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On Customer Value and Improvement in Product Development Processes*

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ABSTRACT

In an effort to improve company operations and their results, more firms are applying the principles of "Lean"—not only to manufacturing but also to systems engineering processes. Too often, however, this is done with a shallow understanding of Lean and/or without a systems view, in which case Lean creates new problems and tensions and may not deliver expected results. Lean is not about just minimizing cost, cycle time, or waste. Lean is about maximizing value. In systems engineering or product development (PD), maximizing value may require doing more activities, not fewer. Since a process is a kind of system, a systems view and systems engineering principles are helpful. As the value of a system is more than the value of its individual components, the value of a process is more than the value of its individual activities. Value is driven not only by the presence of necessary (value-adding) activities in the PD process but also by the way those activities work together to ensure that they use and produce the right work products, services, and information at the right time. This paper discusses how value is added in PD through work on activities and the production of deliverables. It integrates findings from several streams of research and provides bases upon which to build improved value models. It shows how the concept of Lean can broaden from asking "What wasteful activities can we stop doing?" to include insights from asking "What helpful activities can we start doing, and when?" © 2003 Wiley Periodicals, Inc. Syst Eng 6: 49–61, 2003

Key words: value; process modeling; information flow; Lean; product development; process development; process improvement; cost reduction; cycle time reduction; productivity

1. LEAN VERSUS WASTE IN PRODUCT DEVELOPMENT PROCESSES

System or product development (PD) spans the gamut of marketing, design, management, and other activities

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done between defining a market opportunity and starting production.[1] The goal of the PD process is to create a "recipe" for producing a product [Reinertsen, 1999]. The recipe must conform to the requirements stemming from customer or market needs. The recipe includes the product design, its constituent materials, its production process, and plans for its distribution, operation, support, and disposal. The PD process consists of a myriad of activities working together to produce the recipe.[2] Value supposedly accumulates as these activities yield results. To improve the competitiveness of their PD processes, firms are attempting to apply Lean principles, which have shown benefits in improving production processes.[3]

According to Womack and Jones [1996], the first step in getting Lean is to understand and specify what portions of a process add value to the customer. They define three types of activities: (Type 1) those that add value, (Type 2) those that do not but are necessary to enable value production ("necessary waste"), and (Type 3) those that do not and are unnecessary ("pure waste"). Once found, Type 3 activities should be removed, and Type 2 activities should be made as efficient as possible. This approach has caused Lean to be thought of (and even defined) in terms of removing waste. It is process improvement based on asking the question, "What are we now doing that we can stop doing?" It has yielded impressive cost- and time-cutting results in repetitive production and business processes.

But PD processes are different from production and other business processes in several ways. PD is a problem-solving process. Terms like "iterative" and "creative" apply. Designers may start with one design, find it deficient in several ways, and then change it [Braha and Maimon, 1997]. Especially with novel products, designers learn much along the way about what will work and what will not [Nightingale, 2000; Petroski, 1985]. The desire is to create useful information, which is acted upon by a number of activities and disciplines. The information is valuable if it decreases the risk that the product will be something other than what it is supposed to be—i.e., if it improves confidence in the recipe [Browning et al., 2003]. Trying, analyzing, evaluating, testing, experimenting, demonstrating, verifying, and validating can create valuable information [Reinertsen, 1998; Thomke, 2001; Thomke and Bell, 1999]—but all of these may be considered "waste" according to the "three types" definition. In fact, by that definition, most if not all of the CMM-I's® generic practices (listed in Table 1) would be branded as Type 2 activities as well.[4]

Table I. Capability Maturity Model—Integrated® (CMM-I®) Generic Practices

- Establish policy
- Allocate adequate resources
- Assign responsibility
- Ensure training
- Document the process
- Plan the process
- Use a repeatable process
- Manage configurations
- Assess process compliance
- Verify work products
- Measure process
- Review status
- Coordinate within the project
- Standardize the process
- Use defined process

Thus, when an interdisciplinary group attempts to categorize PD activities according to the three types, it typically experiences some passionate debate. PD activities can be difficult to classify, and no one wants to see their activity branded as "waste," necessary or not. Fortunately, a lot of this difficulty can be avoided. Think of the PD process as a hierarchy of activities, with large, general activities containing smaller, more specific activities. The non-value-adding activities are part of value-adding activities. In the largest sense, the overall PD process adds value (i.e., is a Type 1 activity). Yet, decompose it into its constituent activities, and activities of all three types emerge. Continue decomposing the remaining Type 1 activities, and activities of all three types continue to appear. Decompose *ad infinitum*, and the only Type 1 "activity" left is the final result materializing out of thin air![5] Hence, debating whether an activity is Type 1 or Type 2 is not very helpful in practice, since the former contains

[1] There is not necessarily a clean break between development and production: Some test and evaluation units may be produced prior to the "official" start of production, as part of PD (verification and validation), and some development work may continue past production start.

[2] Michael Hammer has defined a process as an organized group of related activities that work together to create a result of value.

[3] For an overview of the evolution and application of Lean principles and practices, see Murman et al. [2002], Womack and Jones [1996], and Womack, Jones, and Roos [1990].

[4] It would not sound too good to advertise the CMM-I® as "how to improve your process by adding waste." The tension between CMM® and Lean approaches to process improvement is discussed in the Conclusion. CMM-I® is a registered trademark of Carnegie Mellon University.

[5] Actually, according to the "three types" definition, the product recipe does not add customer value either, unless (as in some government contracting) the customer values the development effort alone. However, we will take as given that the product recipe is the "result of value" generated by the PD process. Note also that the product recipe determines what will be the value-adding activities in the production phase: most of the product's cost is set during the design phase.

much of the latter anyway. Just think of the entire process in economic terms: Remove Type 3 activities and make everything else as productive as possible.[6] The concept of "necessary waste" can be an unnecessary distraction in PD processes.

Even more disturbingly, the notion of "value-added activities" can entirely overlook the true sources of waste and value in PD—and therefore the best ways to improve. By focusing on individual activities (the parts instead of the whole), the concept fails to address the wastes caused by structure of the process—i.e., the integration of the activities. In many cases, *lack of value stems less from doing unnecessary activities and more from doing necessary activities with the wrong information* (and then having to redo them). The value provided by the output of an activity—product, service, deliverable, or information—is a function of the quality of the inputs (interim products, services, deliverables, information, or assumptions) used to create it. A completely necessary, 100% value-adding activity cannot produce high quality results based on poor quality inputs ("garbage in, garbage out") [Ring, 2001]. When citing drivers of cost and schedule overruns and risk, people often mention rework and iteration [Browning, 1998; Cooper, 1993], which can cascade through a process. So, *value is driven by the deliverables (inputs and outputs) as well as by the activities.* Thus, **the architecture of the PD process—the sequencing and coordination of activities and their deliverables—has a large impact on value, *regardless* of the value of the activities and deliverables themselves.**

The need for a system perspective on how PD activities work together underscores the need to understand the PD process architecture. To complicate matters, the PD process is more like a network or web than a chain, because of the large number of concurrent, interrelated activities [Negele et al., 1999]. A process model can help provide visibility into and understanding of the structure of interactions between activities. This structure can be good or bad, better or worse, and it has a great influence on the competitiveness or "Leanness" of the process [Browning and Eppinger, 2003]. *Getting the right deliverables to the right place at the right time is extremely important in adding value*. Without an integrated and synchronized process to organize them, doing value-adding activities does not guarantee a value-adding result [Browning, 2002].

This paper discusses how value is added in PD through work on activities and the production of deliverables. It integrates findings from several streams of research and provides bases upon which to build improved value models. It shows how the concept of Lean can broaden from asking "What wasteful activities can we stop doing?" to include insights from asking "What helpful activities can we start doing, and when?"

[6] As Sam Goldwyn put it, "Spare no expense to make everything as economical as possible."

2. LIPOSUCTION OR DIET AND EXERCISE? BECOMING EMACIATED OR COMPETITIVE

> Classic American business style may be characterized as a collection of projects, going on perpetually, aimed at removing the deficiencies from the operation… But when you remove the things you don't want, you don't necessarily get what you do want.
>
> —Russell Ackoff

> Because a waste is a terrible thing to mind…

To use a physical metaphor, the quest for Lean can be thought of as striving to get an enterprise "in shape" for competition. Of course, getting in shape includes "leanness." But a focus on simply *losing weight* will not win a race. A competitive athlete has to improve fitness and skills, though exercise and practice.

Developing the metaphor, Table 2 summarizes two general approaches to getting Lean. The first, liposuction, entails looking for "non-value-added" activities and removing them from processes. However, much of the lack of value in PD processes may not be attributable to discrete activities. Removing waste in PD requires a holistic, system perspective. Diet and exercise, the second approach, focuses on becoming competitive and healthy rather than on short-term, surface appearances. The difference between these two approaches can be the difference in an organization distinguishing fat from atrophied muscle and becoming emaciated or competitive.

While they may seem to be "cheaper" on paper, emaciated processes do not have the critical capability to sense, respond, and adapt to change [Haeckel, 1999; Pall, 1999]. In fact, Lawson [2002] mentions numerous examples of problems caused by organizations that focused too heavily on efficiency—from nuclear and naval accidents, to California's recent energy woes, to the U.S. healthcare system. In another case, General Motors' reliance on lean, just-in-time manufacturing systems is seen to have contributed to the vulnerability of its entire North American operations to a labor strike at a single parts plant in 1998—ultimately resulting in lost production of 576,000 vehicles and an estimated $2.2 billion in lost sales.[7] Recent failures in the U.S. space program's Mars missions have also been attrib-

[7] R. Blumenstein [1998] and R. Blumenstein and G. White [1998].

Table II. Two Perspectives on Getting Lean

Liposuction	Diet and Exercise
• Is effective only when there are large, easy-to-find chunks of fat	• Is effective for removing waste throughout
• Can compromise the overall health of a recipient	• Improves recipient's overall health and fitness
• Does not address the system that produced the fat in the first place	• Improves the system that produced the fat in the first place
• Does nothing for recipient's strength, agility, or flexibility	• Improves recipient's strength, agility, and flexibility
• Is relatively cheap and quick	• Requires ongoing investment and commitment
• Focuses on "doing less"	• Sometimes requires "doing more"
• Measures fat removed	• Measures fat and muscle (realizing that muscle may "weigh" more)
• Focuses on reducing waste	• Focuses on improving value
Examples: • Just removing "non-value-added activities" • Uninformed cutting of activities or reduction of headcount • Demolishing an old process and jumping to a new, Lean process without first verifying that it is feasible and effective in context	Examples: • Adding activities that help ensure the valued result • Ensuring activities and processes consume and produce the right deliverables at the right time • Investing to achieve increased understanding of how the work really gets done and how value flows

uted to the pressures of focusing on "faster and cheaper" PD.

3. CUSTOMER VALUE DRIVEN BY PRODUCT AND PROCESS ATTRIBUTES

The value of a product (or service) to a customer depends on customer preferences and alternatives.[8] Economics literature addresses the allocation of customer resources, demand for goods, etc. [e.g., Deaton and Muellbauer, 1980]. An amount of research explores the value of products and services—e.g., the value engineering literature [e.g., Green, 1994; Park, 1998]. Customer value has two aspects:

- *Absolute*: the intrinsic value of the product or service; how well its attributes address customer needs. Marketing literature looks at determining the vector of product attributes and specifying the optimum level of each attribute [e.g., Urban and Hauser, 1993]. Quality Function Deployment (QFD) also serves this purpose [e.g., Akao, 1990; Hauser and Clausing, 1988].
- *Relative*: the change in a product's value depending on competing or alternative solutions to customer needs (substitute products). For example, a horse may become more valuable for transportation if there are not any cars.

Several authors have proposed equations to quantify the absolute component of value. Johansson et al. [1993] propose

$$\text{Value} = \frac{Q \cdot S}{SP \cdot LT},$$

where Q is quality, S is service, SP is sale price, and LT is lead time. Slack [1999] defines product value as

$$\text{Value} = \frac{N \cdot A \cdot f(t)}{C},$$

where N is the need for the product or service, A is the ability of the product or service to satisfy the customer need, $f(t)$ is the dependency for the timing of the product or service, and C is the cost of ownership, which is a function of product attributes and PD process efficiency. Park [1998] reviews the work and value equations of five authors and arrives at

$$\text{Value} = \frac{\text{Function}}{\text{Cost}},$$

noting that the ratio of function to price in the market is a matter of customer opinion. Interestingly, since work is supposed to add value, definitions of produc-

[8] Lean principles tend to focus on value to customers [Womack and Jones, 1996]. However, it is also important to consider value to other stakeholders—such as the enterprise, its employees, its shareholders, its suppliers, etc. Additional stakeholders are discussed further in the Conclusion.

tivity take a similar form. For example, Putnam [1992] defines productivity as

$$\text{Process Productivity} = \frac{\text{Product}}{(\text{Effort})(\text{Time})}.$$

Finally, Weinstein and Johnson [1999] defines value as

$$\text{Value} = \frac{\text{Perceived Benefits}}{\text{Perceived Price}},$$

where perceived benefits and price are both measured relative to competing products or services.

All of the above equations define value essentially as a ratio of benefits to costs:

$$\text{Product Value} \propto \frac{\text{Benefits}}{\text{Costs}},$$

or

$$\text{Product Value} \propto \frac{\text{Product Performance}}{(\text{Price})(\text{Lead Time})}. \quad (1)$$

That is, product value is proportional to the benefits the product provides and inversely proportional to the time and money expended to get those benefits. This definition equates value with productivity towards the purpose of providing benefits to a customer (hence the notion of progress as "earned value"). The definition applies to all kinds of products and processes. If we accept these additional, simplified definitions,

$$\text{Affordability} \propto \frac{1}{\text{PD Cost} + \text{Production Cost} + \text{Operating Cost} + \text{Margin}}$$

and

$$\text{Timeliness} \propto \frac{1}{\text{PD Time} + \text{Production Time} + \text{DistributionTime}},$$

then

$$\text{Value} = f(\text{Performance, Affordability, Timeliness}).^{9}$$

Clearly, both the effectiveness of the result and the efficiency of the process affect value. PD time and cost can thus directly impact customer value. Substituting performance (P), cost (C), and schedule (S) into Eq. (1), we see that a change in any of these factors can cause a change in value (V) [10]:

$$\Delta V \propto \frac{\Delta P}{\Delta C \cdot \Delta S}. \quad (2)$$

Project managers have known for a long time about the need to trade cost, schedule, and quality, but Eqs. (1) and (2) provide no insight on how to balance these in congruence with the preferences of the market or customer. Methods such as conjoint analysis [e.g., Rosenau, 1990] or multiattribute utility theory [MAUT—e.g., de Neufville, 1990] can be helpful in this regard.[11] A change in value or utility typically implies a change in demand for a product or service.

The above discussion demonstrates that, in PD, value is a function of both the product recipe and the process that produces it. Processes provide benefits at some cost. Figure 1 depicts this dual influence. Thus, a value measure should account for cost, schedule, and performance—whose pressures influence decisions throughout PD—and their potential tradeoffs. The statement "faster, better, cheaper" conveys no information about the appropriate tradeoffs and balance. While managers may try to weigh the effects of decisions on all three areas, such evaluations are difficult because information about each area is typically gathered, tracked, and presented in a number of disparate formats, often by separate groups.

4. MEASURING BENEFITS IN PD AS PERFORMANCE RISK REDUCTION

A particular market segment, customer, or user will prefer a certain balance of product performance characteristics. For example, one aircraft customer may favor payload and another range. In most companies, the marketing function plays a large role in improving the organization's understanding of market needs and preferences and in translating these into product requirements.[12] Designers make tradeoffs among product attributes to satisfy a range of requirements, providing a product recipe with a *balance* of attributes and their

[9] See the Appendix for a more sophisticated definition of affordability. Even more sophisticated definitions of both affordability and timeliness are possible.

[10] Cost, schedule, performance, and value *risks* can also be addressed by treating C, S, P, and V as random variables [Browning, 1998]—i.e., as a distribution of possible outcomes, some of which have adverse impacts. The probability of these adverse impacts and their consequences together determine the amount of risk in each area. The probability of missing a target level of value and the impact of that shortfall yields a measure of *value risk* for the product or deliverable.

[11] These and related methods have their limitations [Bahill, Dahlberg, and Lowe, 1998; Otto and Antonsson, 1991].

[12] *Market risk* denotes the possibility and consequences of a discrepancy between product requirements and market needs and preferences.

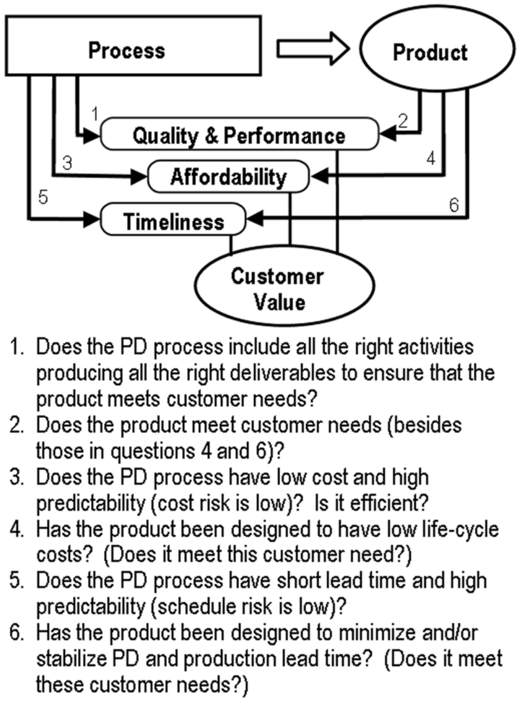

Figure 1. Both product and process attributes affect customer value. Adapted from a figure in [Browning, 2000] ©2000 IEEE.

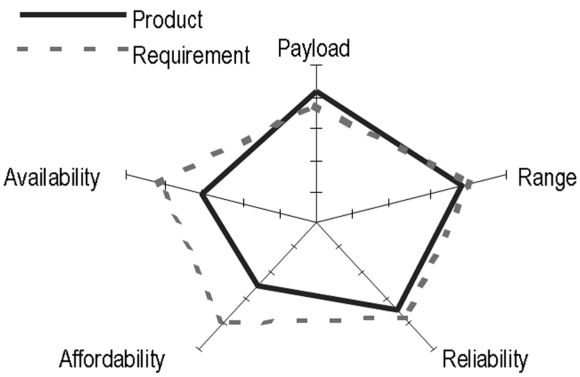

Figure 2. Incongruence of product attributes and requirements.

levels that satisfies specific customers (or that is robust to the preferences of an amorphous market). The balance of product attributes and their levels must be *congruent* with the balance desired by a given customer for that customer to prefer the product. Figure 2 illustrates the condition of incongruent attribute levels: While payload exceeds what is needed and range is close, reliability, affordability, and availability do not meet requirements. Customers prefer products that match their every need. The consequences of an incongruent product design are decreased demand,[13] customer dissatisfaction, loss of reputation, etc.

What are the benefits of activities that merely analyze, measure, review, test, prototype, etc.? These activities may not change the performance level of a design at all (although they may force a decision causing another activity to do so). The purpose of many PD activities is to produce information that increases *certainty* about the ability of the design to meet requirements—i.e., these activities decrease performance uncertainty. Since risk is the product of uncertainty and consequences, reducing uncertainty equates to reducing risk in many cases. Some verification and validation activities may also be direct requirements from the customer or for certification.

In complex system development, the goal is essentially to reduce the risk that the product recipe is unacceptable [Browning et al., 2003]. Added value in PD is productivity towards this purpose. Browning et al. [2003] discuss how both (1) increasing the performance level and (2) reducing performance risk can be accounted for by a single measure of added benefit. They also provide a framework and approach—the *risk value method*—for measuring the overall technical performance of a product design in terms of its dimensions of performance valued by a customer or market. Each dimension of product technical performance is quantified by a technical performance measure (TPM) or measure of effectiveness (MoE) [e.g., Blanchard, 1997; Coleman, Kulick, and Pisano, 1996; DSMC, 1990; NASA, 1995; Pisano, 1996]. Risk is often quantified as the product of probability of an occurrence and its consequence or impact:

$$\text{Risk} = (\text{Probability})(\text{Impact}). \qquad (3)$$

Using the uncertainty in each TPM [represented as a probability density function, $f_{TPM}(x_0)$], along with a required level of performance (T_{TPM}) and an impact function expressing the loss in customer utility or value for failing to meet the requirement,

$$\boldsymbol{I}_{TPM} = \kappa_{TPM}[U_{TPM}(T_{TPM}) - U_{TPM}(x_0)], \qquad (4)^{14}$$

a risk factor can be calculated for each dimension of product technical performance or customer benefit:

[13] The relationship between consumer preferences, utility, value, and demand is discussed in economics literature [e.g., Deaton and Muellbauer, 1980].

[14] In Eq. (4), x_0 is an outcome (a TPM level), T_{TPM} is the target (requirement), $U_{TPM}(\bullet)$ is the utility curve function, and κ_{TPM} is a normalization constant (e.g., for converting units of utility to more intuitive measures of value, such as number of units likely to be purchased).

$$\mathcal{R}_{TPM} = \kappa_{TPM} \int_{-\infty}^{T_{TPM}} f_{TPM}(x_0)[U_{TPM}(T_{TPM}) - U_{TPM}(x_0)]\, dx_0. \quad (5)^{15}$$

These risk factors can be combined to arrive at an overall risk index for the product design [using Eq. (6), or through more sophisticated techniques such as MAUT]:

$$\mathcal{R} = \sum_i w_i \mathcal{R}_{TPM,i}. \quad (6)$$

The objective of the PD activities is to drive this index to an acceptable level. PD activities add value if they contribute towards this objective. The activities and approaches under the umbrella of what is called systems engineering are particularly suited to contribute to value in these ways.

5. BASIC ASPECTS OF A VALUE MODEL

Figure 3 shows three views of product value. If customer value is equated only with technical performance (as design engineers sometimes do), then value is assumed to increase continuously as additional time and money are spent on the PD process, albeit with marginal returns (curve 1). On the other hand, timeliness and affordability decrease as time and money are poured into the PD process. The customer expects to wait and pay a certain amount, but, past that point, value decreases (curve 2). The relationship between overall product value to the customer and time and money spent on the PD process is a combination of these effects—something like the dashed curve. It increases to the point (the star in Figure 3) where additional time and money are not worth the marginal improvements in technical performance. This point needs to be better understood, because it should affect all PD decisions. The actual location of the point is determined by the shapes of the other two curves, which depend on customer preferences and the productivity of the PD process.

Given the ability to affect product value by addressing benefits as well as costs, process improvement requires more thought than if the focus is just on cost reduction or liposuction. How will efforts to lean and improve processes affect overall value? Does a particular investment in process improvement provide a sufficient return in net value? The value model can help answer these questions. Consider the four actions listed in Table 3. The first two options, doing fewer things and

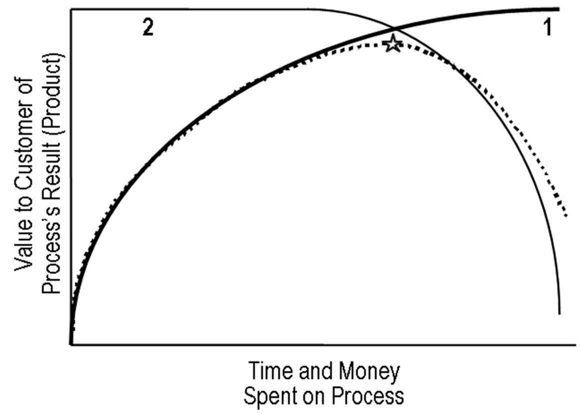

Figure 3. Three views of work product value.

doing things faster, both tend to reduce development cost and time. (That is, they reduce cost and time if they do not lead to mistakes or inefficiencies later in the process.) However, not doing some things or doing some things too fast can compromise the reduction of performance risk (might cut "muscle" along with "fat"). Hence, the net impact of these options on product value, in general, is unclear. Each opportunity must be analyzed on a case-by-case basis. Similarly, overlapping activities, a popular approach to faster PD, can also compromise product performance (because people do their work based on assumptions and incomplete information about the outcomes of other work). Overlapping activities that depend on each other for information can lead to additional rework. Again, the net impact on product value is, in general, indeterminate. Finally, doing additional iterations of design activities tends to reduce technical performance risk, at the expense of time and money. The decision to conduct additional iterations—or to do any rework or design change, for that matter—should depend on an analysis of the net effect on overall product value.

In industry, there is a need to stop focusing on process changes that solely provide "waste" reductions without considering the effects on process outcomes (which may not be clear until the reengineered process actually executes). Just as it is wrong to focus solely on technical performance without recognizing effects on affordability and timeliness, it is likewise naïve to address PD cost or schedule as independent variables. In fact, cost, schedule, and performance are quite interdependent—especially in a concurrent engineering context. A value-based perspective provides a platform for analyzing, trading-off, and balancing "faster," "better," and "cheaper."

[15] Equation (5) shows the case of a "larger is better" TPM; reverse the limits of integration for a "smaller is better" TPM.

Table III. General Effects of Certain Actions on PD Metrics

Effect of...	...on Technical Performance	...on Development Lead Time	...on Development Cost	...on Product Value
• Removing activities from the PD process	Can be bad	Can be good	Can be good	Indeterminate
• Decreasing individual PD activity span times	Can be bad	Can be good	Can be good	Indeterminate
• Overlapping PD activities	Can be bad	Can be good	Unclear	Indeterminate
• Iteration of activities in PD process	Can be good	Usually bad	Usually bad	Indeterminate

6. BASIS FOR A VALUE MODEL: ACTIVITY COSTS AND DELIVERABLE BENEFITS

We have seen how, generally, value is a function of both product and process attributes. Specifically, portions of that value are functions of activities and interim deliverables or results. Consider a single activity in a PD process: It is not the activity but its result that provides a benefit. Executing the activity without producing the result would not provide benefit, but getting the result without doing the activity would. Activities and processes exist to produce stakeholder benefits. They are means to an end.

As shown in Figure 4, costs (resources) are expended (to execute an activity) to produce a benefit (the deliverable). If the benefit can be quantified as a contribution to the whole product, then any activity in the PD process, large or small, can be evaluated "atomically" in terms of its costs and benefits. At a high level, processes and their products can be evaluated in the same way, often by aggregating the contributions of their constituent activities.

Differentiating costs and benefits and their respective contributions to value is important. It enables one to move beyond the liposuction perspective of Lean, with its emphasis on cutting time and cost, to a perspective where increasing performance—and, most importantly, balancing all of these in congruence with customer preferences—is valuable as well.

A change in value can be effected via the numerator, the denominator, or both in Eq. (2). The denominator depends on process and activity costs. The PD process is a network of activities and deliverables. Final deliverables provide value to the customer. Interim activities and deliverables enable the production of the final deliverables, so they also affect value, both in terms of benefits and costs. The cost and duration of PD is affected by the architecture of the PD process [Browning and Eppinger, 2002].

When is it worth increasing cost or lead time to improve performance? When is it worth decreasing affordability to improve timeliness? How will project decisions and actions over a given time span affect the product's value to customers? Some research has recognized the need to make PD decisions in light of the overall effect on value. Cook et al. [Cook, 1992; Cook and Devor, 1991; Cook and Gill, 1993; Cook and Kolli, 1994] develop a model of product attributes (including price) and the value they deliver. They equate the PD management task with specifying and achieving the most appropriate levels for each attribute. Yet, there remains a need to account explicitly for the effects of the PD process and its interim products on value. Unfortunately, the value literature is poorly linked to the process modeling literature, which recognizes the importance of the structure of the activity network, information flow (interim products), and iteration in the PD process.

The value perspective provides a good way to think about process improvements. Value can be improved by decreasing costs or increasing benefits. Which approach to take depends on customer preferences for the appropriate balance of technical performance, affordability, and timeliness. Therefore, the amount of value added by a PD process can be increased by *adding* activities as well as by removing them. As enterprises strive to become Lean, they must strive to increase the value they provide. Trying to increase value by attack-

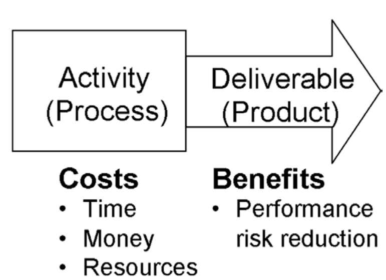

Figure 4. Foundation for an "atom" of value. Adapted from a figure in [Browning, 2000] ©2000 IEEE.

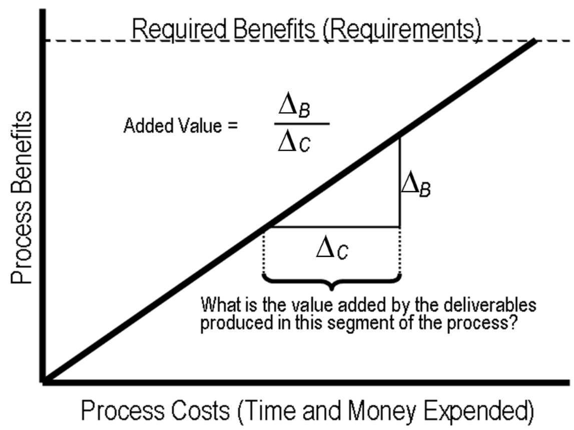

Figure 5. Benefit to cost ratio for each activity leads to value trajectory for process.

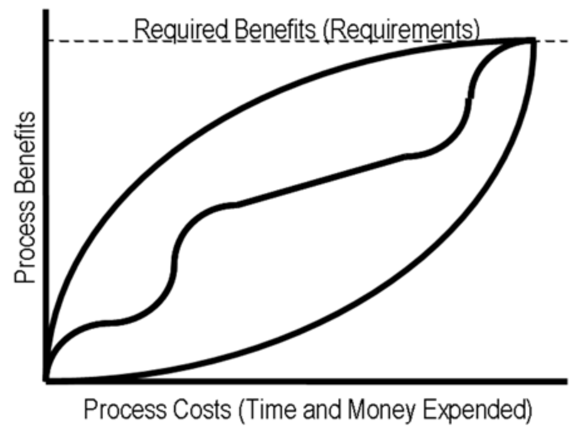

Figure 6. Alternative value trajectories.

ing only one side of the problem—by doing less—can miss the point, and may ultimately cut muscle instead of fat and decrease value. When dealing with complex systems, sometimes actions towards a desired result can lead to the opposite result!

7. VALUE TRAJECTORIES AND PROCESS IMPROVEMENT

A process model provides the framework for describing the costs and benefits of the activities and deliverables comprising a process. The structure of the activity network, including the flow of deliverables, characterizes the process architecture. Each process architecture has a characteristic *value trajectory*, such as the one shown in Figure 5 (continuously added value). Each segment of the trajectory is derived from a combination of the "atoms" of value between any two horizontal points. Figure 6 depicts some alternative value trajectories, of which the middle one is probably the most realistic.[16]

When a process architecture and its value trajectory are understood, process improvement consists of attacking the flattest part of the curve, which represents the expenditure of the most time and money for the least benefit. The portion of the PD process represented by the flattest part of the curve may be improved by several means. One should question the methods of producing the deliverables in that portion of the process. Could they be produced more efficiently with a new activity sequence, less iteration, a new approach, or new tools? Thus, the process model and value analysis can serve as the basis for a variety of process improvement analyses and business cases, supporting approaches such as Lean, Six Sigma, Total Quality Management, Reengineering, etc. Process models and value analysis can also help in preparing "change impact statements" during a PD project. An analysis of the net value implications of particular options provides a means of simultaneously addressing cost, schedule, performance, and even risk.

Value trajectories can also be used to analyze whether or not a sufficient stream of value-adding activities exist to achieve the required benefits. Certainly, they should tie to earned value management systems (EVMS), although these tend to focus on cost and schedule more than benefits, quality, and performance [Paquin, Couillard, and Ferrand, 2000]. Flat portions of the value trajectory may also highlight activities that are not adding their planned value, perhaps because their results are not having enough impact on risk reduction.

8. CONCLUSION

> Watch the top line—what you're about.
>
> —Stephen Covey

This paper argues for the need to refocus Lean on the notion of maximizing value, instead of on minimizing cost and time. Value includes both product and process attributes.[17] It includes affordability and timeliness along with technical performance. All efforts to become more competitive and "get Lean" can be viewed through the lens of increasing value. Value can be improved not only by decreasing costs but also by increasing benefits. "Liposuction" focuses on cost reductions. Emaciated processes are not robust and will break in the face of change [Lawson, 2002]. Real improvements require investments and exercise. Some-

[16] The upper and lower curves in Figure 6 compare with Krishnan, Eppinger, and Whitney's [1997] activity evolution rate curves.

[17] Customers of large, complex, unprecedented system developments (such as government customers) realize that they are buying a development process as well as a product—hence their keen interest in the progress and level of risk in development programs.

times more value can be added by doing additional, not fewer, activities. The concepts presented in this paper can be applied in a number of ways, such as in analyzing a PD process to ensure a sufficient stream of value creation, for process improvement, and for demonstrating the value of systems engineering activities and addressing the question, "How much systems engineering is enough?"

A tension can exist between Lean, when it focuses on doing less, and CMM-based approaches to process improvement, which often expose the need for an organization to do more. CMMs contain lists of practices that capable and mature processes should include and exhibit. When assessed, many processes do not include some of them and invest to add them. In process improvement, there is a time to do more and a time to do less. Which to do when—whether to work on the numerator or the denominator of Eqs. (1) and (2)—depends on the net effect on value. As complex systems, processes sometimes exhibit counterintuitive characteristics, such as taking less time and money when more activities are added (and only done once—instead of fewer activities having to be reworked).

Not only activities but also deliverables are important when assessing value. Howard [1998] advocates deliverable-oriented project management [DHBA, 1999]. Often, it is easier to express the value of activities such as systems engineering by showing the value of their deliverables to the success of the product.

The realization that Lean, faster-better-cheaper, and other improvement initiatives all seek to improve customer value simplifies the communication of basic principles throughout the workforce. Instead of asking an engineer "What are you doing to become Lean?" one can ask more intuitive questions such as:

- "What are you doing to improve the performance or quality of your deliverable?"
- "What are you doing to understand better what those who use your data really need it for?"
- "What changes are you making to produce your deliverable faster?"
- "What changes are you making to produce your deliverable more economically?"

More straightforward questions facilitate more pervasive alignment towards goals.

This paper implies that lean PD requires systems engineering applied not only to products but also to processes. Models of process architectures enable the analyses discussed in this paper. Process modeling that increases process understanding and enables process improvement is an important endeavor that can provide competitive advantage [Browning, 2002].

Finally, while this paper focuses on adding customer value in PD, it is important to consider all stakeholders when maximizing value. Optimum value from the customer perspective would be a perfect product, on demand, for free—but this will not sustain an enterprise. The value to other stakeholders—such as shareholders, employees, suppliers, governments, communities, and society—must be balanced with customer value in a firm's value proposition.[18] For example, employees receive value from compensation, interesting work, and career advancement. The enterprise receives value by developing and sustaining competitive capabilities and by learning and adapting to become more capable. More research is needed to explore ways of achieving and sustaining the best balance of value for all stakeholders.

APPENDIX: LONGER DEFINITION OF AFFORDABILITY AND RISKS

A.1. Affordability

Product affordability is an important aspect of customer value. Affordability includes the price the customer pays for the product, and—if the customer realizes it—their operating and disposal costs as well (life cycle costs).[19] Simplistically, affordability is inversely proportional to costs:

$$\text{Affordability} \propto \frac{1}{(\text{Acquisition Cost} + \text{Operating Cost} + \text{Disposal Cost})}.$$

A constant of proportionality could also be added to express affordability in appropriate units.

Acquisition cost is the price the customer pays for the product. A full discussion of pricing theory and strategy is beyond the scope of this paper. A simple formula for price includes the fixed costs of development, production, and other functions; the variable costs of production, sales, distribution, etc.; and the profit to the organization. Per unit of product, the basic formula would look like:

$$\text{Acquisition Cost} = \text{Fixed Cost (per unit)} + \text{Variable Cost} + \text{Margin},$$

[18] Kochan and Rubinstein [2000] discuss additional stakeholders.

[19] Unsophisticated customers may not account for operating and disposal costs in their product preferences. Hence, suppliers to such customers may not have to account for life cycle costs. But customers tend to become more sophisticated with time, forcing suppliers to accommodate their changing preferences in terms of: (1) levels of attributes and (2) addition of new attributes.

where the fixed cost is amortized over the number of units. When that number of units is sold, the fixed costs will be recovered. Cooper and Slagmulder [1999] discuss how to use target costing to set product and component costs as well as profit margins. Acquisition cost could be stated simply as

Unit Acquisition Cost = Unit Development Cost + Unit Production Cost + Unit Margin.

Unit development cost is the cost of the PD process, amortized across a number of units. For simplification, the production cost term can also include distribution and other costs.

A.2. Development Cost Risk

Development cost *risk* is the probability of the development cost exceeding the planned budget and the consequences of overruns. If development cost is expressed as a distribution of possible expenditure level outcomes, $f_C(x_0)$, development cost risk, $\mathcal{R}_C$, is the sum of the adverse outcomes, each weighted by its probability and impact:

$$\mathcal{R}_C = \kappa_C \int_{T_C}^{\infty} f_C(x_0)[U_C(T_C) - U_C(x_0)]\, dx_0, \qquad (7)$$

where κ_C is a normalization constant, T_C is the target budget, and $U_C(T_C) - U_C(x_0)$ is the impact in terms of lost customer utility. This equation is discussed further in Browning [1998].

A.3. Schedule Risk

Development schedule *risk* is the probability of the development cycle time exceeding the planned deadline and the consequences of overruns. If the duration of the PD process is expressed as a distribution of possible durations, $f_S(x_0)$, then development schedule risk, $\mathcal{R}_S$, is the sum of the adverse outcomes, each weighted by its probability and impact:

$$\mathcal{R}_S = \kappa_S \int_{T_S}^{\infty} f_S(x_0)[U_S(T_S) - U_S(x_0)]\, dx_0, \qquad (8)$$

where κ_S is a normalization constant, T_S is the target duration, and $U_S(T_S) - U_S(x_0)$ is the impact in terms of lost customer utility. This equation is discussed further in Browning [1998].

Equations (5), (7), and (8) can be used to express cost, schedule, and performance risks in comparable terms related to customer utility.

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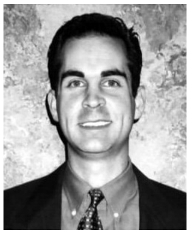

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