Complex System Product Development: Adding Value by Creating Information and Reducing Risk

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Abstract. Many firms expend a great amount of effort to identify and eliminate waste in their processes. Much recent effort has focused on lean manufacturing. Now lean product development has become a goal as well. Yet, in product development, determining how and when value is added is problematic. The goal of a product development process is to produce a product “recipe” that satisfies requirements. Design work is done both to specify the recipe in increasing detail and to verify that it does in fact conform to requirements. As design work proceeds, certainty increases surrounding the ability of the evolving product (and production process) design specifications to be the final product recipe (i.e., performance risk decreases). The goal of this paper is to advance the theory and practice of evaluating progress and added value in complex system product development. The paper proposes that making progress and adding value (to the customer) in complex system product development equate with producing useful information that reduces performance risk. The paper also contributes a methodology—the risk value method—that integrates current approaches such as technical performance measure (TPM) tracking charts and risk waterfall charts.

INTRODUCTION

Over the last decade, lean manufacturing has entrenched itself as part of the Western industrial landscape.1 Many manufacturing firms are expending tremendous efforts in the quest for lean production. Some firms also realize that most of a product’s life cycle cost is determined before production, during the product development (PD) process. To deliver better products faster and cheaper, some firms are attempting to create lean PD processes.

PD spans the gamut of marketing, design, management, and other activities done between defining a market opportunity and starting production. 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, its manufacturing process, and its supply, distribution, and support systems. PD entails a myriad of activities working together to deliver the recipe.

The first step in getting lean is to understand and specify what adds value in a process. According to Womack and Jones, there are three types of activities: (Type 1) those that add value, (Type 2) those that do not but are necessary, and (Type 3) those that do not and are unnecessary. Once found, type 3 activities should be removed. Type 2 activities should be made as efficient as possible. This approach has yielded impressive results in production and business processes (Womack and Jones 1996).

But PD processes are unlike typical business and production processes in several ways. Terms like “iterative” and “creative” apply to PD. Designers may start with one design, find it deficient in several ways, and then change it. Especially with novel products, designers learn much along the way about what will and will not work (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

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1 The book The Machine that Changed the World (Womack et al. 1990) brought several lean concepts to industry’s attention.

2 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, and some development work may continue past production start.
something other than what it is supposed to be—i.e., if it improves confidence in the recipe. Trying, analyzing, evaluating, testing, experimenting, demonstrating, and validating create valuable information (Reinertsen 1998).

When an interdisciplinary group attempts to classify PD activities as one of Womack and Jones’ 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 small, specific activities. Actually, most of the non-value-adding activities are small, buried deep inside value-adding activities. In the largest sense, the overall PD process adds value (i.e., is a type 1 activity). Yet, decompose it and type 2 and type 3 activities appear within. Continue to decompose the type 1 activities, and activities of the other two types continue to appear. Decompose ad infinitum, and the only thing left adding value (by the “three types” definition) is the product recipe (or the product itself) materializing out of thin air! Thus, debating whether an activity is type 1 or type 2 is not very helpful in practice, since the former contains much of the latter anyway. Just think of the entire process in economic terms: remove type 3 activities and make everything else as productive and efficient as possible. The concept of “necessary waste” can be an unnecessary distraction.

In deciding what adds value, it helps to consider the goal—a product design or recipe that conforms to requirements. What information is needed to complete the recipe? How can one be certain that an acceptable recipe will materialize? What is the risk it will not? Figure 1 depicts risk as a function of the availability of useful information. The goal of PD is approached by producing useful information that reduces uncertainty. The activities that ensure that the right recipe materializes are the ones that add value, and their completion constitutes progress in PD.

This paper contributes a method for evaluating the value added in PD as a function of risk reduction—i.e., as a function of the generation of useful information. The risk value method is based on understanding overall product performance risk and its components. The approach integrates several concepts and methods, including: technical performance measures (TPMs), risk waterfall charts, customer preferences, and uncertainty. The goal of the paper is to advance the theory and practice of evaluating progress and added value in PD.

ADDITION VALUE IN PRODUCT DEVELOPMENT
The goal of PD is to produce a product recipe that conforms to requirements with some certainty. PD is a problem solving process. Progress is made by creating useful information that reduces uncertainty and/or ambiguity (Schrader et al. 1993; Sutherland 1977). But it is challenging to produce information at the right time, when it will be most useful.

![Diagram](image)

**Figure 1: Risk Decreases with Availability of Useful Information**

The final product recipe contains a large amount of information, which is based on an enormous amount of supporting data, which in turn rests on still other data, etc. This information structure must be built from the ground up. Certain information must be created before it becomes possible to create other information. The dependencies between PD activities define a necessary sequence in the process of producing useful information. Most of the work done and the decisions made depend on the results of other work and decisions. The value of the information an activity produces is a function of, among other things, the value of the information it receives. In general, then, activities are done to create deliverables, and the value of an activity depends on the value of the deliverables it uses and creates. Thus, 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). Adding value is less a function of doing the right activities than of getting the right information in the right place at the right time. Hence, the focus of lean must turn away from activity “liposuction” and towards addressing the PD process as a system.

It is well known that progress in PD is difficult to gauge. Several authors have noted various reasons contributing to the problem. For example, Goldratt (1997) and others note how, if ten work items must be done, people tend to do the easiest ones first. When eight items are completed, many assume 80% of the work is finished. This is one problem. Rework provides another complication. PD planners often “plan to succeed.” Typically, little attention is paid to process failure modes and their effects (i.e., rework). Furthermore, actually doing PD work unearthed the need

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3 Figure adapted from (Harmon 1999)
for additional information (and additional activities to generate it). Sometimes, these effects and others combine to make “the last 10% of the project take 90% of the time” (implying a schedule overrun, or a cost overrun to prevent one). Thus, one cannot equate value added with progress through an arbitrarily defined statement of work for several reasons: it may contain superfluous activities for which no value is added, its work elements may not be equally valuable, and it may not account for missing activities, rework, or iterations.

Since PD is a discovery process, it is harder to determine what value is added and when. In PD, approaches are proposed, analyzed, evaluated, and advanced or rejected. The effect of one activity changing its approach and outputs can ripple throughout the process, changing other activities' inputs and assumptions and causing rework. A discovery process has lots of change and rework. It is iterative. The values of its activities are not predetermined—they are partly a function of the activities that precede it and those that follow.

When an activity produces some information, the quality of that information is extremely difficult to determine immediately. There is a time lag between the point of value creation and the point of value determination. When does the value actually accrue? Rework can render useless what was previously useful information, because it can negate supposed progress and assumed value. Actually, the desired value was not added in the first place (although perhaps designers learned something). Forecasting which activities will add value and when is problematic in the PD process.

Merely examining the latest performance estimates of the design is also an illusory indicator of progress. When a design baseline is proposed, it is put forward with the expectation that it will be able to satisfy requirements. The collection of performance estimates will look good until a problem is revealed, at which point they may suddenly degrade. Good design performance levels cannot indicate progress unless they include a notion of how much uncertainty remains.

What are the contributions of analysis, measurement, review, test, and prototyping activities to progress and added value in PD? Activities such as these may not change the performance level (read "form, fit, and function") of a design at all (although they may force a decision that may cause another activity to do so). The purpose of these activities is to increase certainty about the ability of the design to meet requirements. That is, these activities decrease performance uncertainty. Since risk is the product of uncertainty and consequences, reducing uncertainty usually reduces risk.

All of these issues point to the need for a way to measure progress that provides a more realistic picture of the state of the project and accounts for how much is known about the product design. This paper proposes tracking the uncertainty surrounding the ability of the design to meet requirements as the way to measure progress and added value in PD. The paper shows how both (1) increasing the performance level and (2) reducing performance risk can be accounted for by a single measure of added value. The approach can help PD managers add value by focusing effort on eliminating the critical sources of risk in their projects.

CONCEPTS AND DEFINITIONS

Technical Performance. Technical performance (sometimes just called performance) refers to a product’s technical attributes and entails a product's conformance to its technical requirements. Does the product do everything it is supposed to do, as well as it should? Is there an absence of defects, bugs, and nonconformances? Is there reasonable confidence about these conditions? Generally, technical performance equates to the benefits provided by a product because of its design, capabilities, and functionality. A product performs well if it does everything it should as well as it should.

Technical Performance Measures (TPMs). Designers use metrics to plan and track the level of each technical performance attribute. These metrics are called technical performance measures (TPMs), measures of effectiveness (MOEs), figures of merit, and other names. TPMs often have the same name as the performance attribute they measure, such as payload, range, etc. TPMs may also measure aggregate defects or nonconformances.

TPMs change as the design progresses. Each TPM may be estimated early in the design process, once a baseline design is established. Initial estimates are very subjective and uncertain. As design work is done, estimates are refined based on data from analyses, simulations, prototypes, demonstrations, etc. Estimates become more and more objective as design work provides TPM verification and uncertainty reduction. When the product design is ready, the TPMs specify the level of performance provided by each of the designed product’s attributes.

The idea that TPMs become more accurate as the design matures leads to an important concept: the reduction of uncertainty. Information produced by design work is used to reduce the uncertainty surrounding TPMs. Some design work (analyses, evaluations, reviews, experiments, tests) may not change the actual capability of the design (the TPM levels), but these kinds of efforts are crucial for reducing the uncertainty in the design.
**Performance Risk** ($\mathcal{R}_{TPM}$). Performance risk is uncertainty that a product design will satisfy technical requirements and the consequences thereof (cf., Browning 1999). Thus, the amount of performance risk associated with any TPM depends on two factors: (1) the number of possible outcomes, cases, or situations that fail to meet requirements and (2) the consequence or impact of each.

**Uncertainty.** The uncertainty component of performance risk can be quantified using the familiar methods of schedule risk assessment. Treating a TPM as a random variable, its possible outcomes can be represented by a *probability density function* (PDF). The PDF in Figure 2 shows the relative likelihood of an aircraft product having various range capabilities. The vertical line at 725 nautical miles (nmiles) signifies the required performance level. The part of the PDF to the left of the requirements line represents the fraction of outcomes that fail to meet requirements—or the probability that the design will not conform to requirements.

![Figure 2: PDF Showing Relative Probability of Various Range TPM Outcomes](image)

How is the shape of the PDF determined? Since the PDF represents possible outcomes and their relative probability, its shape depends on what kinds of outcomes are anticipated and how likely each is thought to be. Usually, one does not have much information about every possible outcome. When information is scarce, it helps to focus on a few important outcomes—the most likely case, the optimistic (best) case, and the pessimistic (worse) case. Estimates of these cases can be used to construct a rough, triangular PDF (triPDF) as in Figure 3. The area under the PDF is usually normalized to one.

**Consequences.** The consequences of failing to meet a requirement must also be considered. Some requirements are absolute thresholds below which the entire design is unacceptable. Other requirements represent customer preferences, where more is better but less might be acceptable. In the case of aircraft range, would missing the requirement by one mile be as bad as missing it by fifty? Customer needs and preferences data can be used to estimate the impacts of various adverse outcomes. For example, the customer may allow missing the range requirement (as long as this lack of value is compensated for in some other product attribute). However, the customer becomes more displeased the more range falls short. This increasing dissatisfaction might be represented using a quadratic impact function, where dissatisfaction grows as the square of the gap between the TPM and the requirement. Figure 4 exhibits (A) quadratic and (B) linear impact functions. Together, the probability of the adverse outcomes and their impacts determine the level of performance risk for a TPM.

![Figure 3: Conversion of Three-Point Estimate to TriPDF](image)

![Figure 4: Two Example Impact Functions Overlaid on TriPDF](image)

Utility curves provide a useful approach for documenting customer preferences for various performance levels. Figure 5 shows an example (piecewise linear) utility curve for aircraft range. The length of the x-axis is chosen to span the continuum from disgusting to delighting the customer or market. In this example, perhaps the customer wants an aircraft for a particular use that requires a 700 nmile range.

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5 Taguchi (1980) highlighted the usefulness of quadratic quality loss functions.
Nothing less will do. Slightly greater range is of marginally increasing value to the customer, to the point that a range of 1000 nmiles would be delightful. The utility curve can be used to determine the impact of various range TPM outcomes in terms of customer utility or value.\(^6\) The impact is the gap between the utility of the outcome and the utility of the requirement:

\[
I_{\text{TPM}} = \kappa_{\text{TPM}} \left[ U(T) - U(x_0) \right] \tag{1}
\]

where \(x_0\) is a TPM outcome, \(T\) is the target (requirement), \(U(\cdot)\) is the utility, and \(\kappa_{\text{TPM}}\) 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). In this case, the shape of the impact function depends on the shape of the aircraft range utility curve and the chosen requirement.

\begin{figure}
\centering
\includegraphics[width=0.5\textwidth]{utility_curve.png}
\caption{Utility Curve for Aircraft Range}
\end{figure}

**Risk.** The performance risk for a “larger is better” (LIB) TPM is the sum of the products of probability and impact for each unacceptable outcome, which, for the continuous case, is:

\[
R_{\text{TPM}} = \kappa_{\text{TPM}} \int_{-\infty}^{T} f_{\text{TPM}}(x_0) \left[ U(T) - U(x_0) \right] dx_0 \tag{2}
\]

where \(f_{\text{TPM}}(x_0)\) is the PDF of all TPM outcomes. The integral is approximated with a summation for the usual case of a finite number of discrete outcomes.

**Product Performance Risk (\(R\)).**\(^7\) The overall performance risk for a product design, \(R\), is the weighted sum of all the \(R_{\text{TPM},i}\):

\[
R = \sum_{i} w_i R_{\text{TPM},i} \tag{3}
\]

\(^6\) For more information on constructing utility curves, see, e.g., (de Neufville 1990).

\(^7\) The methodology in this section was suggested by Hugh McManus. where \(w_i\) is the relative importance of TPM. (It is usually helpful if all the \(w_i\)'s sum to one.)

**METHODS FOR PLANNING AND TRACKING TECHNICAL PERFORMANCE**

This section reviews two performance planning and surveillance methods, the TPM tracking chart and the risk waterfall chart. Both methods are used in a number of system development projects in industry. The two methods are combined and used in the next section to illustrate the risk value method.

**TPM Tracking Chart.** A TPM tracking chart forecasts and monitors an evolving TPM relative to its requirement. Initially, experts with applicable project, system, and technology experiences may forecast a “planned profile” for the TPM. The profile is projected based on a number of factors, including technology risk, planned test and validation activities, historical data, experience, and expert opinion. The planned profile integrates information from these sources into a format that helps planners and managers make decisions. As the project unfolds, demonstrated measures are recorded periodically. Ideally, the actual profile will meet or exceed the requirement, and uncertainty will decrease. TPM tracking also enables margin and risk management methods (e.g., NASA 1995, p. 62).

In Figure 6, an example aircraft design project is planned to last eight months. The requirement for effective mission range is set at 725 nautical miles and is shown in the tracking chart as the dashed, horizontal line. The circles represent a point estimate or measure of the most likely level of performance delivered by the design at various times. Each estimate conveys uncertainty with the high-low bars showing the optimistic and pessimistic possibilities. (In practice, however, many projects omit the uncertainty bars.)

**Risk Waterfall Chart.** Areas requiring risk reduction may be anticipated and tracked using a “risk waterfall” chart. The example in Figure 7 shows an assessed risk level for a particular structural loading case in an aircraft operational scenario. At the outset of the project, it is determined that the risk of unacceptable performance in this case is medium to high. The goal is to plan and track a chain of activities intended to mitigate this risk. As when building a TPM chart, one solicits expert opinion on the appropriate activities to reduce the risk and the amount of reduction anticipated for each, which are indicated in the chart as step functions of risk reduction. In Figure 7, the information produced by activities 1, 2, and 3 directly contributes to reducing the risk that the aircraft will not conform to requirements in this area. The expected, combined effect of the information created by these activities is to decrease the risk to a level deemed acceptable.
random. In many cases, however, the direction and approximate magnitude of a TPM change during a specific interval can be predicted by an experienced person with knowledge of the information created during the interval. If an interval contains a number of design decisions, the expected result may be improved performance. On the other hand, an interval containing many tests and reviews often leads to decreased TPM estimates.

**Figure 6: Example TPM Tracking Chart for Aircraft Range**

**Figure 7: Example Risk Waterfall Chart for Aircraft Structural Loads**

**Combination Chart.** The convenient format of the risk waterfall chart can be applied to the TPM tracking chart to monitor the risk inherent in a TPM level. Figure 8 provides an example, where risk levels (normalized on a zero to one scale) are overlaid on Figure 6. Each risk level is computed using equation (2) and a quadratic impact function.

**TPM BEHAVIOR**

Over the course of a project, the behavior of the TPMs is difficult to predict. Their starting points depend on the quality of initial estimates. For many TPMs, their change over the interval \( t_i \) to \( t_{i+1} \) seems random. For example, Cusumano and Selby show defect (bug) TPMs for Microsoft Excel 5.0 and Microsoft Word 4.0 where the overall effect is a gradual decrease but the localized fluctuation seems random (1995, pp. 318, 324). McDaniel (1996) also documents that design quality does not improve monotonically over design time. While progress occurs in one area, other activities discover new problems. There is no guarantee that problems will be solved faster than they are discovered during any given interval. Globally, performance seems to improve more steadily; locally (represented by a TPM), performance seems more

If adding value equates with reducing performance risk, \( R \), how can this effect be measured over specific time intervals? How much value is delivered between \( t_i \) and \( t_j \)? Or, how much has \( R \) been reduced between \( t_i \) and \( t_j \)? Figure 9 shows an example risk reduction profile for a project (cf., Figure 1). During some interval, \( \Delta t \), information is created that provides some risk reduction, \( \Delta R \). The profile in Figure 9 represents Womack and Jones’ ideal project—continuously added value. Figure 10 depicts some alternative performance risk reduction profiles. Project A reduces risk quickly and then has diminishing returns. Project B makes slow progress at first but then advances quickly. Project C has periods of risk increase when problems are detected; this profile is probably the most realistic. Project D is never able to reduce performance risk to satisfactory levels.

The profiles are functions of how new information affects the TPMs (including uncertainty) and the impact of falling short of requirements. To illustrate this more specifically, consider the TPM tracking chart in Figure 8. Let \( t_i \) be 1/99 and let \( t_j \) be 7/99, six months later. Figure 11 shows the TPM at these two times with the uncertainties represented by PDFs. At time \( t_j \), useful information has been created that has reigned in the uncertainty that was evident at time \( t_i \). The probability

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This assertion has not been verified empirically.
of an unacceptable outcome has decreased, and especially poor outcomes with greater consequences have been eliminated. The combined effect is a reduction in risk (as tracked in Figure 8) for this TPM.

![Figure 9: Change in Performance Risk Over Time](image)

![Figure 10: Alternative Performance Risk Reduction Profiles](image)

**CONCLUSION**

"To solve our basic problem [of improving the product development process], any methodology that is to be developed must be useful in evaluating the partially-developed product at any time during its development life."

—Sidney Sobelman (1958)

The problems of how to evaluate the status of a product design and how to measure progress or value added in PD are very similar. This paper presented an integrated concept and methodology—the risk value method—that addresses these issues. The value of the PD process as a whole (and of every activity within it) is based on the value of its product(s). Many of the products of PD activities serve not only to improve the design but also to confirm it. During PD, activities contribute value by creating information that increases certainty about the ability of the design to satisfy requirements.

Until an actual product is produced and used, its performance level is uncertain. In the early stages of PD, a baseline design is proposed that is supposed to satisfy requirements and deliver desired performance. During PD, new information is created as the design is analyzed and tested. This information may reveal that the design or some portion of it does not suffice. The performance level of the evolving product design will fluctuate over time. The only thing that increases monotonically with time is the amount of useful information available. The value of that information provides an improved way to think about progress and added value in PD.\(^7\) The risk value method really gets more at how value is measured than it does at how value is created. But the measure is what guides decisions about what additional value remains to be added and what the PD project will do about it.

![Figure 11: Reduction in Unacceptable Outcomes from \(t_1\) to \(t_2\)](image)

Therefore, the risk value method is a useful and helpful technique in PD project planning and control. It has many applications and benefits. It can help in deciding what information should be created (and therefore what activities should be executed) to produce an expected risk reduction profile and ensure a sufficient stream of value creation (Weiss and Warmkessel 1999).\(^8\) When the contributions of each activity are tracked, their cost and cycle time can be used to determine their productivity or efficiency in adding value. (These types of applications require a sufficient process model or description—one that accounts for the information dependencies among activities.\(^9\)) In addition, the approach enables analyses of the effects of iteration, rework, testing, and other types of activities on value. Perhaps the expected value

\(^7\) Note, however, that the value of the information is not guaranteed to increase monotonically, since the value attached to any given portion of the information can change based on new information.

\(^8\) At least one systems engineering text (Oliver et al. 1997) lists "Assess Available Information" as an explicit step in the core technical process.

\(^9\) An excellent tool for this purpose is the design structure matrix (DSM—Browning 1998; Eppinger et al. 1994; Steward 1981)
of additional iterations of design activities can be forecast. The risk value method also facilitates post-project analysis and learning. Planned risk reduction profiles can be compared to actual achievements to evaluate a firm’s project planning and control capabilities and to improve the PD process. New activities may be used to create certain information in future projects.

Furthermore, the risk value method emphasizes the importance of making a rough estimate of each TPM and its uncertainty during the first parts of the design process, perhaps as early as when a concept or architecture is seriously considered. Early estimates help ensure that primary TPMs are not overlooked during the initial stages of design.

Finally, paying more attention to the uncertainty connected with each TPM emphasizes the importance of risk reduction and maintained flexibility. Early risk reduction can be achieved by earlier, more directed testing and validation of uncertain aspects of the design and more appropriately timed and posted design reviews. Maintained flexibility is necessary when uncertainty persists. Paying explicit attention to uncertainty can decrease the focus on point solutions and increase the attractiveness of approaches such as set-based design (e.g., Ward et al. 1995) and robust design (e.g., Phadke 1989). All of these advantages accrue when using the risk value method in practice. Companies that effectively manage and reduce uncertainty and risk should realize competitive advantages (Levy 1999).

Although the risk value method provides an improved measure of progress and value added, it has some limitations. Certainly, metrics are no better than the data used to construct them. Most of the information assessing uncertainty and risk in a PD project is subjective. Nevertheless, the risk value method integrates the most useful information available in a meaningful way to support decision-making. It facilitates trading off various dimensions of performance to achieve a correctly balanced product. A strong argument for the risk value method, despite its limitations, is that these same, subjective data—used in an ad hoc, unsystematic, and unintegrated fashion—constitute the current state of practice.

Another limitation is that measures can be “gamed.” The PD organization culture must exhibit proper attitudes towards performance measures and uncertainty if the measures will be meaningful. If process participants merely pad uncertainty estimates to justify more uncertainty reduction activities, the PD process may not be able to clear a business case hurdle. After all, adding value continuously is a means to an effective enterprise, not an end in itself. Value must be delivered as efficiently as possible.

In closing, consider the value of certainty and predictability, both to the PD organization and to the customer. Customers of commercial products usually assume the PD organization is certain about its products. The PD firm has a reputation to maintain. This aspect of certainty is primarily valuable to the PD organization. However, especially in the case of large, novel, complex systems, certainty (termed “low risk”) is clearly a criterion of customer preference. At least in these cases, if not more generally, certainty is of direct value to the customer.

It is also helpful to turn the problem around and consider the cost of uncertainty. Uncertainty has many costs during PD—e.g., costs of resource buffers and options—and these costs are passed along to the customer as higher acquisition costs. Whether the customer considers certainty explicitly or not, product costs reflect the costs of uncertainty. Reducing uncertainty in PD can improve affordability and thereby increase value to the customer.

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