited, including twelve sites and over eighty engineers and managers.[14] In each case, an introduction to the facility was provided, followed by time with lean practitioners and product development teams. The interviews were primarily exploratory, but they surfaced several predominant themes, including the importance of resources (specifically software applications and people).

Table 6.6: Interviews Across Aerospace Product Development

Type of Organization		Sites Visited	People Interviewed
A	Commercial	1	~ 15
B	Commercial	3	~ 36
C	Commercial	3	~ 16
D	Commercial	1	~ 4
E	Government	2	~ 8
F	Government	2	~ 5

6.3.2 Interview Notes and Literature Review

To surface the principal elements of resource value, the combined notes from the site visits and literature review were consulted. The framework for resource value was created from this information. It is discussed in Section 7.2 and Appendix A.

6.4 Methodology for Environmental Research

Earlier (in Sections 2.2.3, 3.2, and 3.4), it was suggested that a collaborative environment is an important element of value in product development. With this in mind, research was undertaken to understand the value inherent in communication. Table 6.7 illustrates the key questions and methodology relevant to this section of the research.

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[14] In addition to site visits, industry members were engaged at seminars and conferences.

Table 6.7: Methodology for Environmental Value

Key Questions Addressed	Methodology	
Q1: How much time is spent on communication versus isolated work in product development?	6.4.1	Surveys created to measure communication time and effectiveness
Q2: How effective do industry members consider different forms of communication?	6.4.2	Resulting data from engineers and managers analyzed (**Q1** and **Q2**)
Q3: What are the characteristics of the environment of some successful product development teams?	6.4.3	Brief case studies conducted on successful teams
	6.4.4	Case study data combined to form suggestions for the environment (**Q3**)

6.4.1 Communication Survey

The survey, shown in Appendix D, was created to address two principal questions regarding communication in product development: (i) how much time is spent on various forms of communication? and (ii) how effective are different forms of communication? The survey requested the participants to estimate the amount of time spent on activities, such as meetings (of assorted sizes), email, literature, etc. Additionally, the participants were asked to rate the effectiveness of each form of communication. A summary of the survey participants is shown in Table 6.8. Participants were from a pool of engineers and managers that (i) had been involved in the initial site visits or (ii) active members of the NASA Academy Alumni Association.[15]

Table 6.8: Communication Survey Participants

Section of Survey	Organizations[16]	Participants	Engineers	Managers
Time Allocation	10	46	23	23
Communication Effectiveness	14	56	30	26

6.4.2 Data Analysis

Despite the small sample size, surprising agreement was found for both time allocation and communication effectiveness. The data were aggregated by whether participants were engineers or managers. The averages, for time allocation and communication effectiveness, were

[15] Members of this organization include engineers and managers in the aerospace industry.

[16] Participants included members from the six sites visited and (to a lesser degree) from eight other organizations

compared for each type of communication. Additionally, all of the data was combined into a single chart, which plotted relative cost against importance (or, in this case, time versus effectiveness). The results showed statistically significant differences between engineers and managers, as discussed in Section 7.3.

6.4.3 Case Studies on Successful Environments

Data were also gathered via three case studies of small industry teams. The teams were chosen based on their previous success and the degree of readily available information. Data were collected via a few interviews at each site (specific to this study for one of the site visits) and a few public sources (see Table 6.9).

Table 6.9: Summary of Case Study Data

Brief Case Studies	Days on Site	Interviews	Other Sources
"12 Days of August," F/A-18 E/F, Boeing	2	6	2
Developing New Products, Jet Propulsion Laboratory, NASA	1	4	1
Mission Control Center, Johnson Space Center, NASA	1	3	2

6.4.4 Data Analysis

For each site, a brief description of the team and accomplishments was created (see Appendix B). Attention was given to the type of environment of each team, and similarities were grouped together and are presented in Section 7.3.

6.5 Methodology for Management Research

Typically, cost, schedule, and projected performance are tracked to manage the product development process. Product development sites, however, place varying amounts of stress on the desired metrics. It has been proposed (Browning, 1998; Browning, 2001; Deyst, 2001) that the uncertainty of technical performance metrics could be used as an alternate metric. Table 6.10 reflects two questions regarding what type of management approach is most suitable for product development.

Table 6.10: Methodology and Management Value

Key Questions Addressed	Methodology	
Q1: How effective is a traditional management approach[17] versus a more stringent approach such as earned value management?	6.5.1	Industry data obtained on program task completion (using two management approaches)
	6.5.2	Subtask and task levels analyzed for success of management in controlling tasks (**Q1**)
Q2: Is measuring technical uncertainty a viable alternative for managing programs.	6.5.3	Task survey created to measure the uncertainty of technical performance measures (**Q2**)

6.5.1 Task Completion Data

Data on the completion of tasks were acquired from four sources. Teams A-2 and A-5 contributed data that included estimates of percent completion at intervals throughout the tasks, and included final task completion times. These teams used a Gantt chart (similar to most aerospace sites) to manage the program. The next two teams, B-5 and B-6, submitted task completion data that was managed via the earned value management system. Table 6.11 presents a summary of the data.

Table 6.11: Sources of Data for Task Completion

Source	Type of Data	Tasks	Management Approach
A-2	Mid-task and task completion	55	Gantt Chart
A-5	Mid-task and task completion	51	Gantt Chart
B-5	Task completion	109	Earned Value Management
B-6	Task completion	20	Earned Value management

6.5.2 Data Analysis

The data of Table 6.11 presents an opportunity to compare a Gantt chart approach with an earned value management system. The results of this comparison are presented in Section 7.4 and include a small amount of manufacturing data (Spear and Bowen, 1999) provided as a sharp contrast to the product development data.

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[17] A traditional approach generally relies on a Gantt chart (or task deadlines) as the principal form of process control.

6.5.3 Technical Uncertainty Data

A survey (shown in Appendix D) was created to measure technical uncertainty by collecting the mean, minimum, and maximum values of technical performance measures following product development tasks. Considerable difficulty, however, was experienced in finding participants for the study. From more than 15 teams visited, only one was willing to contribute to the research, and even then, this team was unable to submit uncertainty estimates over the two months of the study (see Table 6.12). This result, or lack of a result, suggests that managing programs via technical uncertainty is difficult without a major discussion of the concepts and approach.

Table 6.12: Technical Uncertainty Data

Source	Surveys	Comments
A-4	0	Only one participant was found, despite visiting three organizations (including more than 15 teams)

Chapter 7: Analysis and Results

This chapter provides the analysis and results of the research outlined in the previous chapter. Following the structure of the proposed framework, it is separated into the areas of tasks, resources, environment, and management. For each section, the results are stated, followed by analysis and discussion.

7.1 Task Research

The results from an analysis of the value contributed by industry tasks are below.

1) An analysis of WBS's showed a large variance in the types of value contributed, suggesting the difficulty of any single approach to maximizing value.
2) The majority (85%) of WBS tasks defined at a high level contribute value directly, whereas a finer decomposition of tasks revealed fewer value-added tasks (54%).
3) WBS's from programs with greater lean penetration emphasize cost/schedule to a greater extent than programs with less lean penetration.
4) Although some difficulty was experienced in obtaining an adequate amount of industry data, a study of an academic population showed that assessments of task value are useful for process improvement.

7.1.1 Analysis of Work Breakdown Structures

Generally, product development programs use work breakdown structures (WBS's) to describe the specific tasks that lead to the desired product. WBS's gathered from several product development teams are analyzed below.

Types of Industry Tasks

To determine the most common types of tasks in product development, a word analysis was employed. The WBS's were combined to form a single list of 3,353 items, including phases, activities, tasks, and subtasks. This list was further refined into 2,233 unique words, of which 86 surfaced as the principal verbs and nouns of product development.[18] Table 7.1 places these words into 21 specific categories.

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[18] Separating words into verbs and nouns corresponds with functional analysis theory proposed by Miles (1961).

Table 7.1: Work Breakdown Structure Word Analysis

	Category & Definition[19]	Synonyms Found[20]
Verbs	**Plan-** To devise or project a course of action	Plan, manage, control, schedule
	Design- To fashion according to a plan	Design, develop, prepare, establish, draft, define, identify, create, estimate, draw, derive
	Analyze- To study the factors of a situation or a problem in detail, leading to a solution	Analyze, study, model, evaluate, consider
	Update- To bring up to date	Update, modify, upgrade, revise
	Complete- To bring to entirety or perfection	Finalize, complete, release, signoff, transport, submit
	Fabricate- To construct	Fabricate, machine, integrate, install, drill, cast, build
	Test- To put to the test or proof	Test, demonstrate, verify, perform, validate, experiment
	Procure- To obtain by any means	Procure, accept, receive, locate, contract, obtain, acquire
	Document- To furnish documentary evidence of	Report, document
	Review- To come together for a common purpose	Review, meet
Nouns	**Requirements-** Requisite conditions	Requirements, rules, constraints
	Architecture- A unifying form or structure	Architecture, interface, ICD
	Software- Computer programs	Software
	Material- The substances, parts, or goods of which anything is composed or may be made	Material, part
	Subsystems- Subordinate portions of a system	Avionics, subsystem, nozzle, hardware, thruster, nose
	System- An assemblage of objects united by some form of regular interaction or interdependence	Assembly, system
	Tools- Anything which serves as a means to an end	Fixture, tools, equipment
	Production- The manufacture of goods	Manufacturing, production
	Process- A series of actions or operations definitely conducing to an end	Process, BTP, procedure, method
	Cost- The outlay of money, time, labor, etc.	Cost, schedule
	Performance- The execution of the functions or operations of a product	Safety, risk, performance, hazard

Using the categories, each task from the work breakdown structures was individually examined and placed into the appropriate categories of Table 7.1. The results, shown in Table 7.2, are listed in terms of percentage, calculated using Equation 1. To avoid the duplication of tasks,

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[19] Definitions are adapted from *Webster's New Collegiate Dictionary* (1956 & 2001).

[20] Words listed include all associated forms.

only detailed tasks (or those with no subtasks) were considered, which reduced the list to 77% of the original tasks. Additionally, the average values are shown for processes and programs. The results show significant variance, a characteristic of the product development process.

$$\% = \frac{\text{\# of tasks with designated attribute}}{\text{\# of detailed tasks per program/process}} \tag{1}$$

Table 7.2: Analysis of Work Breakdown Structures

Task Categories	Percentage of Tasks Found in Programs or Detailed Processes															Average	
	A-1	A-2	A-3	A-4	A-5	B-1	B-2	C-1	C-2	C-3	D-1	D-2	E-1	G-1	H-1	Processes	Programs
Plan	4	0	-	0	4	0	0	15	0	3	4	2	0	0	0	1	3
Design	45	38	-	2	24	15	0	28	0	0	32	33	15	44	8	5	29
Analyze	25	25	-	32	18	22	8	25	33	38	4	15	14	63	46	30	25
Update	11	7	-	5	47	11	0	7	2	3	24	17	25	22	0	3	18
Complete	4	11	-	9	0	19	31	4	10	12	4	24	21	4	0	14	9
Fabricate	9	2	-	18	0	0	0	9	0	0	8	2	0	0	0	0	5
Test	6	2	-	18	4	0	0	11	0	0	24	2	5	0	0	0	8
Procure	3	9	-	6	10	0	0	1	17	9	0	7	0	0	15	8	4
Document	25	22	-	8	12	22	62	10	19	18	60	29	65	33	15	27	29
Review	14	2	-	4	0	7	15	5	12	0	32	5	13	11	23	12	10
Requirements	12	2	-	0	4	0	23	15	0	0	28	19	19	11	0	5	12
Architecture	22	2	-	0	2	0	0	15	0	0	36	5	25	41	0	0	16
Software	11	4	-	3	80	0	0	25	0	0	52	3	3	0	15	3	20
Material	8	5	-	6	2	0	0	7	0	0	0	7	0	7	0	0	5
Subsystems	31	51	-	23	12	26	15	28	0	0	0	20	37	48	92	27	28
System	3	0	-	28	0	0	0	2	0	0	16	6	12	26	0	0	10
Tools	6	11	-	18	0	0	0	16	0	0	0	7	3	7	0	0	8
Production	0	11	-	0	0	0	0	7	0	0	0	18	2	11	0	0	6
Process	12	18	-	11	4	74	62	7	2	94	8	21	10	4	0	46	11
Cost	2	15	-	0	4	0	0	12	69	0	20	6	0	11	0	14	8
Performance	9	11	-	6	0	0	0	14	0	0	16	22	21	37	38	8	15
Other	2	0	-	7	0	7	8	5	29	21	8	3	0	4	0	13	3

0 – 9%   10 – 19%   20 – 49%   50 – 100%

Tasks and Value Attributes

To characterize the relationships between task categories from the previous subsection and the value attributes proposed in Chapter 5, Table 7.3 displays the proposed relationships, produced by considering what categories of value from Table 5.3 would be generated by each of the 110 verb-noun pairs. For instance, designing the requirements or subsystems contributes directly to the functional performance of the end product (V1). Similarly, testing the software or system is analogous to reducing uncertainty (V3). One exception is employee job satisfaction (V9), where the nature of the task offers little evidence for how the employee feels about a specific task. Additionally, some of the tasks provide multiple types of value, such as design tasks contributing to functional performance (V1) and learning (V8).

Table 7.3: Proposed Relationships between Task Categories and Value Attributes

Actions \ Objects	Requirements	Architecture	Software	Material	Subsystems	System	Tools	Production	Process	Cost	Performance
Plan	V6	V6	V6	V6	V6	V6	V6	V6	V6	V3/V7	V3
Design	V1/V8	V1/V8	V1/V8	V1/V8	V1/V8	V1/V8	V2/V8	V2/V8	V2/V8	V3/V7	V3/V8
Analyze	V3	V3	V3	V3	V3	V3	V3	V3	V3	V3/V7	V3
Update	V1	V1	V1	V1	V1	V1	V2	V2	V2	V3/V7	V3
Complete	V1	V1	V1	V1	V1	V1	V2	V2	V2	V3/V7	V3
Fabricate	-	-	V3	V3	V3	V3	V3	V3	-	-	-
Test	-	-	V3/V8	V3/V8	V3/V8	V3/V8	V3/V8	V3/V8	-	-	-
Procure	V1	V1	V1	V1	V1	V1	V2	V2	V2	-	-
Document	V6	V6	V4	V4	V4	V4	V6	V4	V6	V6	V6
Meet[21]	V5/V8	V5/V8	V5/V8	V5/V8	V5/V8	V5/V8	V5/V8	V5/V8	V5/V8	V5/V7	V5/V8

V1	Functional performance of end product	V5	Facilitating communication
V2	Definition of processes to deliver product	V6	Enabling other tasks
V3	Reduction of risks and uncertainties	V7	Cost and schedule emphasis
V4	Form of final output	V8	Learning or resource improvement

[21] Although discussion often reduces risk, it is not included as a formal means of reducing risk and uncertainty.

The use of Table 7.3 allows reduction of the WBS's to 10 categories for comparing and contrasting programs and processes. The disadvantages include the coarseness of the resulting reduced data and its binary nature, since no weighting is given for either the *magnitude* of value contributed or the relative importance or duration of the task. The results are shown in Table 7.4, separated by programs with lean penetration, programs without lean penetration, and processes.[22] The averages are listed at the bottom of the chart.

Table 7.4: Value Contribution of Tasks from Programs and Processes

Programs and Processes		Days per Task	Percent of Program/Process Tasks with Given Attribute									
			V1	V2	V3	V4	V5	V6	V7	V8	V9	V10
Programs w/lean Pen.	C-1	-	30	15	54	5	5	10	11	42	-	5
	D-1	22[23]	48	4	48	28	32	44	20	72	-	8
	D-2	76	41	34	34	17	5	19	6	38	-	3
	G-1	8	44	11	63	11	11	30	7	48	-	4
Programs w/o Lean Penetration	A-1	-	48	15	42	7	14	24	1	58	-	2
	A-2	41	38	16	35	4	2	18	11	40	-	0
	A-4	4	10	12	67	2	4	6	0	24	-	7
	A-5	17	75	2	22	8	0	14	6	27	-	0
	E-1	59	46	14	32	33	13	50	0	33	-	0
Processes	C-2	-	0	0	45	0	12	19	50	2	-	29
	H-1	-	15	0	46	15	23	15	0	31	-	0
	C-3	1[23]	0	24	38	0	0	21	0	0	-	21
	B-1	-	4	41	22	7	7	15	0	22	-	7
	B-2	2[23]	0	31	8	15	15	46	0	15	-	8
Average			**34**	**16**	**40**	**11**	**10**	**24**	**8**	**32**	**-**	**7**
Standard Dev.			**±29**	**± 13**	**± 16**	**± 10**	**± 9**	**± 14**	**± 13**	**± 20**	**-**	**± 8**

0 – 9% | 10 – 19% | 20 – 49% | 50 – 100%

Table 7.4 displays the data from this analysis, including the number of days (or in some cases hours) per task. An initial observation is the large number of design (V1), risk reduction (V3),

[22] Lean penetration is discussed further in the following subsection.

[23] Number represents working hours per task, rather than days per task, and is not included in the calculations.

and resource improvement (V8) tasks, followed closely by enabling tasks (V6). The data help to give a sense of what activities are conducted in product development. For example, 34% of tasks are related to product development (V1), whereas only 16% are process development (V2). There is large variability in the data, shown by the high standard deviations.

Lean Penetration of Organizations and Teams

As an example of the type of comparisons that may be made, programs may be compared with respect to varying degrees of lean penetration, where lean penetration is the corporate knowledge of lean methods. An assessment of lean penetration is made for each program in Table 7.5, based on (i) industry recognition such as awards, accomplishments, and contracts, (ii) LAI literature including theses and unpublished reports, and (iii) personal or advisor observations from visiting and interviewing program personnel. More specific evidence is not provided, since the programs cannot be identified for proprietary reasons. The work breakdown structures were not consulted to avoid bias.

Table 7.5: Assessment of Lean Penetration in Product Development

Program or Process	Assessment of Lean Penetration	Supporting Evidence
A-1	Low	LAI literature, personal observation
A-2	Low	LAI literature
A-3	Low	LAI literature, personal observation
A-4	Low	LAI literature, personal observation
A-5	Low	Personal observation
B-1	Low	Personal observation
B-2	Low	Personal observation
C-1	High	LAI literature
C-2	Low	Personal observation
C-3	Low	Personal observation
D-1	High	Industry recognition, LAI literature, personal observation
D-2	High	Industry recognition, LAI literature, personal observation
E-1	Low	LAI literature, personal observation
G-1	High	LAI literature
H-1	Low	Advisor observation

Comparison of Value Attributes in Work Breakdown Structures

Table 7.6 presents a comparison of value attributes between programs and detailed processes. The results are displayed at two levels, presented earlier in Table 5.2. At a high-level, the four perspectives of customer, intermediary, shareholder, and other value are used, and at a lower level, the individual value attributes (V1-V8) are shown. The results show considerable heterogeneity, or diversity, illustrating the complexity of the product development process. Thus, a single approach for addressing value would most likely be ineffective. There are, however, some statistically significant pairs of data. For example, at a higher level (that is, programs), there are more tasks (specified by WBS's) that are in the category of creating customer value, whereas at the process level there are more supporting or enabling (and possibly wasteful) tasks. These data would validate similar notions posed by researchers, including Browning (1999).

Table 7.6: Comparison of Programs and Detailed Processes

	Customer Value			Intermediary Value			Shareholder Value		Other
Programs	85 ± 4			35 ± 22			47 ± 18		3 ± 3
Detailed Processes	54 ± 12			36 ± 19			14 ± 13		13 ±11
	V1	**V2**	**V3**	**V4**	**V5**	**V6**	**V7**	**V8**	**V10**
Programs	42 ±17	14 ± 9	44 ±15	13 ±11	9 ±10	24 ±15	7 ± 6	43 ±15	3 ± 3
Detailed Processes	4 ± 7	19 ±18	32 ±17	8 ± 8	12 ± 9	23 ±13	0 ± 0	14 ±13	13 ±11

Pairs of data points that are statistically significant (that is, one-tail t-test < 0.05)

Another comparison is shown in Table 7.7, where the results are depicted with respect to the level of lean penetration. Of primary interest are the similarities and differences in the pairs of data. Customer and intermediary value are similar, whereas shareholder value shows a significant difference. At a more detailed level, the sole statistically significant difference is the emphasis on cost and schedule (V7), suggesting that programs with greater knowledge of lean include larger emphasis on cost and schedule performance in their work breakdown structures. Examples of this cost/schedule prominence include time management activities, earned value management meetings, and design for cost tasks.

Table 7.7: Comparison of High and Low Lean Penetration

Programs	Customer Value			Intermediary Value			Shareholder Value		Other
High Lean Penetration	87 ± 3			36 ± 18			58 ± 18		5 ± 2
Low Lean Penetration	85 ± 5			34 ± 26			39 ± 14		2 ± 3
	V1	**V2**	**V3**	**V4**	**V5**	**V6**	**V7**	**V8**	**V10**
High Lean Penetration	41 ± 8	16 ±13	50 ±12	15 ±10	13 ±13	26 ±15	11 ± 6	50 ±15	5 ± 2
Low Lean Penetration	43 ±23	12 ± 6	39 ±17	11 ±13	6 ± 6	23 ±17	4 ± 5	36 ±13	2 ± 3

7.1.2 Analysis of Industry and Academic Surveys

The previous approach (Section 7.1) used the proposed attributes of value to review industry work breakdown structures. This section employs more direct input from employees (via surveys) to evaluate industry tasks. Industry and academic teams submitted surveys over the course of several weeks, which measured value using a 1-5 rating system for each value attribute, and then aggregated the results to generate suggestions for process improvement.

Industry Task Surveys

Forty-six surveys were collected from industry participants. The results are shown in reduced form in Table 7.8. The scores (from 1-5) of how much each task contributed to each value attribute were summed for all tasks in the process. The results were normalized such that a 100% score meant that the survey participants thought all the tasks contributed at the 5 level to the value attribute in question.

There are several problems with the industry data, limiting the results. The high scores indicated that the survey participants tended to give high assessments to most tasks. The participants were allowed to assign multiple aspects of value to each task, which they clearly did. Even more problematic, however, are the low number of surveys collected (~8 per process) and the lack of a lean set of processes for comparison. Due to these problems from the industry data, the results are of limited use, and an additional study was conducted on academic research teams.

Table 7.8: Value Contribution of Tasks from Industry Processes

Industry Processes		Hours / Task	Percent of Tasks with Given Attribute									
			V1	V2	V3	V4	V5	V6	V7	V8	V9	V10
A-4	Portion of Rocket Testing	-	73	82	73	60	3	75	33	53	45	0
B-1	Engineering Change	0.6	29	66	37	91	97	-	26	34	94	0
B-2.1	Engineering Redesign Proposal	2.2	20	60	40	100	100	-	24	52	92	0
B-2.2	Engineering Redesign Proposal	1.7	20	84	32	92	96	-	20	60	84	0
B-2.3	Engineering Redesign Proposal	1.3	3	0	18	17	37	83	2	12	54	0
H-1	Structural Analysis	-	60	60	40	60	40	-	0	40	50	8
Average		**1.4**	**34**	**59**	**40**	**70**	**62**	**79**	**17**	**42**	**70**	**1**
Standard Deviation		**±0.7**	**±27**	**±31**	**±18**	**±31**	**±41**	**±6**	**±14**	**±17**	**±23**	**±3**

Academic Task Surveys

The academic research study was more successful in obtaining data (see Appendix C). The preliminary results from 125 surveys are shown in Table 7.9. Collecting the data involved a methodology similar to the one discussed earlier in the chapter, with differences noted.[24] In general, the tasks averaged five hours in length and were similar in scope, usually consisting of literature reviews, meetings, presentations, and site visits. For these tasks, a different set of value attributes was developed, as illustrated in Table 7.9.

The attributes may be partitioned into four categories, based on their values. The first four (S1, S2, S3, & S4) represent contributions to creating the research framework of the student, and in each case occur in approximately 30% of the tasks. The next two (S5 & S6) involve results, following the development of a framework. Since the participants were first-year graduate students, it is understandable that they would not yet have completed this section of the thesis. The third section is the contribution to advisor and industry knowledge. These areas are similar and most likely reflect a general feeling that something has been accomplished. Finally, student satisfaction and knowledge are well correlated, suggesting that learning and satisfaction are correlated.

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[24] See Appendix C for a summary of the methodology and results of the academic data.

Table 7.9: Value Contribution of Tasks from Academic Research

Academic Research Projects		Hours / Task	Percent of Tasks with Given Value Attribute									
			S1	S2	S3	S4	S5	S6	S7	S8	S9	S10
I-1.1	Graduate Research on Lean	2.3	34	30	15	39	13	1	35	8	62	57
I-1.2	Graduate Research on Lean	6.5	44	28	35	42	27	5	32	19	45	51
I-1.3	Graduate Research on Lean	4.7	20	43	27	27	0	0	7	33	70	77
I-1.4	Graduate Research on Lean	8.3	28	23	18	5	15	20	23	2	42	42
I-1.5	Graduate Research on Lean	5.5	18	29	18	18	0	0	24	24	64	60
I-2	Technical Graduate Research	2.5	45	50	53	42	3	5	38	38	88	83
Average		**5.0**	**32**	**34**	**28**	**29**	**10**	**5**	**27**	**21**	**62**	**62**
Standard Deviation		**±2.3**	**±12**	**±10**	**±15**	**±15**	**±11**	**±8**	**±11**	**±14**	**±17**	**±16**

S1	Contribution to problem definition	**S6**	Contribution to results
S2	Contribution to background	**S7**	Contribution to advisor knowledge
S3	Contribution to discussion	**S8**	Contribution to industry knowledge
S4	Contribution to framework or hypothesis	**S9**	Contribution to student satisfaction
S5	Contribution to case study or experiment	**S10**	Contribution to student knowledge

Shillito and DeMarle (1992) state that the importance of a task and the time contributed to it should be proportional. As previously shown (in Figure 4.2), ideal tasks should lie near a 45-degree slope within the optimum value zone (Tanaka, 1973). Thus, the data in Table 7.9 may be grouped in distinct sets to determine which characteristics contribute the most value. One example of this analysis is shown in Figure 7.1, which combines the data by the type of task. The data are plotted by relative time (that is, the relative durations of the activities) versus relative thesis contribution (which is the average contribution to S1 through S5 of each activity).

Figure 7.1 shows that most research tasks fall near the “optimal” line. The only two points that lie outside the optimum value zone are focused meetings and literature reviews. These tasks typically involve information gathering (the former through discussion and the latter through reading). It would be more efficient for the student to gather information from discussion, but this value does not account for the time of the other participants. The literature review, however, involves more work, but does not require additional personnel. Thus, the graph successfully identifies elements that could be improved. Also, most of the activities relate to information gathering, whereas only one (model development) relates to direct, isolated research.

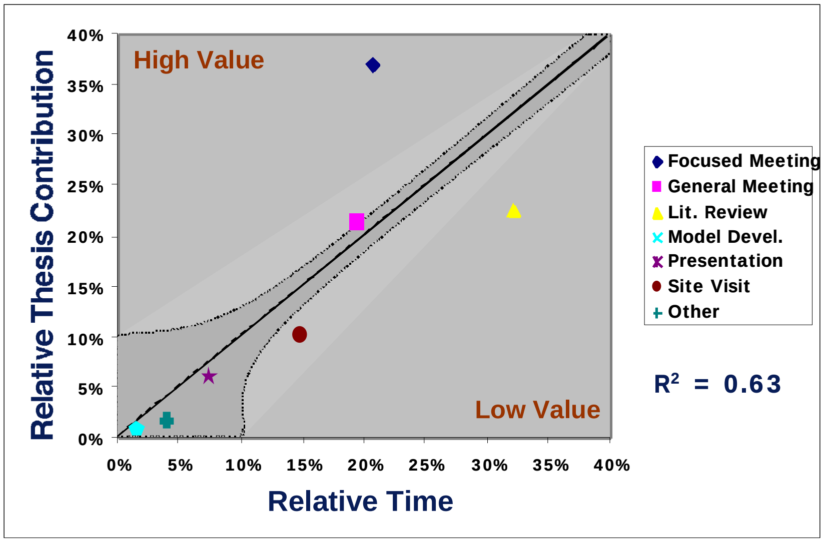

Figure 7.1: Value versus Time (Type of Task)

The next graph, Figure 7.2, places the 125 tasks into groups centered on student satisfaction. The three categories are no/slight enjoyment, moderate enjoyment, and high enjoyment. The data were then analyzed using these categories via the same technique as Figure 7.3. The result is a near perfect correlation (0.98) that runs almost perpendicular to the optimal value zone. In other words, the tasks that provide value to the research process, proportionately to the amount of time spent on them, also provide the greatest satisfaction to the students.

Although the data presented in Figure 7.2 are based on academic research, related information may be found in industry. According to a company-wide Boeing survey, the leading desires by employees are (#1) involvement in decisions and (#2) encouragement to come up with new and better ways ("Mixed Results," 2000). In lean terminology, these are equivalent to empowerment, which is central to the lean philosophy. Several other factors, including job security and pay, rank near last in the list of twelve employee desires. The industry statistics in conjunction with Figure 7.2 suggest that a link may exist between value creation and employee satisfaction.

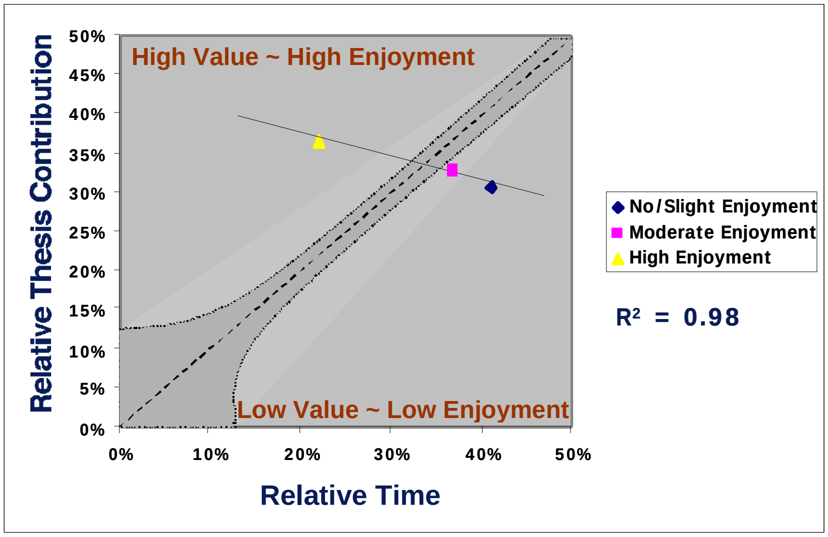

Figure 7.2: Value versus Time (Student Satisfaction)

7.1.3 Discussion of Task Value

The percentage of tasks extracted from the WBS, addressing various aspects of value, differed markedly from program to program and process to process (see Table 7.4). This supports the idea that there is not a single definition of "the product development process" at anything but the highest level.

On average, the tasks of program WBS's, defined at a relatively high level, appeared to concentrate on designing the product, producing the product definition, or reducing product uncertainty or risk (activities that are assumed to create direct value for the user). However, when tasks were further decomposed (in the process WBS's), a larger percentage of the subtasks fell into supporting and enabling categories. This illustrates a dilemma when considering task value; that is, a high-level perspective will indicate that all tasks directly contribute value, while a finer decomposition of the same process will reveal required non-value added, or even purely wasteful activities.[25] However, this fine decomposition comes at greater and greater effort, and may reach a meaningless limit. For example, in one of the process studies, engineers were asked how they followed the very detailed process WBS, and their response was that the very detailed

[25] Browning (1999) proposed the existence of this relationship.

WBS list was not followed. For any given application, many of the tasks in the WBS were clearly unnecessary, and thus the engineers wisely skipped them. Hence improvement efforts focused on WBS's will fail to see waste if focused too high, and will be difficult and possibly unconnected with real problems if focused too low.

The WBS's of programs judged to be taking place in more lean environments showed *more* supporting tasks, primarily those concerned with cost and schedule management than in traditional environments. This is interpreted as reflecting a higher consciousness of the need to explicitly deal with cost and schedule issues, and it may or may not reflect more actual effort in those areas.

Attempts to directly gauge task value by surveys were mostly unsuccessful. The results from industry were both insufficiently numerous and highly inconsistent. The pilot study performed on students developing theses was more successful, identifying (at least relatively) higher and lower value tasks; this indicates that this method may have some utility if broadly applied.

7.2 Resource Value

The research on resource value, in contrast to the quantitative results of the previous section, is anecdotal and derived from a large pool of interviews. Thus, the value attributes, shown earlier in Table 5.4, represent the principal result from this component of the research. A summary of this research is presented below, and a detailed discussion of the attributes is presented in Appendix A.

Resources in product development may be considered the people, tools, and knowledge that translate raw information into a finished product. The value of these resources reflects many factors that are difficult to quantify. For instance, organizational value may be described by the attributes of proficiency, diversity, empowerment, mentorship, and leadership. These attributes may seem to conflict, but as Toyota has shown, their successful development is critical to achieving a lean organization. Similarly, tools are increasingly providing value to industry programs by facilitating information gathering and improving knowledge application.

7.3 Research on Communication in the Environment

The third area of value in product development is the environment. The right environment is an effective location and layout for promoting communication and continuous flow. Additionally, the environment should provide access to other stakeholders, such as the manufacturer, customer, and end-user. Two primary results emerge from a survey on communication and a study of three successful product development teams.

1) Industry surveys suggest a high ratio (perhaps three to one) exists between interpersonal and isolated activities.
2) Face-to-face and small group discussion continue to be the most effective forms of communication, despite advances in technology.

The environment is a critical element of successful product development. As Miles (2000) suggests, managers "must invest in the design of an organizational setting in which collaboration-driven innovation can be sustained and its output exploited." Allen (1977) conducted extensive research on the relationship between performance, communication, and co-location. He concluded that communication and performance are well-correlated, and co-location increases communication substantially. The research conducted in this thesis seeks to expand upon his work, as the product development environment has shifted considerably in the last two decades.

7.3.1 Analysis of Communication Surveys

Surveys were collected that requested engineers and managers to assess the time spent on a variety of communication modes and their effectiveness in contributing value to the program.

Time Allocation

In Table 7.10, time allocation data were collected that emphasizes the communication aspect of product development. Fifty-nine surveys were obtained, of which 23 were from engineers and 23 were from managers in product development. The remaining thirteen surveys were from manufacturing, operations, and business support and did not provide a statistically significant sample size for comparison.

Table 7.10: Current Time Allocation in Product Development (in %)

Modes of Communication	Total for Product Development (n = 46)	Engineers (n = 23)	Managers (n = 23)
Face-to-face	16.5	19.1	14.1
Meeting (with 2-5 people)	10.4	8.7	12.0
Meeting (with 6+ people)	7.7	5.4	9.8
Telephone	6.3	6.1	6.6
Teleconference	3.5	3.3	3.7
Voicemail	2.6	2.0	3.1
Instant Messenger	0.8	0.6	1.0
Memos	2.0	1.5	2.4
Email	15.7	13.8	17.4
Mail	0.7	0.2	1.1
Reading formal literature	3.1	2.8	3.4
Reading informal literature	3.3	2.3	4.2
Browsing the web	3.5	4.8	2.4
Network other than web	2.8	4.1	1.5
Other time[26]	20.9	26.2	16.3
Hours per week	47.4 hours	44.6 hours	50.2 hours

Highlighted boxes represent statistically significant differences (t-test < 0.05)

An immediate observation from Table 7.10 is the large percentage of time spent on communication-related tasks for both engineers and managers (respectively, 73.8% and 83.7%). The number is reasonable for managers, but surprising for engineers, as one might assume that they would spend a greater percentage of their time on isolated tasks, such as design or analysis.

Communication Effectiveness

Communication is generally useful in providing information over three broad areas: technical work, process related work, and team building. These areas are similar to the three dimensions discussed in Section 3.3, following the work of Warfield (1976) and Eppinger (2001). The

[26] This category was not explicitly included in the first few surveys, and six surveys were adjusted to include this category.

definitions of these areas used in the survey are listed in Appendix D. Each mode of communication was evaluated on a 1-3 scale (that is, not effective, effective, and very effective), following the definitions provided. The results of the communication effectiveness survey are shown in Figure 7.3.

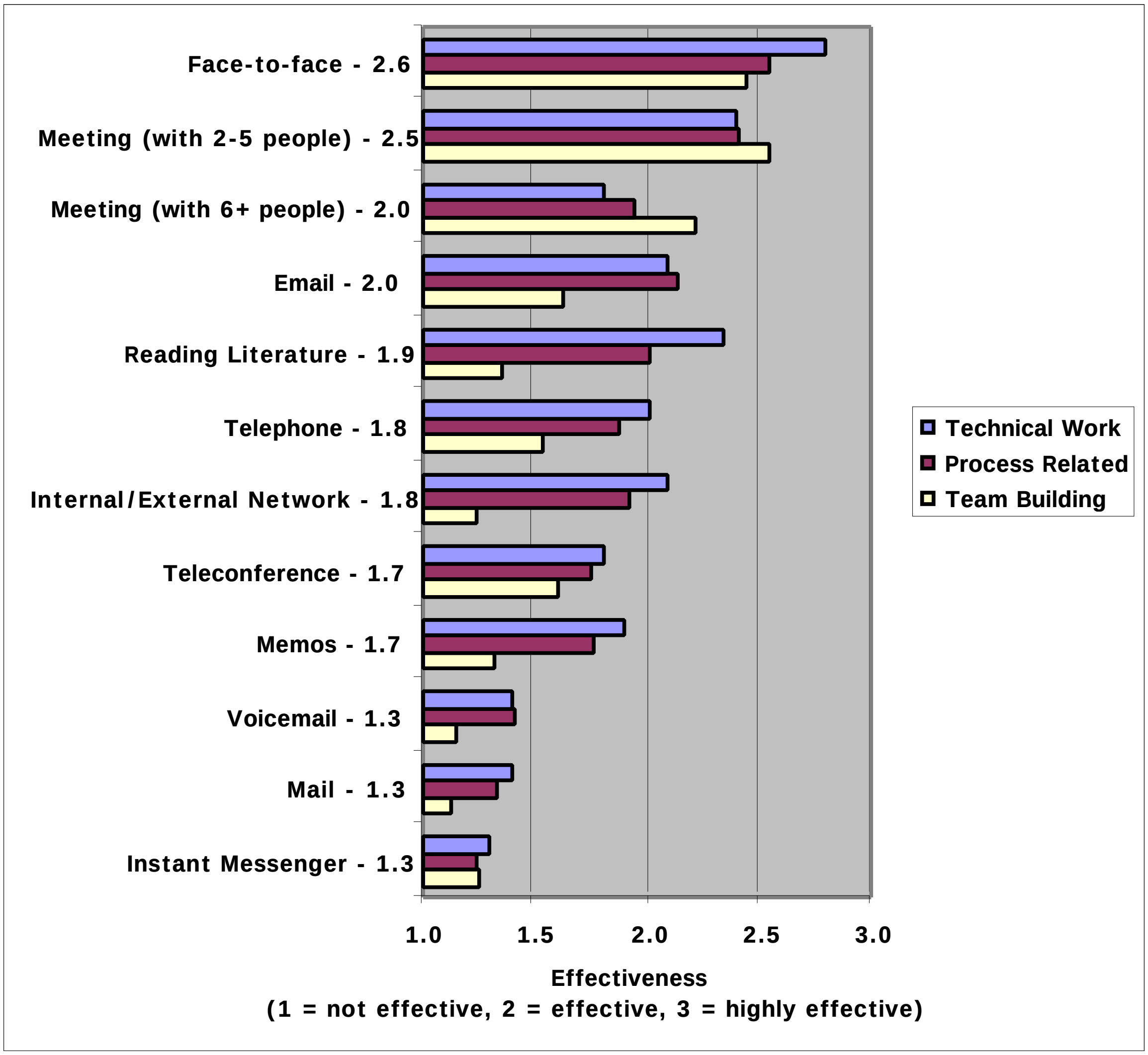

Figure 7.3: Effectiveness of Communication Modes

The modes of communication are listed in decreasing order of their average effectiveness. For example, face-to-face communication was rated the most effective form, with an average score of 2.6 (or fairly effective). Similarly, meetings of two to five people were rated 2.5. However, a large drop (from 2.5 to 2.0) occurred as meetings increased beyond five members. (This trend follows intuition in that as the number of people increase, the effectiveness decreases.)

Figure 7.3 also shows how modes of communication vary in effectiveness depending on their function. In general, unless all communication occurs in person, a variety of communication forms will be required, each contributing different types of value. Furthermore, interpersonal communication is a critical element. It provides much more effective technical and process communication than the other forms, and it is the primary source of team building value. Thus, an effective workplace should emphasize this type of communication over other forms.

Another analysis was conducted on how engineers and managers consider different forms of communication useful. Table 7.11 illustrates differences between the engineering and management view of effectiveness. For process-related work, engineers consider voicemail or memos more effective, whereas managers believe large meetings are effective for their purposes. This suggests that perhaps there should be less large meetings through greater use of voicemail or memos. In terms of technical work, engineers consider online networks and formal literature more effective than their management counterparts.

Table 7.11: Comparison of Communication Effectiveness for Engineers and Managers

Communication Mode	Function	Engineers (n = 23)	Managers (n = 23)	T-Test Value[27]
Voicemail	Process Related	1.7	1.3	0.015
Memos	Process Related	2.2	1.7	0.025
Meetings (6+ people)	Process Related	1.7	2.1	0.026
Browsing web	Technical Work	2.2	1.9	0.060
Face-to-face	Team Building	2.3	2.6	0.072
Formal Literature	Technical Work	2.6	2.3	0.074
Internal Network	Technical Work	2.3	1.9	0.099

Using the time allocation data of the previous subsection and effectiveness data of this subsection, a time versus value chart was constructed (see Figure 7.4). The chart uses Shillito and DeMarle's (1992) method to define areas for improvement. Figure 7.4 reveals the *relative*

[27] T-test values of less than 0.05 represent statistical significance.

usefulness per time of various communication modes. The trend line shown provides the same insight as the line proposed by Tanaka (1973); that is, activities above the line should be given additional time, whereas activities below the line are targets for improvement. The trend line suggests that more time should be allocated for face-to-face discussion and small group meetings, and it targets email (and to some extent the telephone) for improvement.

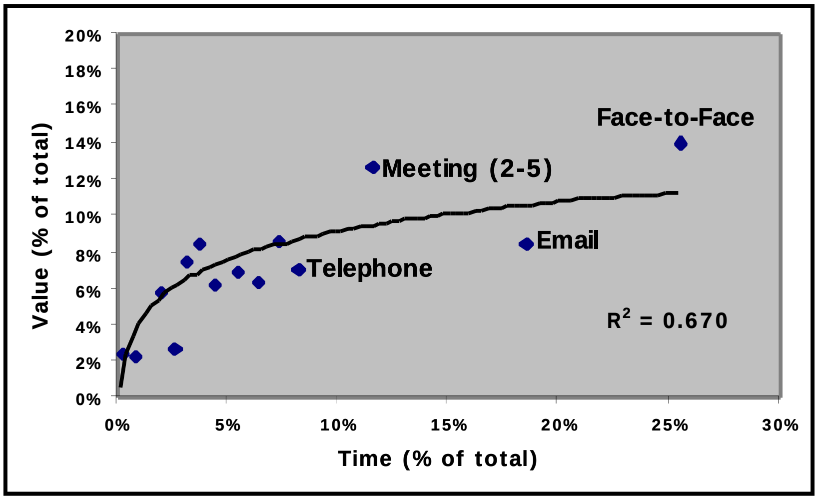

Figure 7.4: Time versus Value of Communication Modes

7.3.2 Brief Case Studies of Successful Industry Teams

To provide a broader perspective on the environment, three successful industry teams were selected as instances where the environment has contributed to the successful completion of an objective. The information presented here is publicly available, although site visits were conducted to interview relevant personnel. The three teams include the F/A-18 E/F program (Boeing), Developing New Products (DNP) Team (NASA), and Mission Control Center (NASA).

The results are presented in Table 7.12, and a brief discussion of each is presented in Appendix B. Although most product development programs lack the characteristics suggested, each of the teams studied exhibit the majority of them. All three programs provided separation between regular activities conducted in the individual office and the work at hand. The three programs used a display screen to provide constant communication of the design to each team member.

Two of the programs used support staff to help locate necessary information, and two brought in outside stakeholders for their perspective.

Table 7.12: Proposed Suggestions for the Product Development Environment

Characteristics of the Environment	"Twelve Days of August", F-18E/F	Developing New Products, JPL	Mission Control Center, JSC
Design and analysis activities are isolated from other tasks in an area devoid of distractions and apart from individual offices	√	√	√
Information gathering is facilitated by a support staff for quickly finding the right information		√	√
Display screens are used to help continuously communicate design information	√	√	√
Relevant stakeholders are invited to participate in the design process for significant periods of time, while continuing to work on their regular tasks	√		√

7.3.3 Discussion of Environment Value

As proposed in Table 5.1, the environment of the product development process should encourage continuous flow, communication, and a lifecycle perspective. With this in mind, research was conducted on time allocation, communication effectiveness, and environments of successful teams. The primary result is a reaffirmation of the importance of communication, as it encompasses a large share of development time. Effort must be made at managing communication to prevent two problems from occurring. The first is that ineffective communication may quickly lead to substantial waste. For example, a geographically separated program, where team members only communicate via teleconferencing and email will suffer through lack of interpersonal contact. The second problem is that too much communication can quickly paralyze a program. Although modern tools have led to significant increases in productivity, there is no substitute for face-to-face communication, which was the only form of communication successful to address technical, process, and team value (Figure 7.3). Managers should emphasize layouts in which interpersonal communication is promoted. The review of three successful product development teams also found that tasks should be accomplished in a distraction free environment with a specific objective at hand.

7.4 Management Research

The final area of value in product development is the management approach. Effective management represents the bridge between process and product value, and it should ensure the product meets performance, cost, and schedule specifications. This section reviews the management approach by studying technical uncertainty and task completion.[28] The principal results of this component of the research are described below.

1) Progress in product development is difficult to estimate accurately from data on the estimated percent completion of tasks.
2) From four programs studied, tight schedule and cost control (that is, application of an earned value management system) showed significantly better schedule performance (that is, 63% versus 27% of tasks were early or on time) than programs using a traditional, or Gantt chart driven, management approach.
3) At a detailed level, engineers found it difficult to estimate the uncertainty in technical performance measures.

7.4.1 Analysis of Schedule Completion Data

Current management techniques for product development have evolved from the manufacturing sector, where the prevailing sentiment suggests consistency and performance to plan as the primary means for guiding resource allocation. This perspective supports tools that measure recurring cost and schedule, stressing the consistent use of resources. In product development, Gantt charts are used in approximately 70% of programs for controlling the process (McManus, 2000). Similarly, the current industry-wide adoption of earned value management (EVM) follows this trend of measuring performance to plan. However, few programs utilize a weekly earned value system, where performance is measured against the plan each week. This technique has proven to be effective (such as, F/A-18 E/F) in managing large, complex programs within schedule and cost, while attaining all technical objectives (Haggerty, 2001). Weekly EVM provides program management with rapid indication of schedule and cost problems, thus allowing timely corrective action.

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[28] Cost is not considered due to the difficulty in obtaining proprietary data.

The successful use of Gantt charts or earned value management requires the process to be predictable. So, program managers can anticipate the needs, strengths, and weaknesses of the program and act accordingly to maximize the output. A question, however, is whether product development processes are adequately predictable. To answer this, data were obtained from four product development programs (see Table 7.13). Programs A-2 and A-5 use a traditional approach (that is, simply providing a deadline for the completion of the tasks), and programs B-5 and B-6 used an earned value management system.

Table 7.13: Programs Used for Evaluating Schedule Consistency

Programs	Tasks	Tasks Measured	Days / Task	Lifecycle Phase (1-6)	
				Start Phase	End Phase
A-2	55	31	16.3	~ 2.5	~ 4.3
A-5	51	24	49.2	-	-
B-5	109	109	78.7	~ 2.5	~ 3.5
B-6	20	20	54.0	~ 3.90	~ 3.95

Traditional Approach

Over the course of the study, data were collected from 106 tasks of programs A-2 and A-5, which includes completion times that ranged from a few hours to several months. In several cases, the tasks were either incomplete or too short (that is, less than 3 days) to be used in the study, resulting in 55 usable cases. After the data were normalized (by dividing the actual by time by the estimated time), there was little difference between the averages of the programs.[29] Thus, the data were combined to form a single set of results as shown in the following figures. In Figure 7.5, mid-task data[30] show the estimated percent completion of each task during its execution. The results suggest that program personnel have great difficulty in estimating their progress, relative to the completion date, for a traditional (or non-EVMS) approach.

[29] The average timeliness ratios for the two programs were 3.8 (±5.6) and 3.8 (±5.1).

[30] A total of 330 data points were obtained, or an average of six from each task.

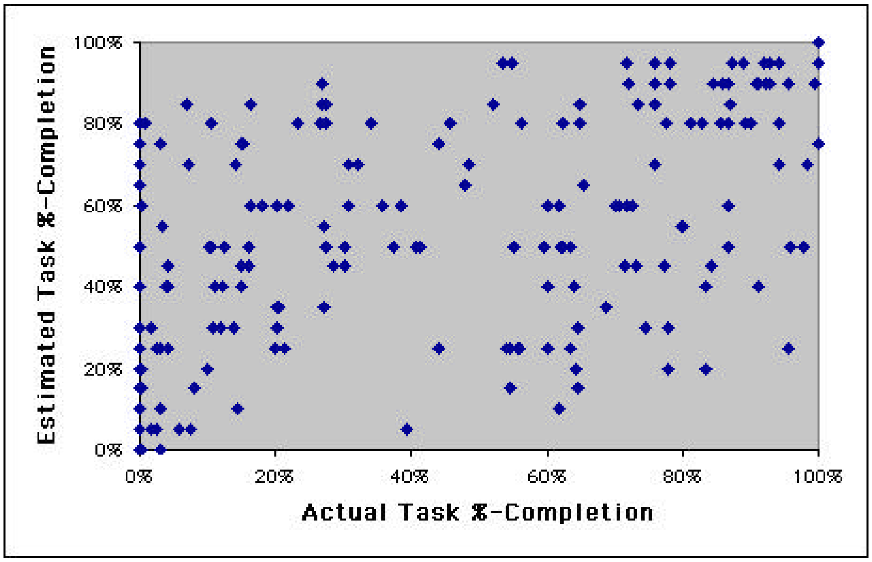

Figure 7.5: Estimated versus Actual Completion (A-2 & A-5)

The relative accuracy is further illustrated in Figure 7.6, where only the data points in the range of 20% to 80% of the actual completion time are plotted. The correlation (or accuracy) of the data is compared against data from manufacturing.[31] The difference in correlations (0.004 versus 1) shows a stark contrast. (The difference is probably an extreme case, since the product development data represent a traditional management approach, whereas the manufacturing data represent the world-class standard of the Toyota Production System.) Nevertheless, a fundamental difference between development and manufacturing is illustrated.

[31] The manufacturing data was obtained from Spear and Bowen (1999), which led to their first rule of the Toyota Production System that "all work shall be highly specified as to content, sequence, timing, and outcome." The example that the data is based on is the installation of a front passenger seat. Toyota specifies the work instructions for this task in intervals of approximately ten seconds. This type of accuracy allows the Toyota Production System to maintain continual awareness of their progress. It should be noted, however, that manufacturing tasks are "repetitive functions" whereas product development tasks are non-recurring "first time" activities.

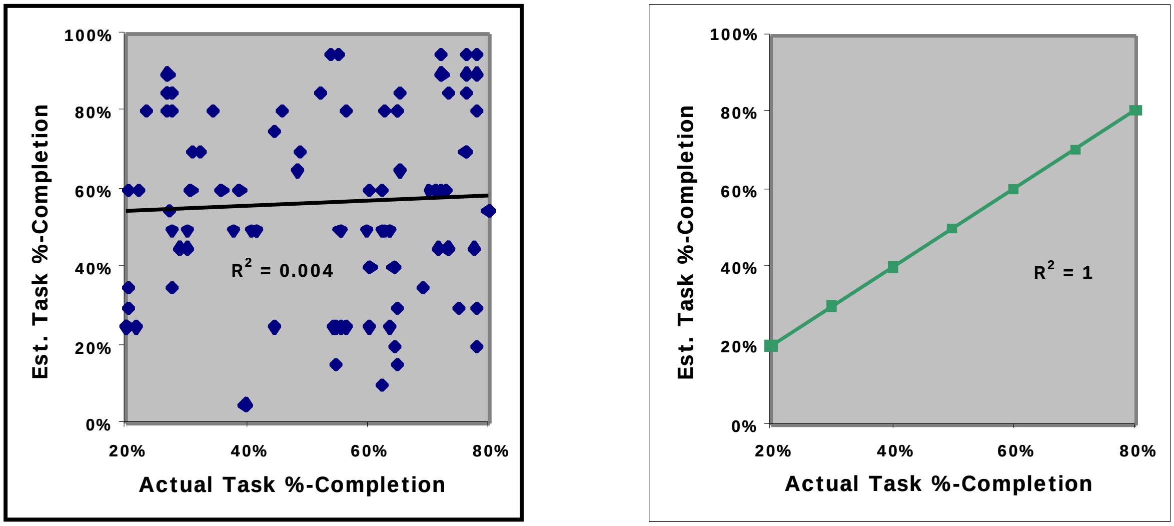

Figure 7.6: Product Development versus Manufacturing Task Completion

The histogram in Figure 7.7 represents the actual versus estimated completion times of the 55 product development tasks in cases A-2 and A-5. In line with past LAI research, the data suggest that tasks are rarely completed ahead of schedule and usually have a decreasing distribution to the right.

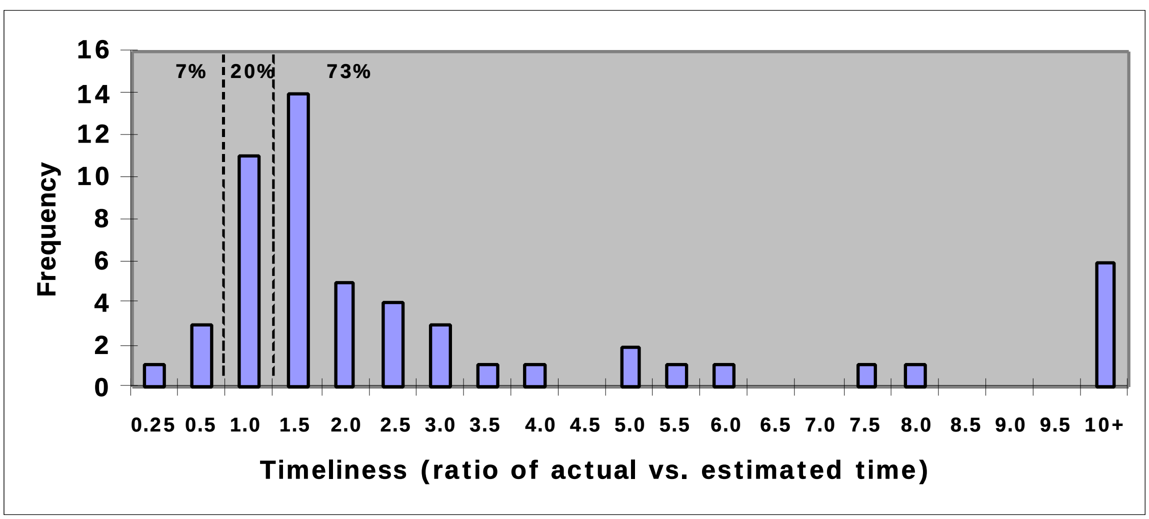

Figure 7.7: Histogram of Product Development Task Completion (A-2 & A-5)

Earned Value Management System (EVMS)

Although the earned value management system was developed a number of years ago, it has recently been the subject of increased attention. The Air Force and several corporations have promoted its use across the industry, and successful implementations have included the F-18 E/F, the B-2 (Solomon, 2000), and the software division of the Oklahoma City Air Logistics Center (Lipke, 2000).

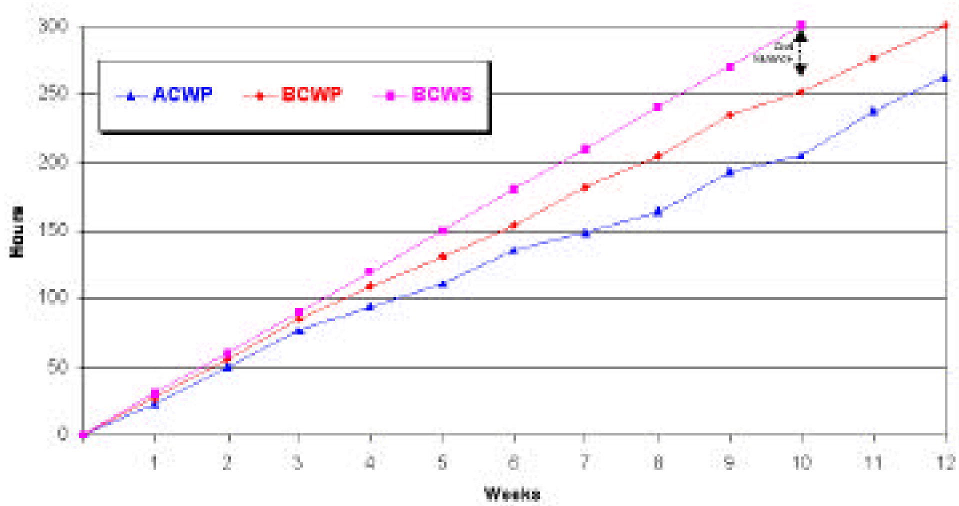

Figure 7.8: Estimated versus Actual Completion (Site B-5)

Figure 7.8 shows the weekly progress measurements of EVMS. ACWP is the *actual cost of the work performed*, BCWP is the *budgeted cost of the work performed*, and BCWS is the *budgeted cost of the work scheduled*. Of these measurements, BCWP is equivalent to the data shown earlier in Figure 7.5 as the intermediate points represent estimates of completion. These data were available for only one task, so it cannot be directly used for comparison with Figure 7.5.

Task completion results were obtained for two programs, B-5 and B-6. The data for B-5 are displayed in Figure 7.9 and show that timeliness has increased from 20% of the tasks being on time to 49% of the tasks being on time. Early completions are up from 7% to 15%, and late completions have been reduced to 37%. The tasks from program B-6 produce a similar result, as 70% were completed on time and only 30% were significantly late. These data from two programs are not conclusive, but it does suggest that product development tasks may be controlled (and thus predicted) to a much greater degree than Figure 7.5 would suggest.

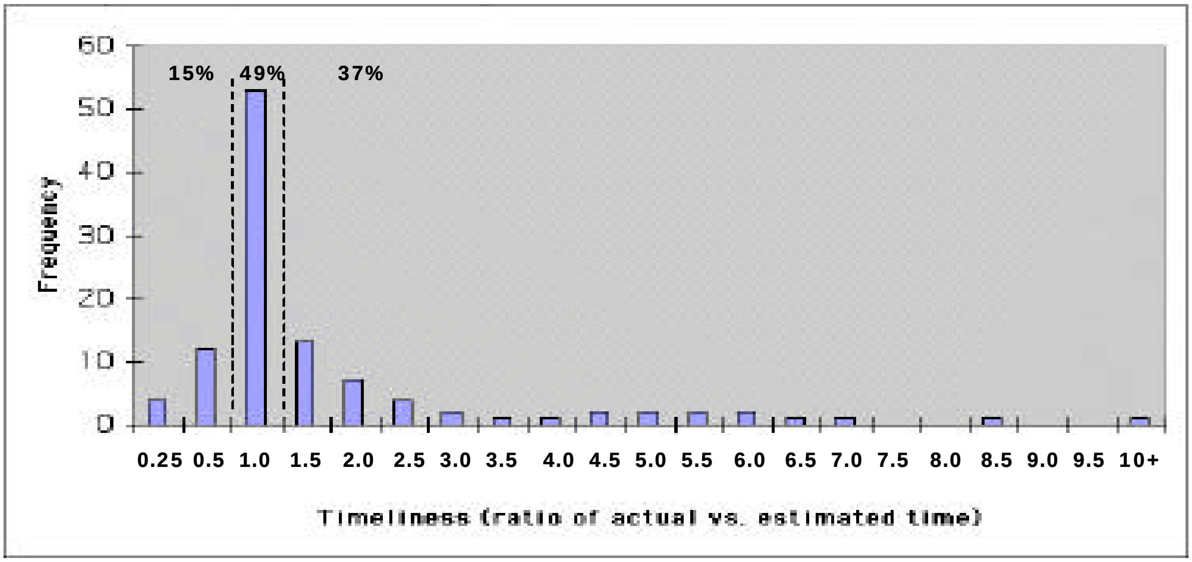

Figure 7.9: Histogram of Product Development Task Completion (B-5)

7.4.2 Managing Technical Uncertainty

Rather than emphasizing the schedule (via performance to plan), other approaches emphasize the pursuit of technical objectives. Many researchers (such as Huff, 1997; Kulick, 1997; Pisano, 1996) have suggested that this value may be quantified using technical performance measures (TPMs).[32] Thus, "by tracking the system's TPMs, the project manager gains visibility into whether the delivered system will actually meet its performance specification" (NASA, 1995). Programs that have successfully implemented this approach, limited to TPM mean values, include the C-17, Apache, and F/A-18 E/F (Haggerty, 2001).

Recently, Browning (1998) and Deyst (2001) have suggested that it is more useful to measure the decreasing uncertainty of technical performance measures (see Figure 7.10). This shift in thinking corresponds with the change from product to process value discussed in Section 4.3. Product value is described by the combined value of TPMs, whereas process value is the reduction in TPM uncertainty contributed by product development activities. This perspective

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[32] Technical performance measures may also be called measures of effectiveness (MOEs), figures of merit (FOMs), and other names (Browning, 2001).

parallels the manufacturing methodologies of Six Sigma and statistical process control (SPC), which ensure desired production yields are realized (Deyst, 2001). This also suggests that management should measure TPM progress throughout the product development process, as a means of ensuring the ability to deliver value to the customer.

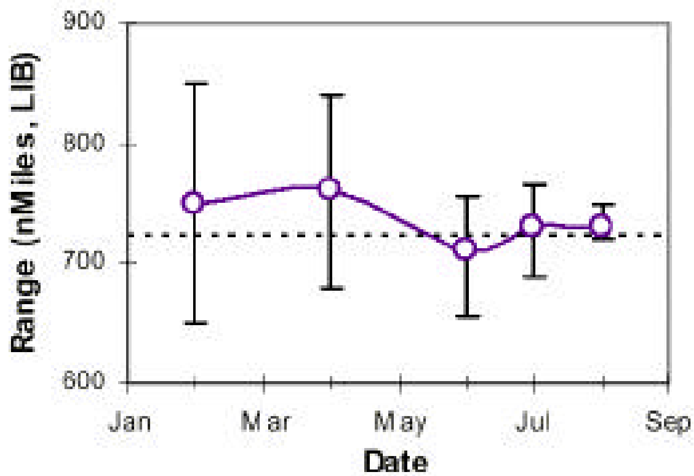

Figure 7.10: TPM Planned Profile and Risk Reduction (Browning, 2001)

Measuring technical uncertainty at a detailed level proved difficult for this research. From the 15 teams that showed initial interest, only one team agreed to submit data, and this team found the measurements quite difficult. Thus, over the course of several months, no data were collected at a weekly or bimonthly level of detail. This result suggests that managing a program through technical uncertainty is a considerable challenge.

7.4.3 Discussion of Management Value

The desired management approach should provide continual awareness of the technical performance, cost, and schedule of the program. The emphasis should allow the program manager to reallocate resources in order to deliver the desired product to the customer on or ahead of schedule, within budget, and meeting all technical specifications. Currently, industry typically uses either Gantt charts or EVMS to manage programs. The Gantt chart is considered the more traditional and less costly approach. However, in the programs studied, a high degree of variability was observed, leading to the significantly delayed completion of tasks. In contrast, the programs using EVMS were completed more often on time. The small sample size of these results prohibits any broad conclusions. However, it offers some evidence that higher degrees of performance may be obtained in product development through a more rigorous management system (such as EVMS). Ultimately, this added visibility and control produces the value that is delivered to the customer. If technical performance measures are included in the EVMS, “the confidence level of achieving schedule, cost, and technical performance of the program, and thus delivering the value promised by the program, is significantly higher” (Haggerty, 2001). Even further, tracking the uncertainty of the TPM’s would be a valuable addition to the mean values; however, this was found to be extremely difficult in practice.

Chapter 8: Summary

This research presented a foundation of lean philosophy, product development process, and value that led to a framework of value creation in the product development process. Data were collected and analyzed, based on this framework. A summary of results is presented below.

Value Creation Framework

1) The product development process may be decomposed into a series of tasks that use resources to create information and reduce risk, resulting in a product delivered to the customer (see Figure 5.1). Within the framework, value may be divided into *product value* and *process value*. In product development, tasks are often too far removed from the customer for product value to be of use, and it is often more useful to focus on process value in process improvement efforts. Process value is the approach of the enterprise in creating a desired product for the customer, a continuing profit for the shareholder, and lifetime satisfaction for the employee. Process value may be decomposed into *tasks*, *resources*, *environment*, and *management*, and then subdivided further into a number of value attributes (see Figure 5.2).

2) A value creation framework has been developed to aid in the visualization of value creation in product development. The framework can be used, as demonstrated by the research, to help analyze the product development process. Validation of the entire framework is beyond the scope of the thesis, but the results from several sets of data are presented below.

Results from Task Research

3) The percentage of tasks that address various aspects of value differ markedly from program to program and process to process (see Table 7.4), implying that there is not a single definition of "the product development process" at anything but the highest level.

4) The majority of tasks defined at a high level appear to contribute directly to value. They are directed at designing the product, defining the production process, or reducing the product uncertainty or risk. However, when tasks are further decomposed (in process WBS's), an appreciable fraction (~30%) fell into supporting and enabling categories. A challenge of

considering task value is that a high-level perspective will indicate that all tasks directly contribute value, while a finer decomposition of the same process will reveal non-value-added activities. This is consistent with the view from Browning (1999) that addressing the value of tasks must occur at the finest, practical level of detail.

5) The WBS's of programs judged to be taking place in more lean environments showed *more* supporting tasks, primarily those concerned with cost and schedule management, than those taking place in traditional environments. This is interpreted as reflecting a higher consciousness of the need to explicitly deal with cost and schedule issues.

6) Attempts to directly gauge task value by surveys were unsuccessful, because the data were too sparse. The pilot study performed on students developing theses was more successful, identifying higher and lower value tasks. The suggestion is that the methodology may have some utility if broadly applied.

Results from Resources Research

7) The site visits conducted as part of this research consistently identified the appropriate resources (primarily people and software tools) as critical to the success of programs. However, metrics for assessing the value-creating potential of "human capital" and software tools were not found. No quantifiable data on resource value were collected in this research.

Results from Environment Research

8) The importance of communication in product development activities, identified by many previous authors (such as Allen, 1977 and Bernstein, 2000) was reinforced by the results of this study. The engineers and managers surveyed gave high importance to face-to-face and small group interactions.

Results from Management Research

9) Almost no correlation existed between estimated percent completion and the actual completion time of industry tasks. Data from an earned value management system, however, showed fewer tasks completed behind schedule (see Figure 7.9), suggesting that some control is possible through a more rigorous management tool.

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Appendix A: Discussion of Resource Value

Thompson and Strickland (1998) describe the value of resources as corporate strengths and capabilities, which they suggest include the following abbreviated list.[33]

- Valuable human assets – an experienced, capable, or talented workforce
- Valuable physical assets – state-of-the-art plants, equipment, or software
- A skill or important expertise – technological or manufacturing know-how

These areas correspond with people, tools, and knowledge, as the ingredients that flow into product development activities. The elements are not independent, since knowledge is often considered a mixture of people and tools, residing as either tacit knowledge in the workforce or explicit knowledge within tools. The discussion presented here stems from a series of interviews. The interviews were conducted with several product development teams (as described in the previous chapter), and the majority of the results stem from three programs that were given "carte blanche" (as stated by one program manager) for obtaining program resources.

A.1 Knowledge

> "The most valuable assets of the 20th century were its production equipment. The most valuable assets of the 21st century will be its knowledge workers and their productivity."
> – Peter Drucker

The growing complexity of product development has led to knowledge as the "key asset whose exploitation will determine success for many firms" (Miles, 2000). Knowledge is the "insights and context from the mind - what the knower knows," and it exists at the integration of people, process, and technology (Wessels, 2000). Furthermore, it is seen as an "essential ingredient for reducing lead times and maintaining the highest quality standards" (Hammersley et al, 1999).

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[33] The entire list includes organizational assets, intangible assets, competitive capabilities, organizational achievement, and corporate alliances, which are considered less relevant to the task level of product development.

Despite the importance of knowledge, however, “research on how organizations recognize, develop, and transfer knowledge is still in its infancy” (Rulke et al, 2000). Moreover, knowledge in the aerospace industry has come to a critical period. Due to downsizing and retirement, many thousands of jobs have been lost (Wessels, 2000). Experience has significantly decreased and many engineers are nearing retirement. For these reasons, several aerospace companies have begun to invest in knowledge management, which is the development of tools to encourage collaboration and capture the tacit knowledge of employees.

A.2 People

The value of employees, however, is not measured simply by their knowledge, but by a variety of factors that contribute innovation as well as experience. Based on the relevant literature and interviews, five attributes were identified to describe organizational value and are discussed below.

A.2.1 Proficiency

Product development in the aerospace industry requires significant technological knowledge to remain proficient. Thus, it is not only important to initially select competent employees, but to provide training to maintain their skills and knowledge. The Air Force (1996) expands this sentiment to include quality, stating that “education and training are essential to implementing quality.” The product development teams visited all had high levels of proficiency and usually years of experience. The one exception mentioned a few times was that design engineers “do not have insight on cost savings and may miss the big picture.” This corresponds with earlier research, which identified a lack of emphasis on cost savings at the detailed level of process.

A.2.2 Diversity

> “I’m not talking about trying to cultivate generalists… To help engineers develop expertise in their core field, we need to provide them with diverse experience in that sector and in peripheral sectors.” – Vice President of Research and Development[34]

[34] Quotation is from Sobek (2000).

A number of program managers and industry experts have stressed the importance of diversity. Rosenau (2000) and Trott (1998) include a "diverse range of skills" as a necessary characteristic of employees. In light of this, the programs visited made determined efforts to get the "best people with diverse experience." Diversity serves not only as a source of new ideas, but more importantly it increases cross-functional cooperation. For example, technology gatekeepers, described by Allen (1977), have led to better product performance due to their extensive communication networks. In industry, this trait was observed in design engineers, who generally maintain good contacts for help in answering design, analysis, and manufacturing questions.

In terms of achieving a balance between proficiency and diversity, Iansiti (1998) conducted a study in computer mainframe development. He found that, "by and large, projects staffed mainly by members with more than 2 full generations of experience did not perform as well as those with some lesser amount of experience." Thus, he concluded that some diversity is necessary at the expense of increased depth.

A.2.3 Empowerment

> "Never tell people how to do things. Tell them what to do and they will surprise you with their ingenuity." -General George S. Patton, Jr. U.S. Army

As discussed earlier, empowerment is one of the tenets of lean theory. The Lean Aerospace Initiative (1999) and Trott (1998), among others, have emphasized its importance. In the programs visited, this was usually evident from the delegation of responsibility, accountability, and authority (RAA) to the employees. Responsibility represents the assignment of a specific task, accountability is ensuring the quality of the task, and authority is the right of an individual to take the necessary actions required to complete the task. In many instances, organizational empowerment was successful. However, several engineers mentioned the loss of mentorship, which is due to a combination of increased empowerment and downsizing in the industry.

A.2.4 Mentorship

Even as empowerment increases in the aerospace industry, mentorship is quickly disappearing. These two attributes, however, should not be considered opposites. The best example of their synchronous implementation can be found at Toyota. Toyota traditionally relies on its employee base to anticipate and solve most problems. However, this process does not happen alone. Everyone at Toyota has a *sempai* (or mentor) who is not their boss (Sobek, 2000). Sobek writes that supervisors actively train their engineers regarding many technical and non-technical issues. Supervisors are "working team leaders," which maintains employee empowerment but provides help as necessary. Unfortunately, this type of mentorship is costly, and even in the model programs visited, managers felt that the money is simply not available.

A.2.5 Leadership

The final component of organizational value is providing the necessary leadership in key positions. At Toyota, the chief engineer is the integration specialist and "totally responsible for the vehicle program (concept, targets, schedule, budget, coordination, and key design decisions)" (Sobek, 2000). Similarly, the U.S. aerospace industry requires a program manager who is administratively and technically skillful and keeps a high level of communication among team members. In addition to these positions, many engineers actually consider design engineers "to add the most value." Since their position must integrate many sources of information into a specific design, it requires a great deal of talent, experience, and authority. Finally, it is important to stress that "establishing a strong quality focus requires substantial time and effort from the leadership team" (Air Force, 1996).

A.3 Tools

Several decades ago, lean began with the use of flexible tools in the Toyota Production System (Womack and Jones, 1990). In the last few years, a similar transformation is being made in product development. Software and information technology tools are providing significant leaps in productivity. For example, the following description of the Boeing 777 program led to a "60 to 90% reduction in rework" from previous airplanes (Condit, 1996).

> The 777 was the first Boeing jetliner designed completely on computers…With the use of interactive graphics, the design teams were able to concurrently release structure, systems, payloads, and other design features of the aircraft with minimal interference and related problems. (Condit, 1996)

Software tools were also used for testing, where they helped conduct thousands of test hours prior to the rollout of the first 777, and similar technology was used on the two other successful programs visited. In each case, few expenses were spared to incorporate modern tools, which are described in this section. This commitment, however, does not necessarily extend beyond these select programs, and industry managers have suggested that many programs have not yet applied the new tools that are available.

A.3.1 Information Gathering Tools

> "Sometimes the telephone number of the right person to speak with is the most valuable piece of information you can give out." – Design Engineer, Site B

Although direct communication is probably the most effective means for gathering information, the size and complexity of product development requires a host of software tools to facilitate this means. These tools include product data management systems, information archives, and communication tools. Their objective is to efficiently provide the right information at the right time. This is generally accomplished via documenting information in archives and enhancing communication among team members.

Industry has had some success documenting information in three areas: issue tracking, engineering skill management, and knowledge retention (Wessels, 2000). Issue tracking involves linking documents to websites for quicker access, and all of the companies observed have integrated this capability to some extent. Skill management was less common and involves the documentation of skills in an effort to retain and promote the best people. Finally, knowledge retention was the least common, as it employs video and online documentation to describe detailed designs, processes, and other useful knowledge. In each of these cases, once the necessary information is documented, it may be retrieved via search engines or hierarchical structures that provide easy access. This efficient access of information has been employed in other industries, where, for example, a 75% reduction in cycle time was achieved in automobile stress analysis (Hammersley, 1999).

Despite the increasing use of documentation to capture knowledge, collaboration remains a more effective means for transferring knowledge. Miles (2000) suggests that "it is now apparent that effective knowledge management depends heavily on a company's ability to collaborate, both inside and outside the company." Burke and Bolf (1986) found that "from a list of 15 sources of learning, managers most value their peers, their immediate supervisor, other supervisors, and external publications," which is inline with related research (Rulke et al, 2000). Finally, Argote and Ingram (2000) have shown that moving technology and tasks is "more effective when accompanied by moving people because people are capable of adapting the tools or technology to the new context." Thus, an emphasis should be placed on facilitating collaboration rather than solely relying on documentation to achieve effective knowledge management.

Given the importance of collaboration, many companies have implemented software tools that assist with communication. For example, one site has introduced virtual collaboration rooms, where engineers, customers, and suppliers can maintain discussions in real time. Several managers believe that this is the direction of product development, despite the appearance of several challenges. For example, some devices offer the capability of sending and receiving messages from anywhere (including during meetings), creating interference in the working environment. Similarly, many product development personnel have characterized email as a constant distraction.

One tool that combines the strengths of documentation and collaboration is the visual information pull system (VIPS). It was developed by Aerojet to introduce the lean principle of pull to product development. VIPS is a web-based system that is used to request the completion of tasks and then tracks their progress. It increases transparency (providing the entire team with access to the progress of ongoing tasks) and is used to send messages to team members (facilitating communication). Another advantage of VIPS is its emphasis on specific tasks. This perspective allows for the introduction of techniques to measure value. For instance, in addition to schedule-related data, other measures may be kept such as cost and balanced scorecard data. Thus, tasks may be more directly analyzed for value adding or enabling efforts, as described in the previous section.

A.3.2 Knowledge Application Tools

During visits, engineers and managers repeatedly characterized computer aided design (CAD) software as "the single most significant contribution" to increased productivity. The strength of CAD tools lies in their ability to simplify and automate much of the process. Furthermore, the tools provide a visual aid that increases communication. For instance, meetings were observed where the design was displayed to several team members, who would discuss problems and suggest changes. This type of collaboration increases understanding, reduces rework, and is fundamentally changing product development as it becomes more common (see Section 3.4.2).

Similarly, those familiar with manufacturing have credited software technology for reducing manufacture and assembly time. Software applications have led to increased design for manufacture (DFM). DFM is “aimed at reducing manufacturing costs while simultaneously improving (or not compromising) product quality, development time, and development cost” (Ulrich and Eppinger, 1995). For instance, some tools allow manufacturing to be simulated, testing for accuracy before actual production. Likewise, other tools allow the assembly to be simulated to ensure that workers can access all necessary areas of the product. This simulation is exported to the assembly line to facilitate understanding, while correspondingly helping to standardize the process. Similarly, other new tools are constantly being introduced to the product development process. For example, over 35 different stress analysis software packages are available, with each having its strengths and weaknesses (Hammersley et al, 1999).

Appendix B: Case Studies of Successful Team Environments

Brief case studies were conducted on the following three teams in order to pool characteristics of successful team environments. The following teams have had notable success, and thus serve as model environments.

B.1 "Twelve Days of August," F-18E/F, Boeing

The first case study is from the F/A-18E/F aircraft development program, where in August of 1991, the program encountered a significant challenge. During the previous nine months, Northrop, General Electric, and the Navy had been working to define the configuration and high-level requirements for the E/F. The work, however, had been largely unsuccessful and the result was "a weapon system that was over weight and over cost" (Springsteen, 1999). To address this problem, a twelve-day meeting (later called the "Twelve Days of August") was convened to create a set of requirements that would not exceed the weight and cost budgets. In other words, the objective was to accomplish in twelve days what had proved unworkable in nine months.

Many of the problems were the result of a lack of cooperation across functional groups. Each group desired the best performance, regardless of the impact on the entire aircraft. For this reason, it was decided to bring together all of the people who were knowledgeable to define the configuration and requirements (Springsteen, 1999). Over 40 people attended the event, gathering as a group each morning and evening, and working in functional teams throughout the remainder of the day. "Over the twelve days they had to trade off weight, fuel, capacity, volume, materials, the size of the radar cross-section, and cost. Operational analysis was going on throughout all of this in order to understand what was being gained at a system level with the changes that the teams were making" (Springsteen, 1999).

The result of this intense effort was a configuration and set of requirements that led to the production of the F/A-18E/F aircraft. This aircraft won the Collier Trophy and was produced below cost, on-schedule, and with comparatively superior performance (Cool, 2001). When interviewed, many participants mentioned that the success of the "Twelve Days of August" was achieved by bringing together the right people in a distraction free environment.

B.2 Developing New Products Team, Jet Propulsion Laboratory, NASA

The second case study is from the NASA Jet Propulsion Laboratory, which has often been considered a world-class designer of unique spacecraft. A problem encountered by engineers at JPL (and similar to the F/A-18E/F program) is the difficulty in creating the configuration, cost estimates, and requirements. This process may require as much as two years, which adds considerable cost to the project. To reduce the cycle time, JPL created the Developing New Products (DNP) team.

The mission of DNP is to "(1) provide an integrated set of people, processes, and tools which will enable JPL to rapidly engineer highly advanced space projects, and (2) maintain risk, yet deliver spacecraft in 1/2 the time and 2/3 of the cost for missions comparable to pathfinder" (Waltham, 2000). To achieve this goal, DNP uses a common area equipped with several new software tools that engineers can use to quickly obtain spacecraft configurations, cost estimates and requirements. The area is isolated from other team members and offers few distractions.

The result is akin to continuous flow, and one successful application reduced cycle time from two years to two months (a 92% reduction). Although other implementations have had mixed success, the DNP group has effectively applied several changes to promote communication.

B.3 Mission Control Center, Johnson Space Center, NASA

The final case study was conducted at the Mission Control Center (MCC) of Johnson Space Center. The MCC (including the old and new versions) have managed numerous missions, including Mercury, Gemini, Apollo, the Space Shuttle, and the International Space Station. In regards to mission operations, it is considered a world-class location.

Although the MCC seems unrelated to product development, the reality is that they have much in common. Both product development activities and the MCC are focused on problem solving. As each group encounters a problem, resolution is sought via a specific procedure, which includes design, analysis, and testing activities. The difference between the groups is that the MCC is faced with considerable time pressure. Problems during space missions often require solutions in seconds or minutes, rather than the weeks and months of product development. To accommodate this emphasis on time, a unique environment has been created.

The environment of the MCC emphasizes rapid communication between knowledgeable personnel. Over 40 people can occupy the MCC, each assigned to a computer terminal where they monitor various functions of the mission. These engineers and managers also have separate offices, thus keeping the MCC clean and orderly. Below the desks, a few manuals are provided, although the majority of resources are located elsewhere. Given the complexity of most missions, many of the personnel in the MCC have support teams that are found in similar rooms. If a problem is encountered, the manager or engineer can direct the problem to their team to provide a timely solution.

The result of the MCC has been considerable success for many years. For example, many computer glitches have been quickly fixed on early and recent missions. Extra-vehicular space walks have been guided by the center, and perhaps the best example is Apollo 13. Most people are familiar with the timely creation of solutions to fix the series of critical problems that occurred during that mission. In each case, the procedure for resolving the situation is the same: bring the right people together, provide them with the right information, and allow them to work in a distraction free environment.

Appendix C: Pilot Study of Academic Research

As a pilot study for quantifying value, six graduate students were selected to participate in a case study involving value in the development of their Masters theses. Surveys were employed to measure value, which emphasized obtaining initial results that could be analyzed.

C.1 Methodology of Academic Case Study

Importance was placed on using value attributes to gauge student research, since this was considered an unproven approach for measuring value. However, the procedure for this method was modified slightly from the industry studies. Rather than the value attributes previously shown, a new set of attributes of value was created. These attributes include problem definition, background, discussion, hypothesis, case study, results, industry knowledge gain, advisor knowledge gain, student satisfaction and student knowledge gain. For each of these, a simple maturity matrix was created that ranked the tasks from -3 to 3 (more recently defined as 1-5).

Over six weeks, students completed surveys on the value of each task they completed. Once familiar with the surveys, students typically completed them within 90 seconds. The surveys resulted in the development of six extensive sets of data, including over 100 tasks. A small portion of one of these is shown in Figure 1. In addition to the attributes, data on the type of task, documentation, and time was also collected.

Once the data had been collected, it was analyzed for various characteristics. Three significant results were discovered that are discussed in the following subsections. First, the data revealed more precisely how different types of tasks contribute to research. Second, the data could be used to compare different projects and was especially helpful in illustrating clear differences in project completion. Finally, the measure for value of tasks was compared against the time spent. This comparison indicated which tasks provided the most return for the investment.

Type	Documentation	Time	Problem Definition	Background	Discussion	Framework/Hypothesis	Case Study	Results	Advisor Value	LAI Community Value	RA Satisfaction	RA Knowledge Gain
General Meeting	1	2	2	1	0	1	0	0	0	0	2	2
Focused Meeting	2	2	2	1	0	2	1	0	3	0	3	2
Literature Review	2	1	0	1	1	1	0	0	1	0	1	2
Model Development	2	1	1	0	0	1	0	0	0	0	1	1
Paper	2	1	2	0	0	2	0	0	0	0	2	0
Model Development	2	3	1	0	0	1	0	0	0	0	1	1
Presentation	2	3	1	0	0	2	0	0	2	0	2	1
General Meeting	1	2	1	1	0	1	2	0	1	0	1	2
Literature Review	2	1	2	2	1	2	2	0	0	0	2	3

Figure C.1: Partial Data Set of Student Research

C.2 Task Value

The initial emphasis can be placed on the value attributes and their evolution through the tasks of the research process. For example, Figure 2 shows student research at MIT progressing with time, as portrayed by four types of value. Notice how value is characterized by gradual upward progress with occasional jumps and plateaus. The objective is to remove as many of the plateaus as possible. In this example, from 80 to 140 hours, there is a minimal amount of value added to all four perspectives. This area was explored in more detail. In this case, the plateau was a combination of three tasks: a work plan to organize the research, several unsuccessful attempts to phone members of industry, and an unsuccessful literature review. In contrast, a site visit near the 50th hour proved highly valuable. The student remarked that it sparked the next several months of research.

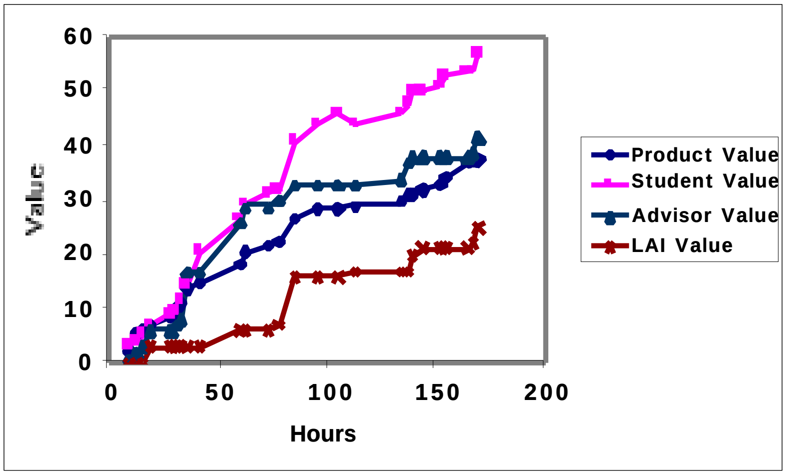

Figure C.2: Cumulative Value of Student Research

In a similar fashion, different research projects may also be compared. For example, one essential component of research is a case study. Despite this importance, students have markedly different success in conducting one. For example, Figure 3 shows the success of each student in obtaining one. Three of the students did not make any progress during the six weeks of this study. The other three were making steady progress until of the 70th hour, when they diverged. From a project management standpoint, this is valuable information that quickly illustrates where potential problems might lie.

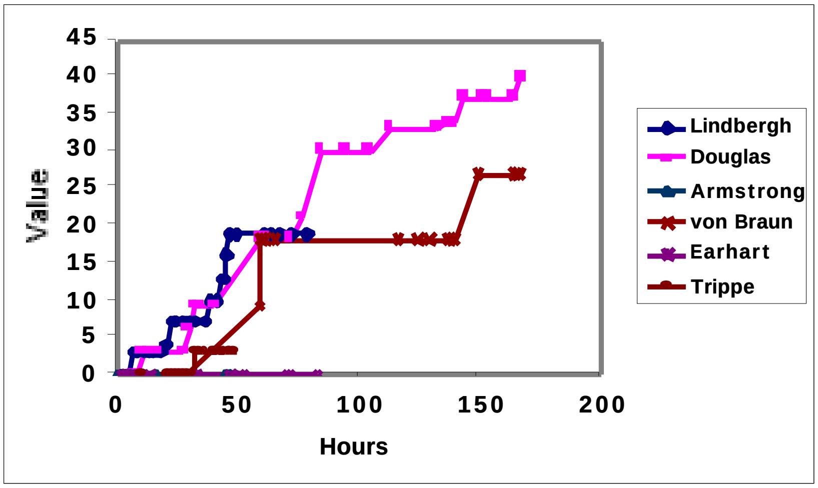

Figure C.3: Comparison of Research Case Studies

C.3 Time versus Task Value

Another comparison is the amount of time spent on different activities versus the value that they create. Figure 4 depicts this association between time and three types of values. One immediate observation is that focused meetings provide a great deal of value, although they do not take up much time. By spending time as a team and working on a specific problem, a great deal can be accomplished. Another insight is that presentations require a large amount of time to create, yet only add value during the actual presentation. In other words, the set-up time is necessary, but non-value-added. These insights are not new to research, but this structured methodology lends them new credence.

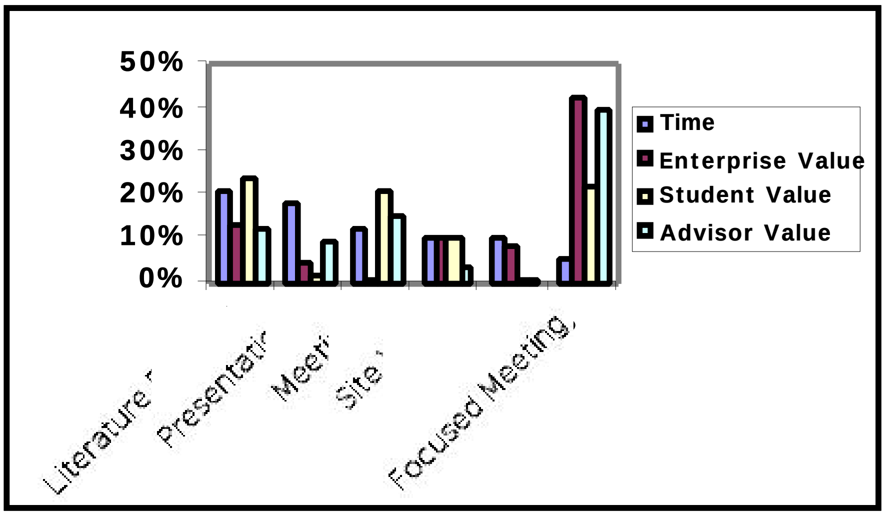

Figure C.4: Activity Value Summary

C.4 Results of the Pilot Study

This case study has surfaced several interesting phenomena. Specifically, tasks have been highlighted that are potentially non-value-added, such as set-up time for presentations. Another insight is that the progress on a research project can be clearly indicated via indirect measures of research value. According to the data, one student can be progressing steadily, while another might be at a standstill. Further research can determine what corrective action is necessary, but the objective of the study has been accomplished.

Appendix D: Research Surveys and Definitions

D.1 Informed Consent for Surveys

This survey is designed to characterize three techniques for measuring value in the Product Development process. This study is part of an on-going research project by a consortium involving the U.S. Air Force, a number of firms in the defense aerospace sector, and the Massachusetts Institute of Technology. The research projects focus on the investigation of the application of "Lean" practices in the defense aerospace industry.

Your cooperation is vital to the success of this study! Please answer the questions as they apply to you. Answering of the questions is voluntary. You are not obligated to answer any question. If you are uncomfortable with any question, or feel in any way coerced or pressured into participating in the survey or any part of it, you may decline to answer any or all questions. Your decision to decline to answer a question will be treated with the same confidentiality as positive answers.

Please be accurate in your responses. We understand that you may have concerns about confidentiality. The survey is intended to be anonymous and several measures will be taken to ensure that your responses will remain confidential. Only the researchers named below will have access to the information requested in this survey. All analyses and reviews of the data will be presented in the form of aggregated statistics. No individuals or individual programs will be identified in the analysis, reviews, or reporting of the responses. We understand that the success of any research depends upon the quality of the information on which it is based, and we take seriously our responsibility to ensure that any information you entrust to us will be protected.

Value in Product Development Team
Jim Chase
Professor John Deyst
Professor Ed Greitzer
Dr. Hugh McManus

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Thank you for your participation in this research!

D.2 Task Survey for Measuring Value (Industry)

Task Survey **MIT Research Study**

All data is confidential (click here for more info).

Name or initials:

Task Name (or nearest task): [selection of tasks from WBS]

(If task is unique, specify task name:)

Task contributes to (click here for definitions):

Functional performance of end product	5	4	3	2	1	N/A
Definition of processes to deliver product	5	4	3	2	1	N/A
Form of final output	5	4	3	2	1	N/A
Reduction of risks and uncertainties	5	4	3	2	1	N/A
Improvement of tools, processes, skills, etc.	5	4	3	2	1	N/A
Cost and/or schedule savings	5	4	3	2	1	N/A
Enabling other tasks	5	4	3	2	1	N/A
Facilitating communication	5	4	3	2	1	N/A
Employee job satisfaction	5	4	3	2	1	N/A
Other (describe in comments)	5	4	3	2	1	N/A

Direct effort spent on task completion: Hours

Comments:

Submit

Figure D.1: Online Task Survey for Measuring Value (Industry)

D.3 Original Value Attribute Definitions used in Industry Task Surveys[35]

V1: Functional Performance of End Product

The functional performance of the end product to be delivered to the customer

Task directly affects the functionality of the end product delivered to the customer. A high score means direct specification of function, or direct specification of form that affects function, e.g. requirements specification, design decisions, or specification of parts, major dimensions, materials, etc. Lower scores might include tasks with minor impact on form and function (e.g. specifying detail dimensions). A "one" score might be used for processes which only occasionally affect form and function (e.g. analyses which may turn up problems but usually do not).

V2: Definition of Processes to Deliver Product

The definition of processes necessary to deliver the end product to the customer

Task directly affects the processes necessary to deliver the end product to the customer. A high score means direct specification of manufacturing, test, certification, or other downstream processes necessary to deliver the product and have it accepted by the customer. Lower scores might include tasks with minor impact these plans or processes; a "one" score might indicate only a chance of affecting these plans and processes.

V3: Form of Final Output

The form of the output of this project (e.g. report, build-to-package, etc.)

Task directly contributes to the document or information package that will form the output to the customer. High scores would include direct contribution to the deliverable documents, e.g. drawings called for in the build-to package. Lower scores might be used for intermediate documentation (e.g. internal reports) some of which may form part of the deliverable documentation, or which might be used directly to prepare it. A "one" might indicate documentation that has only a chance of inclusion in any final product.

V4: Reduction of Risks and Uncertainties

The reduction of risks and uncertainties

Task contributes to eliminating uncertainty in the design or reduces the risk of technical failure or program (cost and schedule) problems. High scores would include direct elimination of uncertainties (e.g. design decisions that eliminate ambiguities in the design) or direct ruling out of risk factors (e.g. analyses that assure performance and/or rule out suspected failure modes), or plans to handle known risk factors. Lower scores might be used for tasks that address less important risks or address only pieces of a problem (e.g. analyses of non-critical components, partial analyses). A "one" might indicate work that has only a chance of impacting program risk or uncertainty.

[35] Originally contributed by McManus (2000b).

V5: Improvement of Tools, Processes, Skills, Etc.

The improvement of tools, processes, technologies or skills relevant to E1-E4

Task contributes to the skill base necessary to do future work, but improving the tools, processes or technologies applied to design processes, and/or the skills of the engineers and others that do the work. A high score might indicate direct work on development of design tools, training, or critical technology. A lower score might be used for incremental improvements in methods, or important work-experience gained. A "one" might indicate incidental (but not trivial) gains in knowledge or work experience.

V6: Cost and/or Schedule Savings

Task saves money and/or cuts schedule time. A high score would indicate that the task directly resulted in major cost or time savings. A lower score might indicate minor savings, or savings as a byproduct rather than direct result of the task; a "one" might indicate incidental savings, or only a chance of savings.

V7: Enabling Other Tasks

Enabling other tasks (e.g. task is required for other tasks to proceed)

Task is necessary for other tasks to proceed, even if it does not itself directly contribute to the above categories of value. Examples include gathering necessary information, getting approvals, set up of models or analyses, meetings to initiate other tasks, etc. A high score would indicate the task is a critical prerequisite to a major value added task. Lower scores would indicate lower levels of criticality (e.g. following tasks could proceed with limitations without this task) or uncertainty (this task is sometimes, but not always, necessary)

V8: Facilitating Communication

Facilitating necessary communication between tasks and/or employees

Task directly aids necessary communication. A high score would indicate direct contribution to free flow of critical information, e.g. setting up information systems, critical kick-off or other meetings, communication of critical information from/to customers, etc. Lower scores would indicate lower levels of criticality or bandwidth; a "one" might indicate incidental contribution to communication.

V9: Employee Job Satisfaction

The employee's own job satisfaction

Task is interesting, fun to do, results in increases in skills or positive experience, or otherwise contributes to job satisfaction. This is necessarily highly subjective. A high score indicates enjoyment of the task - a good reason to come to work. Lower scores indicate routine work; a "one" or "N/A" score might indicate an undesirable or unpleasant task.

V10: Other

Addresses other aspects of value not covered above (specify briefly in comments)

Task performs a necessary or valuable function not covered in the above categories. Examples might include contributions to safety, work environment, or environmental impact reduction; satisfying of regulatory or contractual requirements, the following of existing processes, or other needs we haven't thought of.

D.4 Task Survey for Measuring Value (Academia)

Task Survey **MIT Research Study**

All data is confidential (click here for more info).

Name or initials:

Task Name:

Type of Task: [Lit. Review, Site Visit, Meeting, etc.]

Task contributes to (click here for definitions):

Problem Definition	5	4	3	2	1	N/A
Background	5	4	3	2	1	N/A
Discussion	5	4	3	2	1	N/A
Framework or Hypothesis	5	4	3	2	1	N/A
Case Study or Experiment	5	4	3	2	1	N/A
Contribution to Results	5	4	3	2	1	N/A
Advisor Knowledge	5	4	3	2	1	N/A
Industry Knowledge	5	4	3	2	1	N/A
Student Satisfaction	5	4	3	2	1	N/A
Student Knowledge	5	4	3	2	1	N/A

Direct effort spent on task completion: Hours

Comments:

Submit

Figure D.2: Online Task Survey for Measuring Value (Academia)

D.5 Survey for Communication in the Aerospace Industry

Communication in the Aerospace Industry **MIT Research Study**

All data is confidential (click here for more info).

Name (optional): [ ]

Position/Title: [ ]

Company Name: [ ]

Program Area: [Development, Manufacturing, Support, etc.]

On average, how many hours do you work each week? [ ] Hours

Please estimate the following information (leave blank if not applicable):

√ **Level of Effectiveness** √

(1 = not effective, 2 = effective, 3 = very effective)

	Business Use		Technical Work 1	2	3	Process Work 1	2	3	Team Building 1	2	3
Face-to-Face	[ ]	Hrs/wk	O	O	O	O	O	O	O	O	O
Meeting (w/2-5 people)	[ ]	Hrs/wk	O	O	O	O	O	O	O	O	O
Meeting (w/6+ people)	[ ]	Hrs/wk	O	O	O	O	O	O	O	O	O
Telephone	[ ]	Hrs/wk	O	O	O	O	O	O	O	O	O
Teleconference	[ ]	Hrs/wk	O	O	O	O	O	O	O	O	O
Voicemail	[ ]	Hrs/wk	O	O	O	O	O	O	O	O	O

(1 = not effective, 2 = effective, 3 = very effective)

	Business Use		Technical Work 1	2	3	Process Work 1	2	3	Team Building 1	2	3
Instant Messenger	[ ]	Hrs/wk	O	O	O	O	O	O	O	O	O
Memos	[ ]	Hrs/wk	O	O	O	O	O	O	O	O	O
Email	[ ]	Hrs/wk	O	O	O	O	O	O	O	O	O
Mail	[ ]	Hrs/wk	O	O	O	O	O	O	O	O	O
Reading Unpublished Reports	[ ]	Hrs/wk	O	O	O	O	O	O	O	O	O
Reading Published Literature	[ ]	Hrs/wk	O	O	O	O	O	O	O	O	O
Browsing the Web	[ ]	Hrs/wk	O	O	O	O	O	O	O	O	O
Network Other than Web	[ ]	Hrs/wk	O	O	O	O	O	O	O	O	O

On average, how many hours per week do you spend on non-communication-intensive tasks (or those not listed above)? [ ] Hours

Comments: [ ]

Submit

Figure D.3: Online Survey for Communication in the Aerospace Industry

D.6 Definitions for Communication Survey

Technical Work- This aspect of work is the primary function of a job, as outlined by the job description. Each method of communication described below can contribute (effectively or not) to job-related activities. "Not effective" means that this form of communication does not effectively contribute to completing your job. "Effective" means that this contributes positively to completing your job. And, "very effective" means that this form of communication is critical to the success of your job.

Process Work- This aspect of work relates to the process side of a job. Typically, this consists of suggestions or mandated changes in how the job is accomplished. For example, a company-wide initiative to change software/hardware applications would fall under this category. What types of communication are effective in contributing to this process? "Not effective" means that this form of communication is not helpful or effective in implementing process change. "Effective" means this is helpful. And, "very effective" means this form of communication is critical.

Team Building- This aspect of work relates to the social interaction necessary for a good working environment. It is typically very important to be able to communicate effectively with fellow colleagues. What types of communication contribute to this in your environment? "Not effective" means that this form of communication is ineffective or damaging to building good team relationships. "Effective" means this contributes positively, and "very effective" means this is critical for positive social interaction.

Face-to-Face- This type of communication occurs directly between people and occurs in 2-person meetings or in the daily on-the-job interactions.

Meeting (w/2-5 people)- This communication occurs directly in meetings involving 2 to 5 people. These are typically focused meetings that cover a specific subject.

Meeting (w/6+ people)- This form of communication occurs in larger meetings of 6 or more members. Includes team meetings, program meetings, and employee meetings.

Telephone- This is communication that involves use of the phone for direct 1-to-1 conversations.

Teleconference- This form of communication involves the use of the phone for discussion between more than two parties. Often, this might be in concert with a meeting as described above. In which case, it is considered a teleconference if the primary discussion occurs over the phone line.

Voicemail- This form of communication is the sending and receiving of voicemail or machine messages. This includes dialing into the system, sending, and receiving.

Instant Messenger- This type of communication involves the immediate transmission and reception of electronic text. Currently, it is primarily used in personal applications (such as chat rooms), but it can have business applications. Please evaluate it only for business purposes.

Memos- These are common intra-office memos exchanged in the work environment.

Email- This form of communication is the transmission and reception of electronic messages. Common applications include Eudora, Claris Email, Entourage, and Outlook. Some of these (such as Eudora 5.0 include time statistics).

Mail- This type of communication is characterized by mail from within and outside the organization. This would not include memos (previously mentioned) or reports that are sent via the mail.

Reading Reports- This type of communication includes the time necessary to read reports or papers. This could include a variety of documents, typically considered longer than a memo, but shorter than a book.

Reading Books- This communication consists of the knowledge obtained by reading business-related books during working hours.

Browsing the Web- This type of communication consists of using network browsers (usually Netscape & Explorer) to browse the World Wide Web.

Network other than Web- This type of communication consists of applications that communicate with other servers or computers. For example, ERP or more specific applications, such as Configuration Management System (CMS) or the Visual Information Pull System (VIPS), are applications that use network communication to enable job-related activities.

D.7 Technical Uncertainty Survey

Technical Uncertainty Survey **MIT Research Study**

All data is confidential (click here for more info).

Name or initials:

Task Name (or nearest task): [selection of tasks from WBS]

(If task is unique, specify task name:)

Please estimate current TPMs shown below (and normalize as appropriate):

[Technical Performance Measure 1]	Mean:		[units]
	Minimum:		[units]
	Maximum:		[units]
[Technical Performance Measure 2]	Mean:		[units]
	Minimum:		[units]
	Maximum:		[units]
[Technical Performance Measure 3]	Mean:		[units]
	Minimum:		[units]
	Maximum:		[units]

Comments:

Submit

Figure D.4: Online Survey for Measuring Technical Uncertainty