Adding Value in Product Development by Creating Information and Reducing Risk

Tyson R. Browning, John J. Deyst, Steven D. Eppinger, *Member, IEEE*, and Daniel E. Whitney, *Senior Member, IEEE*

***Abstract*—Many firms expend a great amount of effort to increase the customer value of their product development (PD) processes. Yet, in PD, determining how and when value is added is problematic. The goal of a PD 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 design (including its production process) to be the final product recipe (i.e., technical performance risk decreases). The goal of this paper is to advance the theory and practice of evaluating progress and added customer value in PD. The paper proposes that making progress and adding customer value in PD 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 tracking charts and risk reduction profiles. The methods are demonstrated with an industrial example of an uninhabited combat aerial vehicle.**

***Index Terms*—Lean, performance measurement, product development, project management, risk management, systems engineering, value stream.**

I. INTRODUCTION

OVER the last decade, lean manufacturing has entrenched itself as part of the Western industrial landscape [74], [75]. 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 that continuously add customer value—i.e., that sustain a level of "progress" toward their goals. Recent emphasis on "earned value management systems" in project management is another example of this trend.

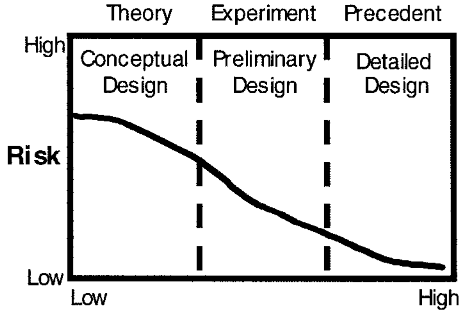

Fig. 1. Risk decreases with availability of useful information.[1]

PD spans the gamut of marketing, design, management, and other activities done between defining a market opportunity and starting production.[2] The goal of the PD process is to create a "recipe" for producing a product [49]. 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.

PD processes are unlike typical business and production processes in several ways. Instead of doing exactly the same thing over and over, PD seeks to create a design that has not existed before. Terms like "iterative" and "creative" apply to PD. Designers may start with one design, find it deficient in several ways, learn more about the problem from it, and then change it [6], [61], [71]. Especially with novel products, designers learn much along the way about what will and will not work [42], [45]. 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. Trying, analyzing, evaluating, testing, experimenting, demonstrating, verifying, and validating can create valuable information [48], [65].

What information is needed to complete the recipe? How can one be confident that an acceptable recipe will materialize? What is the risk it will not? Fig. 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 and risk. The activities that ensure that the right recipe materializes (i.e., that reduce the risk that it will not) are the ones that add value, and their completion constitutes progress in PD.

The goal of this paper is to advance the theory and practice of evaluating progress and added customer value in PD. The paper

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T. R. Browning is with Lockheed Martin Aeronautics Company, Fort Worth, TX 76101 USA (e-mail: tyson@alum.mit.edu).

J. J. Deyst is with the Department of Aeronautics and Astronautics, Massachusetts Institute of Technology, Cambridge, MA 02139 USA (e-mail: deyst@mit.edu).

S. D. Eppinger is with the Sloan School of Management, Massachusetts Institute of Technology, Cambridge, MA 02142 USA (e-mail: eppinger@mit.edu).

D. E. Whitney is with the Center for Technology, Policy, and Industrial Development, Massachusetts Institute of Technology, Cambridge, MA 02142 USA (e-mail: dwhitney@mit.edu).

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[1] Figure adapted from [28]. A similar concept can be found in [1].

[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.

contributes a method for evaluating the customer value added in PD as a function of the generation of useful information that reduces risk. The *risk value method* is based on understanding overall technical performance risk and its components. The approach integrates several concepts and methods, including *technical performance measures* (TPMs), risk reduction profiles, customer preferences, and uncertainty. After discussing the concepts and methods used to formulate the risk value method, the paper shows how to apply the approach using an industrial example, an *uninhabited combat aerial vehicle* (UCAV).

II. ADDING CUSTOMER VALUE IN PRODUCT DEVELOPMENT

> "In an information economy, improving the utility of information is synonymous with creating economic value. Where intelligence resides, so too does value."
>
> —Sawhney and Parikh [51]

The goal of PD is to produce a product recipe that conforms to requirements or acceptance criteria with some certainty. PD is a problem-solving and knowledge-accumulation process. Progress is made and value is added by creating useful information that reduces uncertainty and/or ambiguity [22], [52], [60]. But it is challenging to produce information at the right time, when it will be most useful [57], [66]. Developing complex and/or novel systems multiplies these challenges. This section reviews some important considerations and challenges in adding value in PD and measuring it.

The final product recipe contains a large amount of information, which is based on an enormous amount of supporting data, which in turn rest on still other data, etc. This information structure must be built from the ground up. Certain information must be created and propositions made before it becomes possible to create other information. For example, components must be designed to some level of detail before certain kinds of information is available about assemblies of those components. The dependencies between PD activities define a necessary sequence in the process of producing useful information [13]–[15], [42], [66]. Most of the work done and the decisions made depend on the results of other work and decisions—i.e., on the structure of the activity network [26], [58]. The value of the information an activity produces is a function of, among other things, the value of the information it receives and uses. 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*. A perfectly efficient processor may still produce bad results based on bad inputs. 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 customer value can be *less* a function of doing the right activities (or of not doing the wrong ones) 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 toward addressing the PD process as a system [10].

It is well known that progress in PD is difficult to gauge. Several authors have noted various reasons contributing to the problem. First, Goldratt [27] and others note how, if several work items must be done, people tend to do the easiest ones first. For example, when eight of ten items are completed, many naïvely assume 80% of the work is finished. Rework provides a second complication. PD planners often "plan to succeed," typically paying little attention to *process failure modes* and their effects (i.e., rework). Third, actually doing PD work may unearth the need for additional information (and additional activities to generate it). These three effects and others, combined, can make the last 10% of a project take half of the time (implying a schedule overrun or a cost overrun to prevent one; see, e.g., [18]). Thus, one cannot equate added customer value with progress through an arbitrarily defined statement of work or process 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. This is a significant weakness of the earned value management systems (EVMS) currently used in industry.

Since PD is a nonlinear process [36], [42], it is harder to determine what value is added and when. Especially in novel PD, design elements 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 [10]. PD processes typically have lots of change and rework [19]. PD is iterative, with additional details explored during each pass. The values of its activities are not predetermined—they are partly a function of the information they use and create, and therefore of the activities that precede them and those that follow [10].

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.[3] 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 customer value was not added in the first place—although the designers may have learned something.) Again, forecasting which activities will add value and when is problematic in the PD process.

The latest performance estimates of a design can also be illusory indicators 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. Design performance levels cannot indicate progress unless they include a notion of how much uncertainty remains.

Furthermore, what are the contributions of analysis, measurement, review, test, and prototyping activities to progress and value in PD? Activities such as these may not change the performance level (or "form, fit, and function") of a design at all (although they may create information 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 and 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 a

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[3] As in control systems, time lags contribute to process instability.

project, based on how much is known about a product design. This paper proposes tracking the uncertainty surrounding the ability of the design to meet requirements as a way to measure progress and added customer 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. The approach can help PD managers add value by focusing effort on eliminating the critical sources of risk in their projects. It can also help project planners ensure that a proposed process addresses all of the known significant sources of performance risk.

III. CONCEPTS AND DEFINITIONS

This section discusses how customer value is provided through product attributes and how estimates of these attributes enable calculation of performance risk.

A. Technical Performance

The customer value provided by a product depends on its affordability, lead time, and technical performance. This paper focuses on technical performance (sometimes just called performance), which refers to a product's technical attributes and entails a product's conformance to its technical requirements. Does the product do everything it is required 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 relates to the benefits provided by a product because of its design, capabilities, and functionality. A product performs well technically if it does everything it should as well as it should.[4]

Technical performance typically contains many attributes. An aircraft's technical performance, for example, includes payload, range, reliability, noise level, altitude ceiling, etc. Product performance attributes that the market cares about and expresses preferences for are the primary attributes.

Additional technical performance attributes may be derived and acknowledged within the development organization to guide the design process. For example, weight is an important aspect of aircraft performance because it directly impacts payload, range, and other performance attributes. Yet, it may not be a primary performance attribute because customers may not care about the actual weight of the aircraft as long as it performs well.[5]

The tendency for the primary performance attributes to depend on several lower level attributes suggests that it can be convenient to represent attributes in a hierarchy. Attributes relate to each other horizontally as well as vertically in the hierarchy—i.e., they can be interdependent. For example, payload and range can be traded: the amount of one impacts the amount of the other. Independence is a desirable characteristic of performance attributes [59], however, and sometimes choices can be made to select attributes that are relatively independent (e.g., by combining attributes such as payload, range, and operating cost into "seat cost per mile" for commercial passenger aircraft).

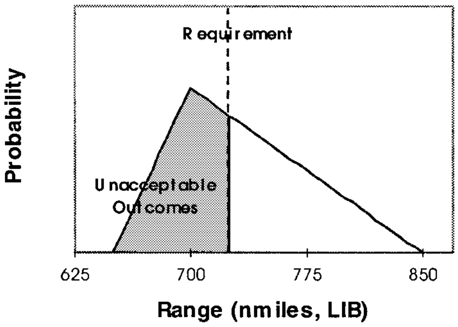

Fig. 2. PDF showing relative probability of various range TPM outcomes.

B. Technical Performance Measures (TPMs)

System designers use metrics to plan and track the level of important technical performance attributes as PD unfolds. These metrics are called *technical performance measures* (TPMs), measures of effectiveness (MOEs), figures of merit (FOMs), and other names [5], [16], [25], [32], [38], [41], [47]. 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 and certain as design work provides TPM verification. When the product recipe is ready, the TPMs indicate the level of performance provided by the product.

The idea that TPMs become more accurate as the design matures relates to 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 (represented by the TPM bounds).

C. Technical Performance Risk $\mathcal{R}(\text{TPM})$

Technical performance risk is uncertainty that a product design will satisfy technical requirements and the consequences thereof (cf., [9]). 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.

1) Uncertainty: The familiar methods of schedule risk assessment apply to quantifying performance uncertainty. Treating a TPM as a random variable, its possible outcomes can be represented by a *probability density function* (PDF). The PDF in Fig. 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

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[4] Whether or not the chosen "design to" requirements are in fact the ones the users would specify (if they could) is a matter of *market risk* [8, Ch. 3].

[5] Yet, weight has such a strong, direct impact on payload and range that aircraft customers tend to be interested in it. Also, weight may be a primary performance attribute if the aircraft will operate on certain types of runways.

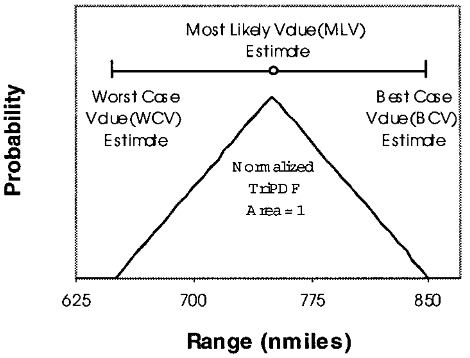

Fig. 3. Conversion of three-point estimate to TriPDF.

represents the fraction of potential outcomes that fail to meet requirements—the probability that the design will not conform to requirements.

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 potential 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 Fig. 3. The area under the PDF is normalized to one.[6]

2) 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 1 nmile be as bad as missing it by 50? 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 decreasing satisfaction might be represented using a quadratic impact function, where dissatisfaction grows as the square of the gap between the TPM and the requirement.[7] Fig. 4 exhibits A) quadratic and B) linear impact functions.

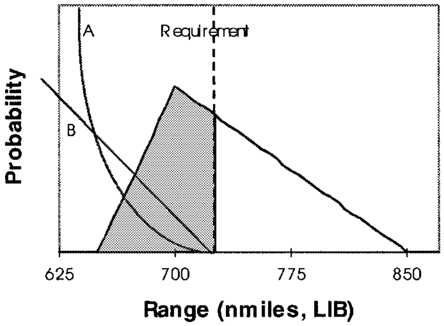

Fig. 4. Two example impact functions overlaid on triPDF.

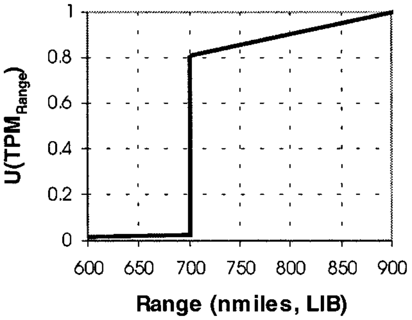

Fig. 5. Utility curve for aircraft range.

Instead of a simple quadratic or linear impact function, utility curves provide a more powerful approach for documenting customer preferences for various performance levels. Fig. 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. 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.[8] The consequence or impact of failing to achieve a target level of performance is a function of the gap between the utility of the outcome and the utility of the target

$$I_{\mathrm{TPM}} = \kappa_{\mathrm{TPM}} \left[U_{\mathrm{TPM}} \left(T_{\mathrm{TPM}} \right) - U_{\mathrm{TPM}} \left(x_0 \right) \right] \tag{1}$$

where x_0 is an outcome (a TPM level), T_{TPM} is the target (requirement), $U_{\mathrm{TPM}}(\bullet)$ 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).

3) Risk: The performance risk in a dimension of product performance is the sum of the products of probability and impact for each unacceptable outcome, which, for the continuous case and a "*larger is better*" (LIB)[9] TPM, is

$$\begin{aligned} \mathscr{R}_{\mathrm{TPM}} = {} & \kappa_{\mathrm{TPM}} \int_{-\infty}^{T_{\mathrm{TPM}}} f_{\mathrm{TPM}}(x_0) \\ & \cdot \left[U_{\mathrm{TPM}}(T_{\mathrm{TPM}}) - U_{\mathrm{TPM}}(x_0) \right] dx_0 \end{aligned} \tag{2}$$

where $f_{\mathrm{TPM}}(x_0)$ 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.

D. Product Performance Risk ($\mathscr{R}$)

The overall performance risk for a product design, $\mathscr{R}$, is the weighted sum of all the $\mathscr{R}_{\mathrm{TPM}}$s

$$\mathscr{R} = \sum_i w_i \, \mathscr{R}_{\mathrm{TPM},\, i} \tag{3}$$

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[6] To allow for best and worse cases beyond those proposed, the area under the TriPDF can be normalized to 0.8 and the assumption made that 10% of the outcomes lie to either side of the range bounded by the given best and worse cases.

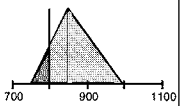
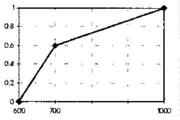
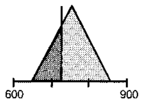
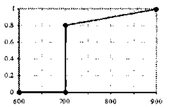
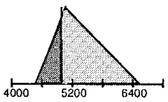
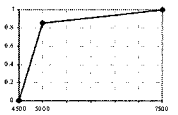
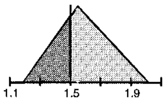
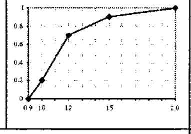
[7] Taguchi [62] highlighted the usefulness of quadratic quality loss functions.

[8] For more information on constructing utility curves, see, e.g., [23].

[9] Aircraft range is a LIB TPM. "Smaller is better" (SIB) and "nominal is best" (NIB) TPMs may characterize other product attributes.

TABLE I

TPM DATA AT A POINT IN PROJECT TIME, t_1

TPM	Target	WCV	MLV	BCV	PDF	Utility Curve	w_i	$\mathcal{R}_{TPM}$	Status
Payload	800 Lbs.	750	850	1000			.3	22	● (Green)
Range	725 nmiles	650	750	900			.25	1019	● (Red)
Reliability (MTBF)	5000 hrs.	4500	5100	6500			.2	584	● (Yellow)
Detectability	1.5 (ratio to previous baseline)	1.2	1.55	2			.25	212	● (Yellow)
						$\mathcal{R}$:	1.0	431	● (Yellow)

*The UCAV capabilities presented in this paper are hypothetical.

where w_i is the relative importance of TPM_i and all w_i sum to one.[10] (The Appendix discusses an alternative approach to calculating the overall performance risk using multiattribute utility theory.)

For example, consider four UCAV TPMs: payload, range, reliability (mean time before failure—MTBF), and detectability ("stealthiness"). At project time t_1, Table I shows TPM targets, PDFs, utility curves, relative importance (weights), risk levels, and—for example—arbitrary statuses (green $=$ low risk; yellow $=$ medium risk; red $=$ high risk).

According to (2), the risk level of each TPM is a function of the PDF shape, the target, and the utility curve.[11] In Table I, $\mathcal{R}_{\text{Range}}$ is large because of the shape of its utility curve and the position of its PDF; a significant portion of the PDF lies in the region where customer utility is zero, indicating a large impact. $\mathcal{R}_{\text{TPM}}$ is not a linear function. It grows quickly as the WCV decreases. Thus, large individual $\mathcal{R}_{\text{TPM}}$ values will have a large influence on $\mathcal{R}$. This effect is helpful, since we do not want a single high-risk TPM to be "washed out" by a large number of low-risk TPMs when determining overall performance risk. The thresholds for assigning statuses are arbitrary, depending on the development organization's level of risk acceptance or aversion.

The risk factor values are primarily significant in a relative sense, as a measure of progress. However, by choosing appropriate units for κ, $\mathcal{R}$ could represent, say, dollars of sales at risk. For example, suppose the development organization assumes that 1000 units will be sold at \$10 million each if all product attributes provide maximum customer utility. Then, $\kappa =$ (\$10 million/unit)(1000 units/full utility)(full utility) $=$ \$10 billion in potential sales. Furthermore, it assumes demand is a linear function of the overall utility level, such that each 0.01 of lost overall utility represents an impact of \$100 million in lost sales. Based on achieving all of the targets listed in Table I, the development firm might estimate selling 821 units (\$8.21 billion). But given the PDFs and risk levels, \$431 million in potential sales are at risk. While this number is interesting, it is extremely sensitive to the assumptions about market size and the relationship between utility and demand (which is not actually linear). Nevertheless, business cases regularly make assumptions about markets and demand, despite the problems with such forecasts. An organization with market savvy and historical data could calibrate κ so that $\mathcal{R}$ would provide useful support for business decisions.

IV. METHODS FOR PLANNING AND TRACKING TECHNICAL PERFORMANCE

This section reviews two performance planning and monitoring methods, the TPM tracking chart and the risk reduction profile [5], [25], [38], [41]. Both methods are used in a number of system development projects in industry (e.g., [16], [32], [34], [47], [50], [53], and [54]). The two methods are combined and used to illustrate the risk value method.

A. TPM Tracking Chart

A TPM tracking chart predicts and monitors an evolving TPM relative to its requirement. Initially, experts with applicable product, project, 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 verification and validation activities, historical data, experience, and expert opinion. As the project unfolds, demonstrated measures are recorded periodically. Ideally, the *actual*

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[10] This form for the overall risk equation was suggested by H. McManus.

[11] For all calculations in Table I, $\kappa = 10^4$ "risk units," yielding risk factors with whole number magnitudes. Equation (2) was solved numerically by dividing the unacceptable region of the PDF into 100 intervals and summing the probability and impact of each.

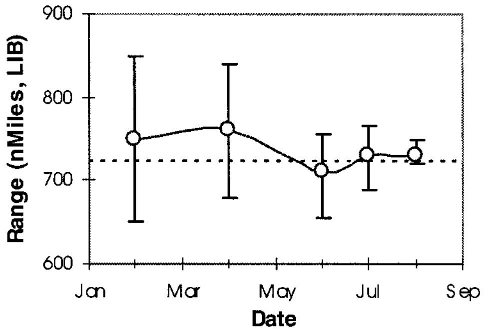

Fig. 6. Example TPM tracking chart for aircraft range.

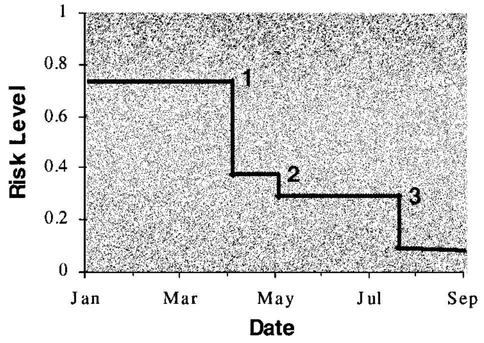

Fig. 7. Example risk reduction profile for aircraft structural loads.

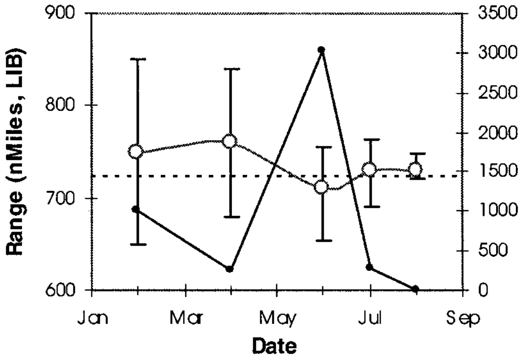

Fig. 8. Combination TPM and risk tracking chart.

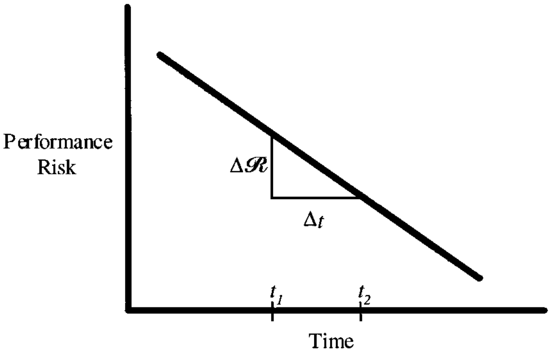

Fig. 9. Change in performance risk over time.

profile will meet or exceed the requirement, and uncertainty will decrease.[12]

In Fig. 6, an example aircraft design project is planned to last eight months. The requirement for effective mission range is set at 725 nautical smiles and is shown in the tracking chart as the dashed, horizontal line. Each circle represents a point estimate or measure of the most likely level of performance delivered by the design at various times. The high–low bars, showing the best and worst case possibilities, convey the uncertainty in each estimate. (In practice, however, many projects unfortunately omit the uncertainty bars.)

B. Risk Reduction Profile Chart

Areas requiring risk reduction may be anticipated and tracked using a risk reduction profile or "risk waterfall" chart. The example in Fig. 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 reduce this risk. The amount of risk reduction anticipated for each activity is indicated on the chart as a step function. In Fig. 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.

C. Combination Chart

The convenient format of the risk reduction profile can be added to the TPM tracking chart to monitor the risk inherent in a TPM level (Fig. 8). Each risk level is computed as discussed in Section III-D.

At the beginning of a project, TPM and risk reduction profiles are plans, forecasts, predictions. Planned profiles like those above are based on the inputs of experts who have experience with similar types of products, projects, and technologies. Planned profiles integrate their experience, knowledge, and opinions into a format that helps planners and managers make decisions. It is by no means a perfect situation, a good planner assumes the forecast is wrong. Yet, using TPM profiles—based on planned events in the PD process—presents the best information available in a helpful format. As the project proceeds, revised TPM estimates or actual values replace or supplement the projections.

V. ADDING CUSTOMER VALUE BY DECREASING PERFORMANCE RISK

If adding customer value equates with reducing performance risk, $\mathcal{R}$, how can this effect be measured over specific time intervals? How much customer value is added between t_1 and t_2? Or, how much has $\mathcal{R}$ been reduced between t_1 and t_2? Fig. 9 shows an example risk reduction profile for a project (cf., Fig. 1). During some interval, Δt, information is created that provides some risk reduction, $\Delta\mathcal{R}$. The profile in Fig. 9 suggests continuously added value. Fig. 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.[13] Project C has pe-

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[12] TPM tracking also enables margin management methods (e.g., [41, p. 62]).

[13] Profiles A and B are like the profiles proposed by Krishnan [37] for task evolution. The concept is similar.

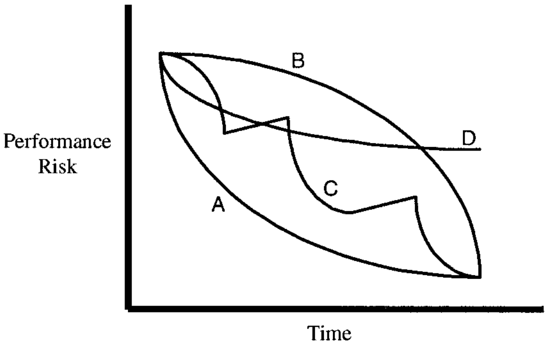

Fig. 10. Alternative performance risk reduction profiles.

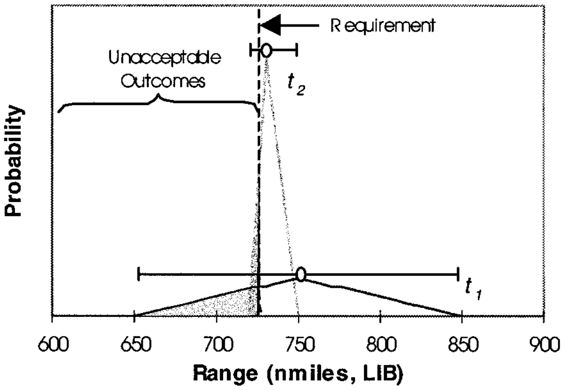

Fig. 11. Reduction in unacceptable outcomes from t_1 to t_2.

riods of increasing risk 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, consider the TPM tracking chart in Fig. 8. Let t_1 be February and let t_2 be August. Fig. 11 shows the TPM at these two times with the uncertainties represented by TriPDFs. At time t_2, useful information has been created that has reined in the uncertainty that was evident at time t_1. The probability of an unacceptable outcome has decreased, and especially poor outcomes with greater consequences have been eliminated. The combined effect is a reduction in risk for this TPM. Fig. 12 shows this effect for all of the data from Fig. 8.

In some circumstances, equating added value with performance risk reduction becomes difficult. For example, some activities may create useful information that reveals an *increased* level of performance risk. Do such activities have negative value? Actually, they are revising (downward) the value supposedly added by previous activities (q.v., the downward-sloped portions of trajectory C in Fig. 10). The value they add is to increase certainty about the value added. Browning [8] discusses market risk (or "customer value risk") as another category of risk in addition to performance risk. Indeed, activities can add value in several areas and from several perspectives, in addition to the customers'. However, this paper focuses on the customer value added through performance risk reduction.

VI. TPM BEHAVIOR

Over the course of a project, predicting TPM behavior is difficult. TPM 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 [20, pp. 318, 324]. McDaniel [40] also documents that design quality did not improve monotonically over design time for aspects of an automotive design process. 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. Global composite performance may improve more steadily, but local performance (represented by a TPM) may seem more 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 [47]. 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 may lead to decreased TPM estimates.

VII. LINKING PERFORMANCE RISK REDUCTION TO PD ACTIVITIES

Linking a TPM change to a risk reduction provides a way to quantify progress that accounts for the value of uncertainty reduction in PD. Current practice involves TPM estimates linked to certain activities and/or events (which result from one or more activities).[14] Risk waterfall charts also show anticipated and actual risk reductions caused by specific activities and/or events. If risk remains high during the course of a project, additional activities may be added to the originally planned set to achieve the desired risk reductions. Hence, current practice supports the link between the *completion of specific activities* and the *reduction of specific risks* [16].

Some activities make a direct contribution to a change in a particular TPM and/or its bounds. Other activities may only make an indirect contribution, by providing information to an activity that has a direct effect. Determining the effect of an activity on a TPM requires thinking about how having that information would affect the TPM, including its bounds.

Each link and its strength can be recorded in an *activity-to-TPM table*, such as the example shown in the next section (Table II). The activity-to-TPM table provides some interesting insights. For example, looking across a row of the table, one gets an idea about the direct effects of an activity on all TPMs. Some activities affect only one or a few TPMs, while other activities may have more global impacts on the design. If the table includes all PD activities, then it may look relatively sparse: many activities may not have a *direct* effect on any TPM. Reading down a column in the table is similar to looking at a TPM's planned trajectory. One can ask if enough activities (e.g., analyses, tests, verifications, etc.) have been

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[14] Here, we define activities broadly as any effort resulting in new information, including decisions and reviews.

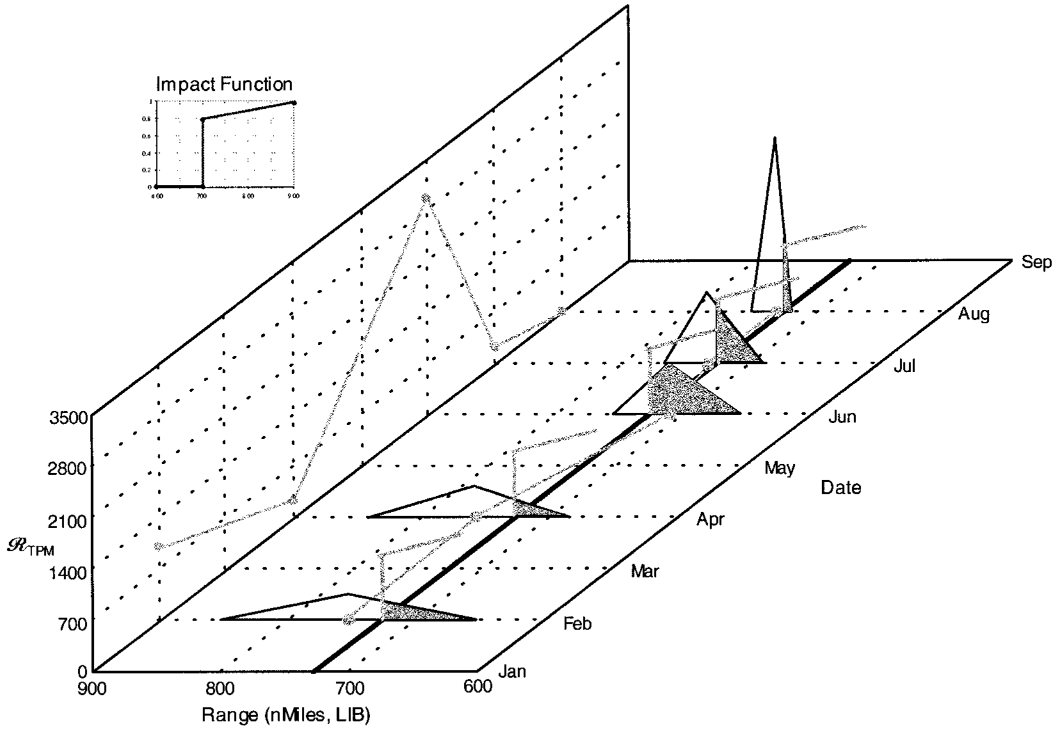

Fig. 12. Another view of the combination TPM and risk tracking chart.

included in the planned PD process to reduce risk sufficiently in a given area. This matter is important since PD activity network models—which are often relied on to analyze cost and schedule risk—assume a deterministic set of activities and relationships.

While it is impossible to forecast accurately the outcomes of future activities, TPMs, and risks, it *is* possible to systematically account for the best historical data and expert knowledge in the development organization regarding the typical effects of certain types of activities on various dimensions of technical performance and risk.

VIII. AN INDUSTRIAL EXAMPLE: UCAV

As the basis for a contrived example of product performance, we use data collected from activities in the preliminary design process of a UCAV.[15] In this case, the purpose of the preliminary design phase is to do the background work necessary for preparation of a proposal to the customer (here, the U.S. Air Force). The designers must create enough information to increase their confidence in the proposed design to a certain level. After all, they must have reasonable confidence that they can actually design (in detail) and build what they propose.

This section presents the UCAV data in the activity-to-TPM table and discusses how insights from the table led to the identification of additional activities. Then, a hypothetical project execution is presented and discussed.

A. Activity-to-TPM Table

The example activity-to-TPM table in Table II lists 14 UCAV preliminary design activities and shows their typical, anticipated, direct effects on each of four TPMs. Listed in the rows of the table, activities are arranged in anticipated chronological order. Columns represent TPMs.[16] Each entry in the table shows the forecasted effect of an activity on a TPM. A "T" represents setting or modifying a target, which is done at the beginning of the project and again when the proposal is prepared at the end of the project. An "IE" entry indicates that an initial estimate is made for a TPM for which no prior estimates or measures existed. Numbered entries correspond to one of the nine types of effects given in Fig. 13. Each numbered effect also has a magnitude, shown by the cell's background pattern and shading. In two cases, two numbers are separated by a comma. These two entries indicate one type of effect on the first pass and another type of effect on successive iterations of the activity.

The data in the activity-to-TPM table are similar to the data in TPM tracking charts, yet with some important differences. An activity-to-TPM table is not intended to replace TPM tracking charts and their graphical advantages. Rather, it links the entire set of project activities and TPMs (not all of which are shown in the example), thereby integrating the planning and management of both with the rest of PD process planning and management. The process of building and verifying an activity-to-TPM table helps project planners ensure that all essential customer value-adding activities are included in the statement of work.

A quick overview of Table II's columns reveals a lack of effect on certain TPMs. This type of examination helps identify missing activities. For example, certain aspects of the UCAV

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[15] The UCAV data were provided by The Boeing Company and are fully documented in [8].

[16] If the number of activities or TPMs becomes large, they can be grouped using hierarchical headings like those used for quality function deployment (QFD) matrices. The activity-to-TPM table is reminiscent of a QFD matrix (e.g., [2] and [29]). However, while a QFD matrix typically (initially) maps customer desires to functional solutions, the activity-to-TPM table maps customer desires to the activities that will create those functional solutions. The use of each method may inform the other.

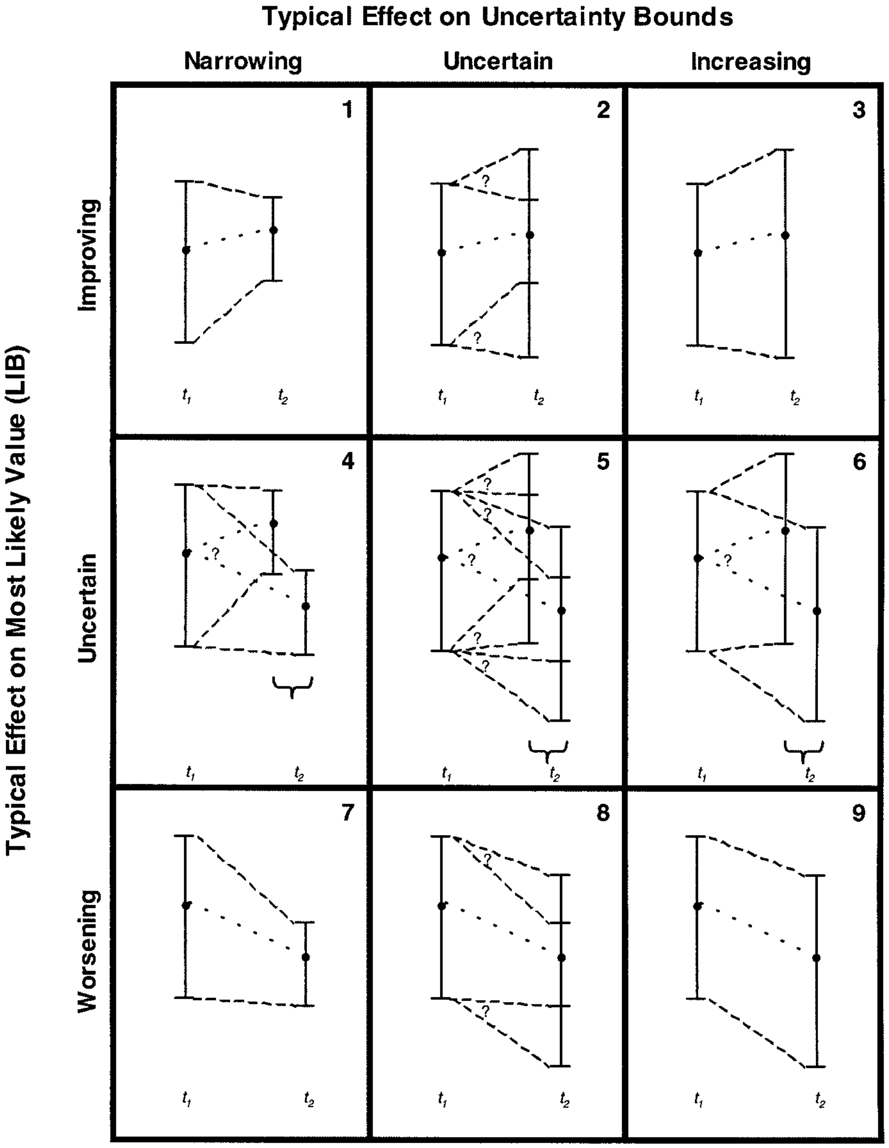

Fig. 13. Types of activity effects on TPMs.

system design such as avionics, propulsion, communications, and other subsystems, which have an impact on reliability, are not accounted for in the existing process. As a result, project participants mentioned several preliminary design activities that they felt ought to be added. These are summarized in an extension to the activity-to-TPM table (Table III). (Since activities were added on a TPM-by-TPM basis, each has not yet been evaluated regarding its potential effects on the other TPMs.) Other activities, such as performance and signature analyses, were also absent from the preliminary design process. Thus, examining columns of the activity-to-TPM table provides an opportunity to establish the bounds of the process more adequately by ensuring the inclusion of all activities necessary to reduce uncertainty in important areas. Or, in some cases, activities may affect a TPM, but the magnitude of the effect might be too small—another case in which additional activities may be necessary. The activity-to-TPM table helps verify the existence of a sufficient chain of value-adding activities designed to reduce risk to acceptable levels for important dimensions of product performance.

The information may affect a TPM in several ways. It may cause the MLV to go up or down, and it may cause the TPM bounds (BCV and WCV) to widen or narrow. Types of effects are categorized in Fig. 13 for a LIB TPM. (Simply exchange the first and third row labels in the figure for a SIB TPM.) In addition to a directional effect, the magnitude of an activity's effect on a TPM may typically be "small," "medium," or "large." When a TPM trajectory or risk reduction profile is forecast early in a PD project, the typical effects of the activities associated with each change can be classified as one of the types and strengths. While effects such as number nine in Fig. 13 may not be desired, sometimes they can be anticipated. For example, those familiar with aircraft design will recognize the trend for aircraft weight estimates (a SIB TPM) to go up as the result of doing certain activities.

At the beginning of a project, data in an activity-to-TPM table represent the estimates, forecasts, and opinions that go into a plan. As the development effort proceeds, entries in the activity-to-TPM table can be replaced by revised estimates and actual results. Alternatively, an activity-to-TPM table can be built

TABLE II
EXAMPLE ACTIVITY-TO-TPM UCAV

Magnitude
▩ **Small**
▒ **Medium**
▓ **Large**

Type
T = set/modify target
IE = make initial estimate
1-9 = (see Figure 13)

	Activities	**TPMs** **Payload**	**Range**	**Reliability**	**Detectability**
1	Prepare UCAV Preliminary DR&O	T	T	T	T
2	Create UCAV Preliminary Design Configuration	▓ 5	▓ 5	IE	
3	Prepare & Distribute Surfaced Models & Int. Arngmt. Drawings				
4	Perform Aerodynamics Analyses & Evaluation				
5	Create Initial Structural Geometry			▒ 0, 5	
6	Prepare Structural Geometry & Notes for FEM				
7	Develop Structural Design Conditions				
8	Perform Weights & Inertias Analyses & Evaluation	▓ 7	▓ 7		
9	Perform S&C Analyses & Evaluation			▒ 0, 4[19]	
10	Develop Balanced Freebody Diagrams & Ext. Applied Loads				
11	Establish Internal Load Distributions	▓ 4	▓ 4		
12	Evaluate Structural Strength, Stiffness, & Life	▓ 4	▓ 4	▓ 4[20]	
13	Perform Preliminary Manufacturing Planning & Analyses			▒ 8[21]	
14	Prepare UCAV Proposal	T	T	T	T

TABLE III
ADDITIONAL ACTIVITIES TO ADD TO UCAV PRELIMINARY DESIGN PROCESS

Magnitude
▩ **Small**
▒ **Medium**
▓ **Large**
░ **(not evaluated)**

Type
1-9 = (see Figure 13)

Activities	**TPMs** **Payload**	**Range**	**Reliability**	**Detectability**
Perform Performance Analyses & Evaluation	▓ 4	▓ 4	░	▒ 7
Perform Propulsion Analyses & Evaluation	░	▒ 5	▓ 4	▓ 4
Design UCAV Avionics Subsystem (Preliminary)	░	░	▓ 4	░
Design UCAV Communications Subsystem (Preliminary)	░	░	▓ 4	░
Design UCAV Hydraulic, Power, Data, etc. Subsystems (Preliminary)	░	░	▓ 4	░
Perform Signature Analyses & Evaluation	░	░	░	▓ 4

with an additional subcolumn under each TPM for actuals as they become available. This format enables quick comparison and post-project analysis of the organization's forecasting capabilities.

B. Hypothetical Project Planning and Execution

Given the activities and TPMs in Table II, project planners might anticipate TPM and risk-level profiles such as those in Fig. 14. Based on the results of the conceptual design phase, each TPM has a PDF and target as shown at week zero of the preliminary design phase.[17] (Week zero corresponds to time t_1 in Table I.) Fig. 15 shows the planned profile for overall risk reduction.

The planned profiles show risk reductions for each TPM except detectability. The lack of effect on detectability should spur project planners to consider adding one or more activities to address the detectability of the UCAV during the preliminary design phase, such as the signature analysis activity suggested in Table III. Similarly, the activities suggested in Table III might also reduce the remaining risk in reliability. The design process will have to be tailored in accordance with the existing design concept and customer preferences so that it contains the appropriate activities to satisfactorily reduce risk.

It is worth pointing out that some activities have a propensity to increase certain risks (as discussed at the end of Section V) and that such activities should not be hastily removed from PD processes as a result. For example, looking at the risk profile for range in Fig. 14, the risk level drops to zero at week 19, after the positive effect of completing the structural strength, stiffness, and life evaluation. Since range risk is then zero, does that mean the PD process no longer must pay attention to UCAV range, and that downstream activities geared to reducing uncer-

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[17] Technically, an initial estimate of reliability is not made until the completion of activity two, about week two.

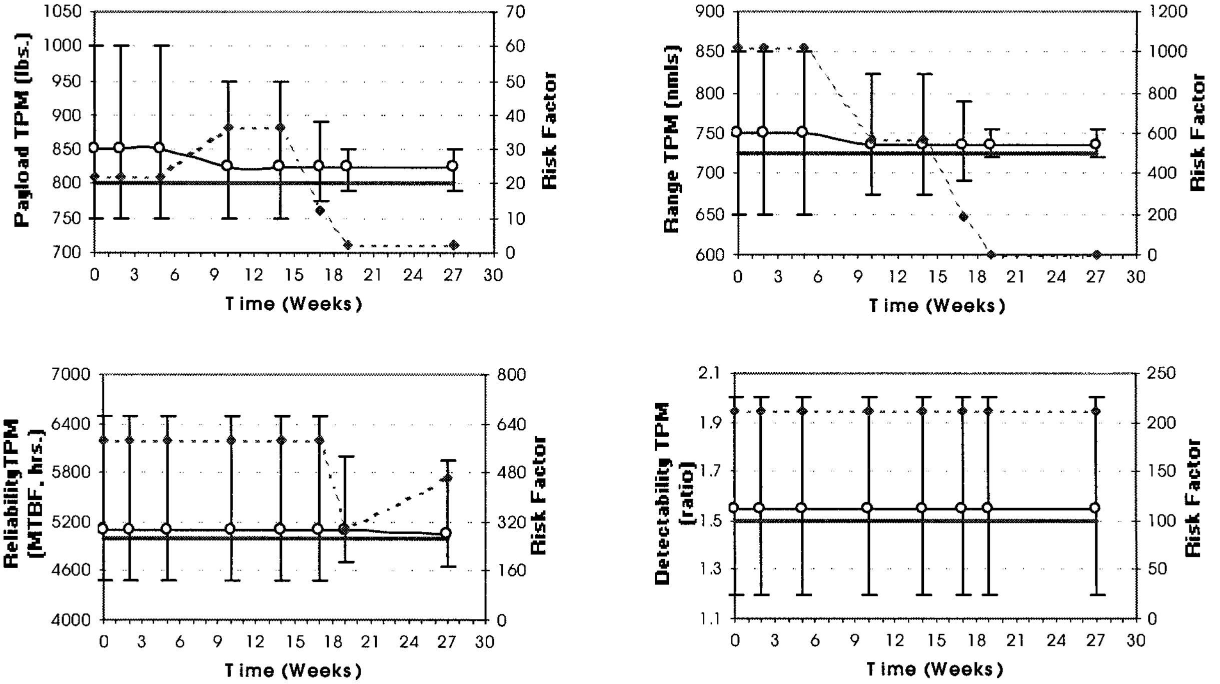

Fig. 14. TPM planned profiles and risk reductions for UCAV preliminary design project.

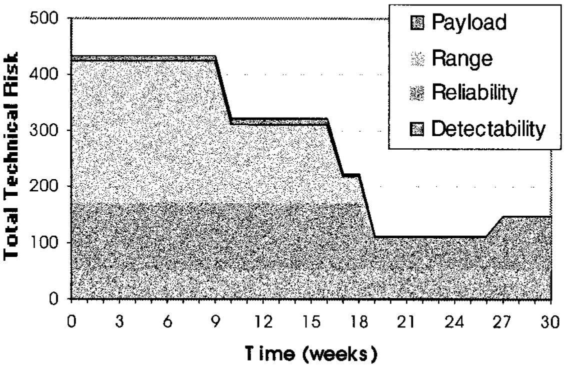

Fig. 15. Overall risk reduction planned profile for UCAV preliminary design project.

tainty in range can be dropped? The answer is "not necessarily" for two reasons: 1) activities can add value in other areas besides performance risk reduction and customer value, and 2) value supposedly added through risk reduction can be destroyed later with the advent of new information: risk can go up as well as down! Nevertheless, the activity-to-TPM table provides a valuable aid to project managers who must decide about the allocation of resources and attention to various aspects of a product design. While it is never a good idea to ignore certain areas, it makes sense to focus on the dimensions of product performance with the highest levels of risk. Some resources should be dynamically reallocated from areas with risks below expectations to areas with risks above expectations.

IX. INSIGHTS FROM THE RISK VALUE METHOD

The risk value method provides several benefits in PD project planning and control. For instance, it supports deciding what information should be created[18] (activity planning) to produce an expected risk reduction profile and to ensure a sufficient stream of customer value creation [73]. New activities ("best practices") may be used to create certain information in future projects. In addition, the method supports post-project analysis and learning. By comparing planned risk reduction profiles to actual achievements, a firm can evaluate its project planning and control capabilities and improve its PD process. The risk value method implies that, primarily, *project management is risk management*[9].

The risk value method draws attention to the uncertainty connected with each TPM, emphasizing the importance of risk reduction and maintained flexibility. The method emphasizes the importance of estimating each TPM early in 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. Then, initial risk reduction can be achieved by earlier, more directed verification and validation of uncertain aspects of the design and more appropriately timed and postured 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., [55]) and robust design (e.g., [46]). It can also enable projects to benefit from additional activity concurrency, since projects with fast uncertainty reduction receive greater benefits from activity overlapping [63]. 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 [39].

A salient aspect of the risk value method is how it links progress and benefits to PD activities. Since the early 1990s,

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[18] At least one systems engineering text [43] lists "Assess Available Information" as an explicit task in the core technical process.

advocates of activity-based management have emphasized the activity as the common basis for cost, schedule, and quality accounting (e.g., [70]). A number of models already exist that evaluate cost and schedule in terms of activity networks. Now, the foundation is laid for models that consider tradeoffs between cost, schedule, and performance in a PD process [8]. By comparing the contributions of each activity not only to technical performance risk reduction by also to project cost and duration, one can determine each activity's productivity or efficiency in adding customer value [10].

X. PRACTICAL LIMITATIONS OF THE APPROACH

Despite its advantages, the risk value method has some limitations in practice, especially those common to all measures and metrics. For instance, metrics can be "gamed." The PD organization must exhibit proper attitudes toward TPMs and uncertainty if the estimates and measures will be meaningful. If developers merely pad uncertainty estimates to justify more uncertainty reduction activities, the PD process may not be able to clear a business case hurdle or win a contract. Furthermore, no metric is better than the data used to calculate it. Most of the information that addresses 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 technical performance to achieve a correctly balanced product. A strong argument for the risk value method, despite the metrics-related challenges, is that these same, subjective data—used in an *ad hoc*, unsystematic, and unintegrated fashion—constitute the current state of practice.

Perhaps a more fundamental limitation of the approach is that many engineers do not think in terms of fuzzy values. Uncertain data are often exchanged in the design process with no accompanying indication of their precision. Significant digits are often overstated or ignored. Designers must think in terms of "spread" and attend to the amount of uncertainty in their estimates and projections. Becoming aware of the drivers of uncertainty and risk in TPMs can help estimators discern the firmness of their data.

XI. NEXT STEPS FOR RESEARCH

The risk value method illuminates several opportunities for further research. More should be done to explore the sensitivities of TPMs to varied impact functions, especially for cases where customer preferences or requirements are fuzzy. Another opportunity to augment the method lies in drawing a connection to the theory of statistical decision-making (Bayes' rule). These ideas apply to PD inasmuch as each state of a project is based on available information and thus can be modeled as *a prior* and *a posterior*. Also, the decision-dependent (contingent) nature of PD could be explored using an options-based model, where the risk value method is used to calculate the value of specific outcomes. Such a model would be useful in determining the value of options, the price at which to purchase flexibility (cf., [31] and [67]). The model could be used to address questions such as: What is the value of an unexercised option in PD? If a set of activities are done "just in case," as a "Plan B," what value do they add?

Additional research is needed to explore further the impacts of iteration and rework on value and progress in the design process. When does it make sense, based on net customer value, to iterate a group of PD activities?

Another research opportunity is to apply the risk value method within smaller PD activities, helping them ascertain the extent to which information should evolve before it is released (cf., [37] and [64]). Activities could first focus on reducing the risk of near-term deliverables to minimize rework for downstream activities.

There is also great potential to apply the risk value method directly to deliverables instead of to the activities that create them. After all, the products or results of activities are what really add customer value. Some of an activity's deliverables may add more customer value than others. Plus, it may be more natural for engineers to talk about the contribution to risk reduction made by deliverables (i.e., specific information). Deliverable-oriented project management is gaining popularity (e.g., [24] and [30]), and it could lead to deliverable-based performance estimating as well [10].

Finally, what happens if we extend the risk value method to utilize the TPM distribution on both sides of the target? That is, in the current approach, risk $=$ uncertainty$*$ impacts, but what if impacts are negative (rewards) and thus risk is negative (opportunity)? Is the goal of PD risk minimization or opportunity maximization or both? Perhaps it is *both*, yet without mixing them, since mixing them allows opportunities to "wash out" and obscure risks. Clarifying these issues and providing guidance on how to recognize and balance opportunities and risks is an important topic for future work.

XII. 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) [56]

The problems of how to evaluate the status of a product design and how to measure progress and added customer value in PD are very similar. This paper presented an integrated concept and methodology—the *risk value method*—to address these issues. The customer value imparted by 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 to customer value by creating information that increases certainty about the ability of the design to satisfy requirements.

The concepts presented in this paper are not yet widely practiced. Ample opportunity exists for additional empirical research in and calibration to specific settings. Nevertheless, this work integrates several theories and practices into a useful framework. The risk value method really gets more at how customer value is *measured* than it does at how it is actually created. But measures are what guide decisions about what additional customer value remains to be added and, therefore, project planning and control.

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 has confidence in its products. After all, the PD firm has a reputation to maintain. This aspect of certainty is primarily of value to the PD enterprise. However, especially in the case of large, novel, complex systems, "low risk" is clearly a criterion of customer preference (because the customer is really buying a PD process as well as a product). At least in these cases, if not more generally, certainty is of direct value to the customer. *Certainty* also translates into an increased ability for PD project managers to establish and fulfill *commitments* and *expectations*. Recently, a government customer project manager said that *credibility*, manifest as the ratio of expectations met to expectations set, was his primary measure of the value provided by contractors.

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 increases customer value by improving affordability.

APPENDIX
COMPOSITE PERFORMANCE MEASURE APPROACH TO QUANTIFYING PERFORMANCE RISK

Composite Performance Measure

The overall performance of complex products depends on a number of TPMs. During PD, a single TPM may fluctuate like an individual security in a stock market. Moreover, TPMs may be coupled in various ways. To get an idea of the overall performance level of a design, one can use a *composite performance measure* (CPM) or global objective function that may take TPM interactions into account. The CPM discussed in this Appendix provides an alternative approach to (3) for determining overall product performance risk, $\mathcal{R}$.

Several issues make it challenging to construct an acceptable CPM. What approach should be used to evaluate the performance of the overall design? Does it depend on the best *balance* of all the TPMs? How much should extremely good or bad TPMs affect the CPM? How can the CPM account for the relative importance of TPMs? Will the design strategy be aggressive (risk taking) or conservative (risk averse)? These issues influence the type of CPM used. Otto and Antonsson [44] discuss them in detail. Another issue is ensuring completeness of the CPM. Also, it may be important that problems deep within the design surface in the CPM. On the other hand, customer perception of the product may depend mostly on just a few TPMs (such as aircraft payload, range, speed, operating cost, and safety), in which case a simple objective function may suffice for some analyses.

Several types of CPMs have been proposed in the literature. (See [12] and [21] for additional reviews.) The simplest is the weighted, arithmetic mean of the TPMs (e.g., [33]), where weighting factors serve both to represent the relative importance of the elements and to normalize the units. The weighting factors can be determined from customer preferences using an approach such as the *analytic hierarchy process* (AHP—e.g., [41], [72]). The advantage of the arithmetic mean is its simplicity. However, it does not handle outliers well: a TPM of relatively minor importance can ruin a product, but this would not show up in the CPM.

A second approach to building a CPM is the weighted geometric mean. This method is similar to the arithmetic mean except that the TPMs and their weighting factors are multiplied instead of added, and the nth root is taken (instead of dividing by n), where n is the number of TPMs. The geometric mean improves the awareness of outliers, because any TPM close to zero will cause the entire CPM to diminish significantly. However, both the geometric and arithmetic means assume a linear relationship between customer preferences and TPM levels. In fact, customer preferences tend to vary nonlinearly with performance levels (e.g., Fig. 5).

A third method for constructing a CPM is based on *multiattribute utility theory* (MAUT—e.g., [23], [35]). The CPM is based on a multiplicative relationship between scaling factors and single attribute utility curves. The utility levels of each TPM are combined to yield the utility of the CPM

$$U(\mathrm{CPM}) = \frac{\{\prod [K k_i U(\mathrm{TPM}_i) + 1]\} - 1}{K} \qquad (4)$$

where K is a normalization factor, determined such that $U(\mathrm{CPM}) = 0$ when all the $U(\mathrm{TPM}_i) = 0$ and $U(\mathrm{CPM}) = 1$ when all the $U(\mathrm{TPM}_i) = 1$, and the k_i are scaling factors [23, p. 410]. Thurston and Locascio [68], [69] applied MAUT to product design evaluation and tradeoff support.[19] The main drawback to the MAUT approach is its relative complexity and the amount of data required (single attribute utility curves and scaling factors). However, these data are not superfluous; they should already exist somewhere, in some format, in the organization. (If not, then they should be documented and made readily available to product designers.)

Other techniques of CPM construction have also been proposed. Cook [17] presents an approach called multiattribute value theory, a hybrid additive and multiplicative method using marginal changes in TPMs derived through ANOVA. Brink *et al.* [7] use a customer satisfaction index similar to MAUT. Rather than striving for a generic CPM technique, some suggest constructing a unique CPM based on the particular relationships between the TPMs involved (e.g., [4]), yet this may be impractical for complex products. Wood *et al.* [44], [76] present the "method of imprecision" as an alternative to MAUT that can accommodate several types of design strategies. Otto and Antonsson [44] also present four axioms for CPM construction.

Three points remain to be noted. First, the concepts and methods presented in this paper could apply using any of the above methods of CPM construction. Second, the CPM must

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[19] The MAUT approach can also be used in reverse to analyze customer preferences for various product scenarios (combinations of TPMs, features, etc.). A designed experiment can maximize the information gathered from a minimal number of scenarios. Analysis of Variance (ANOVA) can be used to extract scaling factors and single attribute utility curves.

completely span the requirements and items valued by the customer. When a complex system has thousands of requirements, this is tough. Sometimes many requirements can be grouped into a TPM called "defects" or "nonconformances." Third, CPMs are an abstraction, and as such they omit certain information. Some of the information neglected by the weighted mean approach was mentioned above. Bahill *et al.*[3] discuss some of the difficulties and pitfalls in using any CPM. Methods for building CPMs remain a fertile area for further research.

Getting To Product Performance Risk $\mathscr{R}$

When the inputs to the CPM are random variables, the CPM becomes a random variable. Thus, a PDF can represent a CPM as well as a TPM.[20] If the PDF in Fig. 2 represents a CPM, then the requirements line is derived as the CPM of the individual TPM requirements. Additional vertical lines could be added to represent competitive products or alternative market segments. Together, the PDF and the requirements line determine the probability of an unacceptable design. These and an impact function determine the composite performance risk. At the CPM level, the consequences of unacceptable designs may be more obvious, e.g., fewer units sold. Using the PDF of the CPM and an appropriate target and impact function, (2) determines $\mathscr{R}$.

An important issue in risk management is whether it is possible or advisable to "roll up" risks from deep within a design. The rollup tends to obscure individual risks. Looking only at the CPM, how can one determine if the risk stems from one extremely risky TPM or from several low-risk TPMs? Part of the problem can be addressed by the choice of impact function. If a shortcoming in a particular TPM will really ruin the whole project, the impact function (and the scaling constants) should reflect this importance. In some cases, for purposes of identifying risk areas, it may be appropriate to roll up the pessimistic (worst case) TPM estimates. In any case, a CPM should not be used alone. A helpful companion is a list of the critical risk contributors, which falls in line with the approach recommended in the body of the paper.

The body of the paper recommends getting $\mathscr{R}$ by simply summing all $\mathscr{R}_{\text{TPM}}s$ [see (3)]. This Appendix has presented an alternative approach, deriving a CPM using MAUT. In comparison, a weakness of the CPM approach is the difficulty in seeing the effect of large risks in particular TPMs. Other drawbacks to the CPM approach are that it is more cumbersome and it requires sophisticated information about customer preferences. The advantage of the MAUT CPM approach lies in its ability to represent confounding effects among TPMs. Single attribute utility curves assume that customer preferences can be evaluated for each TPM independently. However, customer preferences for most attributes are not independent, especially near the extremes of the utility scale. Case studies comparing the $\mathscr{R}$ values generated by the two approaches (and the effort to obtain them) are needed to identify guidelines for their appropriate use in specific situations.

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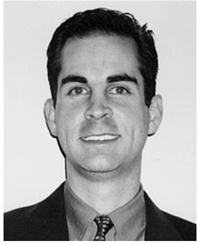


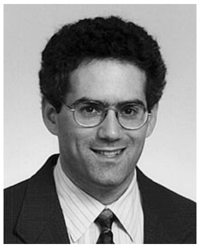
Tyson R. Browning received the B.S. degree in engineering physics from Abilene Christian University, Abilene, TX, and two S.M. degrees and the Ph.D. degree in technology, management and policy (systems engineering and operations management) from Massachusetts Institute of Technology, Cambridge.

He holds the position of Senior Project Manager in Integrated Company Operations at Lockheed Martin Aeronautics Company in Fort Worth, TX. He is the technical lead and chief integrator for a number of teams in developing the enterprise process architecture for the Aeronautics Company. He is also the lead author of company policies and processes driving the transition to a process-based company. He previously worked with the Product Development Focus Team of the Lean Aerospace Initiative at MIT, conducting research at Lockheed Martin, General Electric, Boeing, Raytheon, Sundstrand, and Daimler Chrysler. He has published papers on organizational integration, risk management, the design structure matrix, and process modeling.

Dr. Browning is a member of INCOSE, INFORMS, and AIAA.

John J. Deyst is Professor of aeronautics and astronautics at Massachusetts Institute of Technology (MIT), where he has been teaching and doing research in the general areas of avionics and aerospace product development. Before joining the MIT faculty in 1994, he worked for nearly 30 years as an Engineer and Project Manger on various developments of guidance and control systems for aircraft and spacecraft. His publications include work on fault tolerant systems, control and estimation theory and applications, and methods for enhancing productivity in the development of aerospace systems. He has served on numerous government panels and committees concerned with issues of integrity for fault tolerant avionics and flight control systems; he was a previous Chairman of the AIAA Guidance and Control Committee. Currently he is on the advisory board of the SAE Aerospace Control and Guidance Committee.

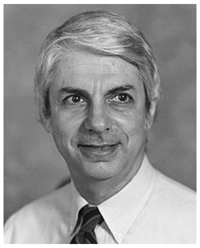
Dr. Deyst is a Fellow of the AIAA.



Steven D. Eppinger (S'86–M'88) received the S.B., S.M., and Sc.D. degrees from the Massachusetts Institute of Technology (MIT), Cambridge, MA.

He is currently the General Motors Professor of Management Science and Engineering Systems at the Sloan School of Management, MIT. He serves as co-director of the Leaders for Manufacturing Program and the System Design and Management Program, both at MIT. His research interests include the management of complex engineering processes. He has published articles in IEEE TRANSACTIONS ON ENGINEERING MANAGEMENT, *Management Science, ASME Journal of Mechanical Design, Research in Engineering Design, Journal of Engineering Design, Harvard Business Review*, and other publications. He also co-authored the textbook entitled *Product Design and Development* (New York: McGraw-Hill, 1995 and 2000).

Dr. Eppinger is a member of INFORMS.



Daniel E. Whitney (M'94-SM'00) is a Senior Research Scientist at the Massachusetts Institute of Technology (MIT) Center for Technology, Policy, and Industrial Development and Senior Lecturer in the Engineering Systems Division. He conducts research on product development, automation, CAD, mechanical assembly, outsourcing strategy, and comparisons of American and Foreign companies. His main activities are in the Leaders for Manufacturing Program, the Center for Innovation in Product Development, the System Design and Management Program, and the Ford-MIT Alliance. He teaches mechanical assembly and product development in the MIT Engineering and Business Schools. Prior to joining MIT, he spent 19 years at Draper Laboratory where he conducted research and consulting on robotics, assembly automation, design for assembly, and CAD tools for assembly processes. He has published over 80 technical articles, co-authored a book on concurrent engineering, and holds a number of patents.

Dr. Whitney is a Fellow of the ASME and a Charter Member of SME/RIA.