A Quantitative Framework for Managing Project Value, Risk, and Opportunity

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Abstract

Projects should create value. That is the desire and plan, but uncertainties cloud the paths to this destination. All project work should add value, in terms of both the resources consumed and the benefits provided (e.g., scope, quality, technical performance, features, and functions), yet adding value is not always straight-forward. Conventional techniques such as earned value management focus on time and cost but do not address quality, uncertainty, risk, and opportunity. An integrated approach is needed to account for all of these. This paper presents an integrated framework for quantifying and monitoring project value in terms of the key attributes that matter to its stakeholders. The framework distinguishes four types of project value: *desired*, *goal*, *likely*, and *actual*. Project management is value management. Project goals, capabilities, risks, and opportunities are evaluated with respect to each key attribute of desired value. The project value, risk, and opportunity (PVRO) framework is useful for project planning, monitoring, control, and tradeoff decision support. An example project, developing a drone aircraft, demonstrates the framework's application to project planning and monitoring, including setting project goals that balance risk and opportunity. New indices for risk, opportunity, and learning are introduced to track project progress and operationalize new constructs for researchers.

Keywords: project management; value management; risk management; opportunity management; technical performance measurement; project quality; project difficulty; setting project goals

1. Introduction

A project is “a temporary endeavor undertaken to create a unique product, service, or result” [4]. Projects are prominent in many industries, such as construction and consulting, and in many types of work, such as product and service development [5]. A project is supposed to create value for its stakeholders. To do so, it must achieve a set of desired outcomes (variously referred to as scope, quality, technical performance, functionality, requirements, etc.) by a deadline and within a budget. This idea of having to balance cost, schedule, and performance has been referred to as the “triple constraint” [4] or the “iron triangle” [e.g., 6]. Furthermore, because a project is an attempt to do something new, once, its time, cost, and performance outcomes are not fully determined until its completion. Before that point, the final outcome in each dimension of the triad is uncertain, bringing risks and opportunities. Project management is the work of delivering project value by meeting the project’s goals. Each decision made by a project manager essentially entails answering the question, “Which choice will add the most value to the project?”

This question is much easier to ask than answer. A great many projects fail to meet their goals (i.e., to provide a planned amount of value). Large, complex projects (or programs) are especially notorious for cost and schedule overruns and late-stage reductions in functionality and performance. Some prominent examples include Denver International Airport [7] and many aerospace systems. And according to The Standish Group International’s “Extreme CHAOS” report [8], even 72% of thousands of short (six months or less), small (up to six people) information technology projects failed to meet all of their goals. In a survey of 120 product development projects at 57 companies, Tatikonda and Montoya-Weiss [9] noted that the average company “reported that it had achieved the objectives … only to a low or moderate extent.” These and other reports suggest that success in terms of time, cost, and performance—indeed, in overall desired value—eludes a great many projects of all kinds.

On relatively simple or well-understood projects, a good project manager may be able to balance the dynamics and uncertainties of time, cost, and performance without formal metrics or decision support systems. However, larger, more complex and novel projects entail so much information—and lack thereof (uncertainty)—about so many people, tasks, tools, components, and possibilities—that effective management requires useful methods for decision support. Perhaps the most widely-discussed framework for measuring project progress and value is earned value management (EVM) [e.g., 4, 10]. However, EVM has several major shortcomings, most notably its omissions of uncertainty, risk, opportunity, and performance (it only accounts for time and cost). An enhanced framework is needed to aid project managers and other stakeholders in gathering, organizing, evaluating, and tracking more of the important information pertaining to project value.

It is essential to distinguish four aspects of project value: *desired*, *actual*, *goal*, and *likely* values. First, stakeholders want a certain amount of value from a project, the project's *desired* value. Second, a completed project provides a certain amount of *actual* value which may or may not match stakeholders' *desired* value. Third, before a project begins, goals (deadline, budget, and technical requirements) are chosen for it that, if met, would yield an amount of value called the project's *goal* value. Fourth, any time before project completion, whether it will meet its goals is uncertain, so the project's ultimate value exists only with some likelihood—i.e., it has a *likely* value. As a project unfolds, the uncertainties in its capabilities and outcomes diminish, and its *likely* value evolves towards its *actual* value—and hopefully also approaches its *goal* value. In some projects, the goals might also change, making the project's *goal* value a moving target. If a project is aiming for the wrong goals, then achieving its *goal* value will not provide the value *desired* by its stakeholders.

Figure 1 shows an example relationship between *desired*, *goal*, and *likely* values at the outset of a project. A project that seems unlikely to achieve its goals (i.e., one with a difference between its *goal* and *likely* values) has a *goal value gap* (GVG), which represents the project's risks of not meeting its goals, given its capabilities. A finished project is usually considered successful if it achieves its goals and its *actual* value equals its *goal* value. But what if the *goal* value "bar" was set too low? Providing the *goal* value will not actually satisfy stakeholders if the wrong goals were chosen. A *stakeholder value gap* (SVG) could also exist, resulting from the selection of inadequate goals.[1] The SVG represents any difference between a project's chosen goals and the goals its stakeholders really desire (which cannot be perfectly known *a priori*). Both the SVG and GVG depend on where the *goal* value "bar" is set: easy (hard) goals decrease (increase) the GVG while increasing (decreasing) the SVG.

[1] Similar distinctions include those between uncertainty in "means" and "ends" [11], "doing the job right" versus "doing the right job," and, in the systems engineering literature, confronting the GVG with verification and the SVG with validation. An SVG is sometimes referred to as market risk.

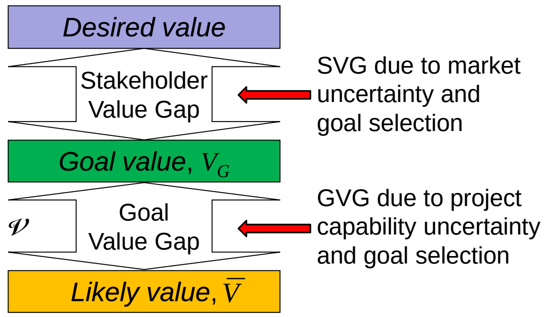


Figure 1: Contrasting the SVG and GVG in terms of setting the *goal* value "bar."

Consider the analogy of a high jumper at a track competition whose capability to achieve a specific height is represented as a probability distribution across a range of potential outcomes. Each jumper has his or her own distribution of outcomes ($\tilde{P}$). Jumpers may be ranked according to their expected capability ($\overline{P}$), although on any given day a jumper could produce an above or below average performance (which is why the competition matters), and this possibility depends on the jumper's consistency (represented by the variation in $\tilde{P}$). Each jumper's risk of not clearing a bar depends on two things: his or her capability ($\tilde{P}$) and the height of the bar (the chosen goals). A low bar (small GVG) implies a high probability of getting over it (and a low probability of not). Raising the bar increases the *goal* value but also increases the risk of failure (the GVG). Lowering the bar decreases the risk (and GVG) but also increases the jumper's likelihood of achieving an outcome beyond the value of the goal, leaving opportunity value "on the table" and perhaps not providing the *desired* value of winning the competition (a large SVG).

Similarly, projects must choose appropriate goals and objectives (set the bar), evaluate their capabilities in terms of their likelihoods of achieving particular outcomes pertaining to each goal, and understand the implied opportunities and risks. For example, a project with a lateness penalty will have less schedule risk as its deadline is relaxed and less cost risk as its budget is increased. Although similar relationships exist with respect to a project's technical performance goals, in contemporary practice these are seldom accounted for in a formal way that integrates with cost and schedule frameworks and allows project managers to compare and trade off cost, schedule, and performance risks and opportunities.

This paper contributes a framework for quantifying these values and gaps and relating them to risks and opportunities in dynamic, uncertain projects. It provides a method for distilling, organizing, and analyzing essential information from diverse areas to facilitate project planning and control. It is firmly grounded in theory and methods from the project management, risk management, marketing, and systems engineering literature. It enables project managers to exploit uncertainties and tradeoffs between time, cost, and performance, and it supports the dynamic re-planning of projects in the face of emerging developments and changing market needs. Throughout the paper, the project value, risk and opportunity (PVRO) framework is demonstrated with a running example, a project to develop a drone aircraft.

2. The Project Value, Risk, and Opportunity (PVRO) Framework

This section presents the components of the PRVO framework and integrates them. Two major components, project goals and capabilities, are introduced separately and then combined to yield project risk and opportunity metrics and value gaps.

2.1 Quantifying a Project's Goal Value

2.1.1 Project Value Attributes

A project seeks to satisfy its stakeholders by proving an outcome they value [12]. A stakeholder is any individual or group with a vested interest in a project or its outcome [13]. Stakeholders include the customer(s), client(s), or market segment(s); the project's owner(s) (the sponsoring firm), including executives, project management, and project participants; suppliers; partners; special interest groups; government regulators; society; etc. Marketing theory suggests that preferences for (or the relative value placed on) something may be modeled as a vector of its attributes [e.g., 14, 15-17]. Such attributes go by a myriad of names in various streams of literature, including stakeholder wants and needs, dimensions of performance, "critical-to-quality" characteristics (CTQs), measures of effectiveness (MOEs), "Whats" (in quality function deployment [18]), critical parameters [19], and value drivers, just to name a few. Adopting this conventional approach, a project and its outcome can be represented as a vector of attributes, each of which can be evaluated in terms of the value provided by the level attained.

Definition 1: The value of a project outcome can be modeled as a vector, ϑ, of *n value attributes*, φ:

$$\vartheta = [\varphi_1 \ \ \varphi_2 \ \ \dots \ \ \varphi_n] \qquad (1)$$

Initially, it may be challenging to determine an appropriate set of prominent, discriminating attributes that account for the bulk of stakeholders' value. Over time, however, firms and their marketing departments can refine this set into the basis for a useful model, often by focusing on the "job" that the project's result does

[20] and the value it provides [12] for its ultimate customers or users. The attributes important to stakeholders may include aspects of the capabilities of the project's result (e.g., power, speed, operating cost, etc.), strategic items (such as establishing a platform for future projects, organizational learning, reputation, and building relationships), and project conditions (e.g., interesting work, networking, career development) [21, 22]. The example drone aircraft project has six primary attributes: Endurance, Maximum Range, Reliability, Stealth, Unit Price, and Delivery Lead-time. It is useful to keep $n < 10$ by emphasizing the top-level attributes most important to stakeholders (and used by them to discriminate among alternatives) and by aggregating lower-level attributes into groups (such as "number of defects") instead of using a separate attribute for each feature or requirement.[2] Although customers and executives care mainly about high-level attributes, these will be determined and influenced by decisions about lower-level attributes.[3] For this reason, "attribute trees" are sometimes used to show how lower-level attributes combine to determine high-level ones [e.g., 18, 23, 24].[4]

2.1.2 Project Value Measures

Each attribute contributes some value to the project. Von Neumann-Morgenstern [25] utility theory [26] and prospect theory [27] (for example) may be used to model how a single-attribute utility function describes the change in stakeholder value as a function of the attribute's level of performance (assuming a satisfactory level of performance in all other attributes). The top center panel in Table 1 shows an example utility function for the drone aircraft's Maximum Range attribute, where the extremes of the *x*-axis span the continuum from "disgusting" to "delighting" the stakeholders.[5] Suppose the primary customer has in mind a specific type of mission requiring a 2,000 nautical mile (nmile) Maximum Range; nothing less will do. Greater Maximum Range is of marginally increasing value, to the point that a Maximum Range of 2,500 nmiles would be delightful. Suppose that an interview with this customer, while accounting for the preferences of other stakeholders, leads to the following utility function (normalized over [0,1]) for various project outcomes of

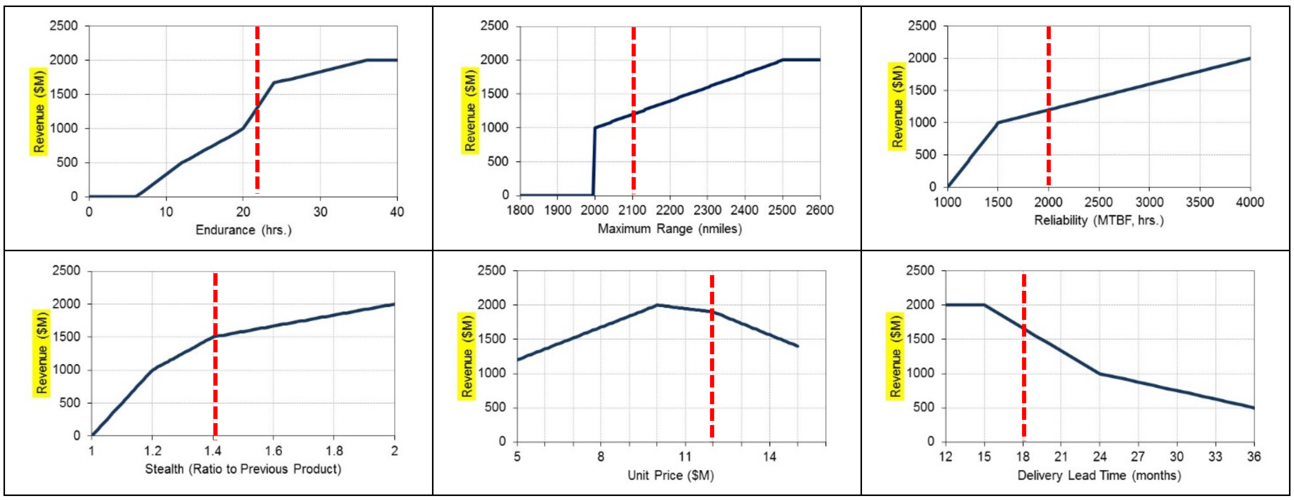
[2] While most attributes will pertain to the outcome achieved (e.g., the attributes of a developed product), attributes may also pertain to *how* the outcome was achieved (e.g., the way the project was carried out, the way the product was produced, etc.).
[3] For example, attributes such as Unit Cost and Delivery Lead-Time are functions of many other attributes, such as development, production, and distribution costs and times.
[4] However, the holistic attributes of a project and product cannot always be derived completely by aggregating lower-level attributes. The appropriate use of lower-level attributes to help anticipate higher-level ones presents an interesting area for further research.
[5] The drone aircraft example is based on data provided by The Boeing Company [28], although the actual specifications of any aircraft are disguised.

aircraft Maximum Range:

$$U_{MaxRange}(x) = \begin{cases} 0 & x < 2000 \\ 0.0004x & 2000 \le x \le 2500 \\ 1 & x > 2500 \end{cases} \tag{2}$$

Three main types of value functions are: larger is better (LIB), an increasing function, as in the top center of Table 1; smaller is better (SIB), a decreasing function, such as unit cost; and nominal is best (NIB), a concave function, where an ideal amount of an attribute provides maximum utility, and more or less than that amount detracts from utility, as in the bottom center of Table 1.[6]

Table 1: Value functions (in terms of revenue) and goals (vertical, dashed line) for the aircraft project attributes.



Value functions of any kind can be challenging to model. Although methods in utility theory and conjoint analysis [e.g., 31, 32-35] are available to address many of the challenges, others remain. A variety of functional forms can be used. A concave function was conventional in the early days of utility theory, but empirical evidence [27, 36] showed that this function often fails to provide a good description of preferences. Thus, Kahneman and Tversky [27] proposed prospect theory with an S-shaped function. Further difficulties stem from the fact that perceptions of value are: subjective, difficult to frame and articulate (especially in novel cases), based on both intrinsic and relative aspects, and dynamic [13]. For example, regardless of the intrinsic characteristics of a project and its outcome, the results of competing projects will affect stakeholders' perceptions of value and success. Moreover, while much of the literature on utility theory deals with individual

[6] Two other types of utility functions include binary, larger target-oriented (LTO), equal to one if a specific amount or more of an attribute is provided, and equal to zero otherwise, and smaller target-oriented (STO), the opposite of LTO [29, 30].

preferences, a project represents the preferences of a diverse set of stakeholders. Perceptions of value will vary by stakeholder and may conflict within a stakeholder group. Various approaches have been proposed to ameliorate this problem, including Thiry's [37] "sensemaking" approach, wherein stakeholders' preferences are elicited in a new, shared paradigm instead of within each individual's own, preexisting paradigm. Some stakeholder conflicts can be represented in a value function by changing its type—e.g., by combining one stakeholder's LIB preferences with another's SIB preferences to yield a NIB value function. Also, when customers' values differ, it is conventional to divide them into separate groups such as market segments [38]. Other stakeholder value disparities may have to be handled on a case-by-case basis. Although taking a broad view of stakeholders (instead of focusing only on a customer) invites these challenges, it also helps uncover unforeseen uncertainties by forcing a broader view of a project's environment and the criteria used to judge its success. Despite the challenges, however, a value function can nevertheless provide a useful model of stakeholders' preferences as they vary with the level of an attribute, and it can often be derived from available market data [39, 40]. In the aircraft example, the utility between specific preference points was assumed via linear interpolation, yielding a set of six piece-wise linear functions, including equation (2).

Often it is desirable to represent value in more useful units than utility theory's conventional [0,1] scale. Two alternatives are anticipated sales and revenue. For instance, the aircraft's sales forecasts may be zero if its Maximum Range is less than 2000 nmiles, 500 units if it is 2000 nmiles, and 1000 units if it is 2500 nmiles or more. Thus, we can render equation (2) in terms of sales volume:

$$\text{Sales}_{\text{MaxRange}}(x)=\begin{cases} U_{MaxRange}(x) & x<2000 \\ 2500U_{MaxRange}(x)-1500 & x\geq 2000 \end{cases} \tag{3}$$

Anticipating a price of $2 million per unit, and substituting equation (2) directly, the total revenue (in $M) is:

$$\text{Revenue}_{\text{MaxRange}}(x)=\begin{cases} 0 & x<2000 \\ 2x-3000 & 2000\leq x\leq 2500 \\ 2000 & x>2500 \end{cases} \tag{4}$$

Organizations frequently use sales and revenue forecasts as a basis for important decisions, so they have developed ways of obtaining actionable estimates. Historical and comparative data often exist to aid in model calibration. The desire is to incorporate this information into a set of value functions.

Definition 2: Stakeholder preference for attribute φ can be represented with a single-attribute value function,

$V_\varphi(x)$. For all attributes, we get a vector of n value functions:

$$\boldsymbol{V}_{\boldsymbol{\vartheta}} = \begin{bmatrix} V_1 & V_2 & \dots & V_n \end{bmatrix} \tag{5}$$

Each V_φ may be expressed in terms of utility, sales, revenue, or other appropriate measure, although the units must be consistent to derive overall project value (discussed later). Table 1 presents the value functions in terms of anticipated revenue for each attribute in the example aircraft project. Whereas Endurance, Maximum Range, Reliability, and Stealth are LIB functions, Delivery Lead-time is a SIB measure, and Unit Price is a NIB measure (balancing customers' preferences for lower prices with the project firm's and its suppliers' preferences for higher prices).

2.1.3 The Goal Value of a Project (V_G)

Project planners are given or must determine a goal (requirement, objective, target, etc.[7]), G_φ, for each attribute.

Definition 3: A set of goals for a project's n value attributes is given by:

$$\boldsymbol{G}_{\boldsymbol{\vartheta}} = \begin{bmatrix} G_1 & G_2 & \dots & G_n \end{bmatrix} \tag{6}$$

Collectively, these goals define "the job to be done" by the project. Doing that job will provide some value.

Definition 4: The *goal value* of a project is the total value provided by achieving the goal (exactly) for each of its n attributes:

$$V_{G\hat{a}} = \sum_{\varphi=1}^{n} w_\varphi V_\varphi \left(G_\varphi\right) \tag{7}$$

where the subscript $\hat{a}$ refers to model $\hat{a}$ and the attribute weights, w_φ, are determined through interactions with stakeholders[8] and normalized such that $\sum_{\varphi=1}^{n} w_\varphi = 1$. Alternatively, V_G can be modeled as constrained by the least valuable[9] goal—here called model $\hat{b}$:

$$V_{G\hat{b}} = \text{MIN}\left(V_1, V_2, \dots, V_n\right) \tag{8}$$

Suppose that the example aircraft project has the following goals (also shown in Table 1): Endurance,

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[7] Although some authors distinguish between these terms, as may be appropriate in some contexts, there is not widespread agreement on the distinctions. Here the term "goal" is used generally and as an approximate synonym for the other terms.
[8] Ullman [41] described a useful method and interactive tool for determining appropriate weights.
[9] The use of the most constrained attribute as the determinant of overall value has been suggested by others [e.g., 42, 43].

22 hours; Maximum Range, 2100 nautical miles; Reliability, mean time between failures (MTBF) of 2000 hours; Stealth, 1.4 ratio to last generation (i.e., a 40% improvement); Unit Price, \$12M; and Delivery Lead-time, 18 months. Using the value functions in Table 1 and $\boldsymbol{w}_{\vartheta}$ = [0.18 0.23 0.18 0.14 0.11 0.16], $V_{G\hat{a}}$ = \$1,418M, which is the anticipated revenue from a project that develops an aircraft that meets the set of goals $\boldsymbol{G}_{\vartheta}$. Meanwhile, $V_{G\hat{b}}$ = MIN(1334, 1200, 1200, 1500, 1900, 1667) = \$1200M, where the project's goals for attributes 2 and 3, Maximum Range and Reliability, constrain its goal value.

Since models $\hat{a}$ and $\hat{b}$ each provide useful insights, the framework will be developed with both. Further empirical investigation is needed to ascertain which model is most useful for a particular situation. Also, these are but two of many models that could be taken: others include a geometric average or multi-attribute utility function. Each approach has advantages and disadvantages. Models $\hat{a}$ and $\hat{b}$ are the foci here because of their relative simplicity (the benefits of which should not be underestimated in practice [44]). Several sources discuss building composite objective functions for multi-attribute optimization [e.g., 45, 46-48], so we will not address all of the issues and subtleties here.

Nevertheless, a few words of general caution are in order. Since value functions will evolve as stakeholders become aware of new wants, needs, priorities, and possibilities, as well as alternative products and services [13], it is important to try to anticipate likely changes in value due to disruptive technologies and competitor actions by using "roadmapping" and scenario planning techniques [e.g., 49, 50]. Stakeholder preferences can also be discovered—and changed, deliberately or inadvertently—through the release of preliminary information or prototypes. Of course, the usual care must be taken in using forecasts of market demand and revenue. Despite these challenges, however, estimates of sales, revenue, preferences, utility, and value are frequently used by organizations as a basis for major marketing, product, and project decisions. While imperfect, the intent is to incorporate the best available information about stakeholder desires into a model that can be easily used by project planners and managers. Also, as organizations become more accustomed to gathering, digesting, and calibrating value data and models, the initial models' accuracies will improve substantially.

2.2 Quantifying a Project's Likely Value

A project's value depends not only on how stakeholders appreciate the job it sets out to do but also on how well it can do the job. It is no use setting high goals if they are unachievable. If a project does not meet its goals, then its *actual value* will be much less than its *goal value*. Before a project is complete, however, its actual value is uncertain and can only be predicted as its *likely value*. A project's capabilities, constraints, and decisions play an important role in estimating and determining its value. Capabilities depend on people, processes, tools, technologies, resources, etc. Characterizing a project's capabilities in terms of the same attributes that determine its value (Equation (1)) enables comparison between its goal and likely values.[10]

2.2.1 Uncertainty in a Project's Capabilities ($\tilde{P}$)

Because it is attempting to do something novel and unique, a project faces uncertainty about whether it will actually achieve its goal value. This uncertainty tends to diminish as a project progresses, as information is gained, decisions are made, events occur (or not), and, all else being equal, less time remains before the end of the project for surprises [51-53]. Although researchers have categorized the uncertainties facing projects by source (e.g., resources, technologies, goals, task durations, or costs) and tractability (e.g., variation, foreseen uncertainty, unforeseen uncertainty, and chaos) [54], this categorization can also be done in terms of the project's value attributes.[11] That is, considerations of uncertainties must be guided by questions pertaining to each attribute, such as, "Given the design and technologies that we plan to use in this project, what will be the Maximum Range of this aircraft?"

To answer such questions, project sponsors and planners must consider the approaches that the project could use, including product, process, and organizational techniques, technologies, resources, personnel skills, facilities, equipment, etc. Planners should have in mind one or more design solutions, sets of tasks, or paths to achieving the goals, including backup approaches—options, alternatives, or contingencies.[12] They should consider both product and process novelties and factors such as process concurrency, formality, and

[10] Although this paper does not discuss any formal mapping of project value attributes (what is desired) to capability components (how it will be provided), such a mapping could be accomplished via a method such as quality function deployment (QFD) [18].
[11] Jaafari [55] claimed that "most risks and uncertainties are associated with the project outcome." Indeed, uncertainties only portend risks to the extent that they have to potential to interfere with a project's capability to meet its goals.
[12] Maintaining sets of design options is explicit in approaches such as set-based design [56].

adaptability [9]. They should also solicit responses from project participants (potential or actual), including a variety of subject matter experts and experienced practitioners [57]. Though such activities, project planners should seek to understand and characterize the range and relative likelihood of potential outcomes for each project value attribute. A form of the Delphi process [e.g., 58] can be very helpful for capturing and refining the best initial knowledge in these areas.[13] Later in a project, other sources of information about uncertainties in project outcomes can emerge from prototypes, tests, simulations, etc. [61].

Knowledge of project capabilities can be represented as a probability distribution[14] for each attribute, $\tilde{P}_{\varphi}$.

Definition 5: $\tilde{P}_{\varphi}(x)$ represents the probability that attribute φ will have outcome *x*. For *n* attributes:

$$\tilde{\boldsymbol{P}}_{\vartheta} = \begin{bmatrix} \tilde{P}_1 & \tilde{P}_2 & \dots & \tilde{P}_n \end{bmatrix} \tag{9}$$

$\overline{P}_{\varphi}$ is the expected value of $\tilde{P}_{\varphi}$ and σ_{φ} is its standard deviation.

In the presence of limited information, one useful approach to defining $\tilde{P}_{\varphi}$ is to seek estimates of the pessimistic, most likely, and optimistic outcomes—*a*, *b*, and *c*, respectively (for a LIB attribute)—and use these to build a triangle distribution[15], where:

$$\tilde{P}(x) = \begin{cases} \dfrac{2(x-a)}{(b-a)(c-a)} & a \le x \le b \\ \dfrac{2(c-x)}{(c-a)(c-b)} & b < x \le c \\ 0 & \text{otherwise} \end{cases} \tag{10}$$

When a triangle distribution is used for $\tilde{P}_{\varphi}$, its mean and standard deviation are given by:

$$\overline{P}_{\varphi} = \frac{a+b+c}{3} \tag{11}$$

$$\sigma_{\varphi} = \frac{a^2+b^2+c^2-ab-bc-ac}{18} \tag{12}$$

Table 2 presents the initial estimates of the capabilities of the example project. Note the fairly wide ranges of

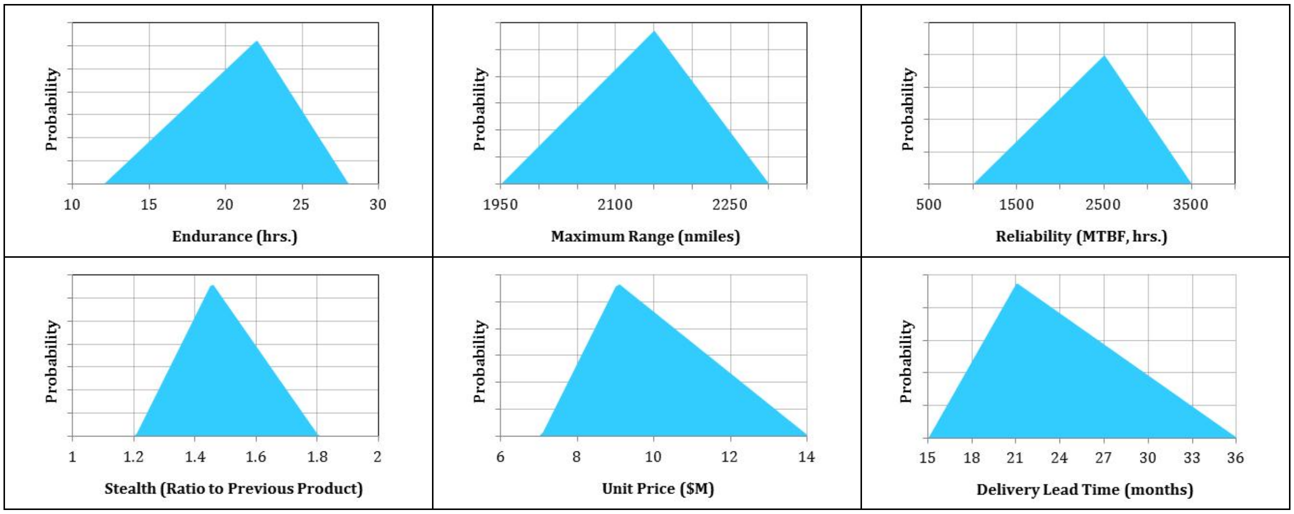
[13] Another interesting possibility for gathering useful data, especially as a project unfolds, is a prediction market [e.g., 59, 60].

[14] In the economics and decision analysis literature, uncertainty is defined as the situation where probabilities cannot be estimated, and risk as the situation where they can [62]. However, this paper follows the conventional definitions of uncertainty and risk in the project management literature [4, 63].

[15] Triangle distributions (1) are useful in practice where only sparse data (such as best, worst, and most likely outcome estimates) are available, (2) retain the advantage of representing skewness, and (3) have precedent in much of the related literature [e.g., 51, 64, 65]. Readers should not confuse *a* or *b* in equations (10)-(12) with $\hat{a}$ or $\hat{b}$ in Definition 4 and elsewhere.

potential outcomes, bounded by projected best and worst case situations. Also, despite differences in their displayed sizes, each triangle is assumed to represent 100% of the possible outcomes of a completed project.

Table 2: Initial capability estimates for the aircraft project's value attributes.



Direct elicitation of these distributions could be augmented or replaced with outputs from models or simulations, as well as historical data, analogous projects, distribution libraries [66], and other forecasting techniques. The literature contains numerous techniques for generating project cost and duration distributions, including parametric estimating techniques [e.g., 67], project evaluation and review technique and critical path method (PERT/CPM) [e.g., 6], Monte Carlo simulation [e.g., 68, 69], etc. Although the distributions have limited justification early in a project, focusing project participants' attention on the estimates of and possibilities for key attributes will encourage updated information to "come out of the woodwork" sooner than it otherwise would. Then, as a project progresses (and on future projects), the distributions will become much better models of the best available knowledge about the project's capabilities regarding each of its attributes. Each of these attribute capability models, and the personnel building and updating them, will become better calibrated with practice and feedback [63].

As with any predictive model, psychological and cultural issues may affect the results. Some respondents may try to mask uncertainties, since they assume that admitting imprecision or a lack of knowledge may be perceived as incompetence. Diagnosing where information is insufficient to justify exactness requires establishing a culture where uncertainty is expected early in a project, and where unjustified precision is viewed with skepticism. On the other hand, overestimating uncertainty is also unhelpful. A respondent who estimates an aircraft Maximum Range outcome between 0 and 100,000 nmiles, if not being facetious, is essentially claiming that no useful information exists, which is highly unlikely. Thus, estimators should draw upon the copious literature on eliciting good estimates from respondents, expert or otherwise [e.g., 63, 70, 71-74]. Of course, estimators must take special care to discern and avoid pressures to justify or impugn a project by "making the numbers come out a certain way." All good practices of estimation and forecasting should be brought to bear.

Building and using even a simple model of the uncertainties surrounding technological capabilities provides a basis for an active, ongoing conversation about which factors are (and are not) accounted for and how. This sets the stage for further uncertainties, possibilities, and threats to come to light and modify the estimates. A project can plan activities, events, experiments, tests, investments, etc. to increase the possibilities of valuable new outcomes and discount others [75], and it can plan activities whose results are expected to reduce the uncertainty in its capability to achieve the attributes [51].

To summarize so far, equation (7) models a project's *goal value* in terms of its most important attributes—i.e., anticipating "the right job" for the project to do. Equation (9) models the project's *likely value* in terms of the potential outcomes for each attribute, representing planners' and participants' knowledge about the project's overall capabilities in each of these important dimensions—i.e., its ability to "do the job right." The PVRO framework accounts for both aspects, because customer preferences and design parameters have been identified as the two main areas of uncertainty [76] and variability [77] in engineering design projects.

2.2.2 The Likely Value of a Project ($\overline{V}$)

The *likely value* of a project is the value of its potential outcomes, weighted by their probabilities (analogous to the concept of statistical expectation).

Definition 6: The *likely value* of a project's capability to provide an outcome for attribute φ is given by:

$$\overline{V}_\varphi = \int_{-\infty}^{\infty} \tilde{P}_\varphi(x) V_\varphi(x) dx \tag{13}$$

Note that in most cases $\overline{V}_\varphi \neq V_\varphi(\overline{P}_\varphi)$ because of the varying slope of the value function.

Definition 7: The *likely value* of an overall *project*, represented by a set of attributes, is given by:

$$\overline{V}_{\hat{a}} = \sum_{\varphi=1}^{n} w_\varphi \overline{V}_\varphi \qquad (14)$$

where the w_φ are specified as in equation (7). Alternatively, $\overline{V}$ can be modeled as:

$$\overline{V}_{\hat{b}} = \text{MIN}\left(\overline{V}_1, \overline{V}_2, \ldots, \overline{V}_n\right) \qquad (15)$$

Note that $\overline{V} \neq V_G$ in most cases (with either model) and that equations (13-15) pertain to an instant in time and will vary with changes in $\tilde{\boldsymbol{P}}_{\vartheta}$. Model $\hat{a}$ allows value overruns in some attributes to compensate for underruns in others, whereas model $\hat{b}$ determines project value only in terms of its least favorable attribute.

For the aircraft example, with $\boldsymbol{V}_{\vartheta}$ and $\tilde{\boldsymbol{P}}_{\vartheta}$ given in Tables 1 and 2, $\overline{\boldsymbol{V}}_{\vartheta}$ = [\$1192M \$1233M \$1316M \$1540M \$1863M \$1126M]. By inspection, attributes 2 and 6, Range and Delivery Lead-time, are providing the least value and pulling down the project's overall likely value. $\overline{V}_{\hat{a}}$ = \$1336M (using the $\boldsymbol{w}_{\vartheta}$ given previously) and $\overline{V}_{\hat{b}}$ = \$1126M (determined by Delivery Lead-time).

2.2.3 A Project's Goal Value Gap (GVG or $\mathcal{V}$)

Definition 8: The *goal value gap* (GVG) of a project is the difference between the instantaneous *likely value* of all of its capabilities and its *goal value*:

$$\mathcal{V} = \overline{V} - V_G \qquad (16)$$

where all three variables may be defined (consistently) according to model $\hat{a}$ or $\hat{b}$. The GVG captures the difference between the project's expected outcomes, given its capabilities, and its goals.

For the aircraft example, $\mathcal{V}_{\hat{a}}$ = \$1336M – \$1418M = –\$82M and $\mathcal{V}_{\hat{b}}$ = \$1126 – \$1200 = –\$74M. Given the prevailing uncertainty in the project's capabilities, these are the anticipated amounts of revenue shortfall relative to the goal value of the project. By either model, the project's likely value is less than its goal value. Positive $\mathcal{V}$ implies a likelihood that the project's actual value will exceed its goal value.

2.3 Quantifying Project Risk ($\mathcal{R}$)

The International Organization for Standardization (ISO) defines risk as the "effect of uncertainty on objectives" [78], meaning that uncertainty only matters insofar as it affects project goals. Since very early work [79, p. 2], and in the project management literature [e.g., 4, 80, 81-83], the risk associated with an outcome has been defined as its consequence weighted by its likelihood:

$$\text{Risk} = \text{Probability} \times \text{Impact} \tag{17}$$

This models risk as the average or "expected loss" from a set of potential outcomes[16] or as the "expected cost of uncertainty." The finance literature discusses the related concepts of "risk exposure" and "value at risk" [e.g., 84]. Equations (5) and (9) provide information about each attribute's potential outcomes, their relative likelihoods, and the value (or lack thereof) of each to the project's stakeholders.

Definition 9: The *impact*, $I_\varphi(x)$, of attribute φ's actual outcome, x, differing from its goal, G_φ, is a value gap:

$$I_\varphi(x) = V_\varphi(x_\varphi) - V_\varphi(G_\varphi) \tag{18}$$

$I_\varphi(x)$ is defined such that a positive impact provides greater value than meeting the goal, whereas a negative impact results from failing to achieve the goal.

Definition 10: The value at *risk* for a LIB attribute is the probabilistically weighted sum of the impacts (value gaps) caused by all adverse outcomes:

$$\mathscr{R}_\varphi = -\int_{-\infty}^{G_\varphi} \tilde{P}_\varphi(x_\varphi) I_\varphi(x_\varphi) dx \tag{19}$$

The leading negative sign cancels the negative values of $I(x)$, making $\mathscr{R}$ a positive term (with deleterious implications). Since any lost value cannot exceed that provided by meeting the goal, $0 \leq \mathscr{R}_\varphi \leq V_\varphi(G_\varphi)$. For a SIB attribute, the integration limits are reversed, from G_φ to ∞. For a NIB attribute, two integrands, a LIB and a SIB, must be combined to capture the risk in both tails of $\tilde{P}_\varphi$ (all outcomes where $I(x) < 0$). For the aircraft example, with $\boldsymbol{V}_\vartheta$ and $\tilde{\boldsymbol{P}}_\vartheta$ given in Tables 1 and 2 and using the $\boldsymbol{G}_\vartheta$ given previously, the initial risks are $\boldsymbol{\mathscr{R}}_\vartheta$ = [\$236M \$66M \$53M \$44M \$63M \$547M]. The largest risks stem from the high likelihoods of Endurance and Delivery Lead-time outcomes that destroy value.

Definition 11: The value at *risk* for an overall project is given by:

$$\mathscr{R}_a = \sum_{\varphi=1}^{n} w_\varphi \mathscr{R}_\varphi \tag{20}$$

[16] For a single event, since it either occurs or does not, the concept of average loss is not necessarily meaningful. Risk indices are mainly used in a relative sense to establish priorities. Most risk indices implicitly assume a *set* of independent events where the occurrence of some and not others will tend towards the probabilistically-weighted average of their impacts.

where the w_φ come from equation (7). Alternatively, $\mathcal{R}$ can be modeled as:

$$\mathcal{R}_{\hat{b}} = \text{MAX}(\mathcal{R}_1, \mathcal{R}_2, \ldots, \mathcal{R}_n) \tag{21}$$

where the value at risk is determined by the single riskiest attribute. In both models, $0 \leq \mathcal{R} \leq V_G$. Model $\hat{a}$ is useful when the majority of outcomes are proximate to their goals for all attributes. Model $\hat{b}$ is more useful when one or more attributes is far from its goal and therefore likely to dominate stakeholder attention. For the aircraft example, $\mathcal{R}_{\hat{a}}$ = \$168M (using the $\boldsymbol{w}_\vartheta$ given previously) and $\mathcal{R}_{\hat{b}}$ = \$547M (due to the Delivery Lead Time attribute). Model $\hat{a}$ expresses the expected loss in value (from the project's goal value) weighted by the contribution of each attribute, whereas model $\hat{b}$ expresses the value at risk due to the single worst attribute. In this project it would probably make sense to start by using model $\hat{b}$ until it is more in line with model $\hat{a}$.

Note that equations (17), (19), and (20) assume a neutral attitude towards risk. While this assumption is useful for comparing the relative contributions to overall project risk from different value attributes, it does not account for the tendency of many to be risk-averse towards extreme impacts [e.g., 63], and it is independent from the decision of how much risk a project would be willing to take on. The PVRO framework supports such discussions and decisions but does not determine them. Also, by highlighting the riskiest attribute, model $\hat{b}$ provides a more risk-averse picture of the situation at the overall project level.

2.4 Quantifying Project Opportunity ($\mathcal{O}$)

Opportunities are uncertain outcomes that would increase a project's value if they happened—the "upside" of uncertainty. Formal opportunity management grew out of risk management, since similar methods can be used to assess both the positive and negative implications of uncertainty [63]. Although mentions of opportunity management are now common in the risk management literature [e.g., 80, 85] and in many firms' methodologies, many projects still place insufficient emphasis on identifying and managing opportunities [86, 87]. Perhaps this is because project managers receive marginally less credit for exceeding expectations than for meeting them, and because engineers are trained to avoid failure rather than illuminate propitious opportunities [88]. Nevertheless, projects can realize dramatic increases in value if they are positioned to seize opportunities that arise. This strategy and capability has been explicitly advocated for projects and managers facing unforeseen uncertainty and chaos [54]. As with risks, many opportunities can be anticipated—if project managers take a proactive stance and project participants are put in that mindset [89]. Indeed, many opportunities *are* anticipated by *someone* associated with a project—but not communicated to project management in an effective manner. Use of the PVRO framework can encourage pertinent information to emerge from project participants.

Opportunity is the "expected gain" implied by the potential of some project outcomes for a value attribute to exceed their goal. It is the expected "benefit of uncertainty" or the "opportunity value," and it can be modeled similarly to risk (equation (19)), although the impacts are positive.

Definition 12: The *opportunity* value for an LIB attribute is given by the probabilistically weighted sum of the rewards of all favorable outcomes:

$$\mathcal{O}_\varphi = \int_{G_\varphi}^{\infty} \tilde{P}_\varphi(x_\varphi) I_\varphi(x_\varphi) dx \tag{22}$$

$\mathcal{O}_\varphi$ is bounded by $0 \leq \mathcal{O}_\varphi \leq V_\varphi(\text{MAX}(x)) - V_\varphi(G_\varphi)$, meaning that the reward attainable through proactive and effective management of opportunities cannot exceed the difference between the project's maximum capabilities and its goal value.[17] For a SIB attribute the integration occurs over the limits $-\infty$ to G_φ, and for a NIB attribute the integration occurs over all outcomes where $I(x) > 0$. $\mathcal{O}$ provides a useful, scalar index of the potential gain above and beyond the goal project value due to the upsides of uncertainties in project capability. For the aircraft example, with $\boldsymbol{V}_\vartheta$ and $\tilde{\boldsymbol{P}}_\vartheta$ given in Tables 1 and 2 and using the $\boldsymbol{G}_\vartheta$ given previously, the initial opportunities are $\boldsymbol{\mathcal{O}}_\vartheta$ = [\$94M \$99M \$169M \$84M \$27M \$8M]. The Reliability attribute provides the greatest opportunity value for exceeding its goal because of the project's strong capabilities in this area—i.e., its high probability of attaining MTBF > 2,000 hrs.

The Reliability attribute also has relatively small $\mathcal{R}$ (as noted prior to equation (20)). An inverse relationship exists between $\mathcal{R}_\varphi$ and $\mathcal{O}_\varphi$, although its degree can vary depending on $\tilde{P}_\varphi$ and V_φ. Table 3 shows how

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[17] Opportunities might stem from exceeding the "maximum" value outcomes—i.e., what was originally determined to "delight" the stakeholders. However, because the value function was originally defined only over a particular region, it would have to be redefined in light of such new information (potentially resetting stakeholder expectations). Thus, the definition of a bound holds, albeit one dependent on $V_\varphi(x)$. Dynamic value functions are mentioned at the end of the paper.

$\mathcal{R}_\varphi$ and $\mathcal{O}_\varphi$ accumulate over the range of outcomes by plotting $\tilde{P}_\varphi(x_\varphi) I_\varphi(x_\varphi)$ for each attribute. (The *y*-axes have identical scale in all six plots, but the *x*-axes differ in scale, thereby complicating visual size comparisons. The vertical, dashed lines represent the goals. Note that because unit price is a NIB attribute, $\mathcal{R}_{\text{UnitPrice}}$ accumulates on both sides of *G*.) The attributes with the highest risks and opportunities are now clearer.

Definition 13: For an overall project, the *opportunity* value, $\mathcal{O}$, is given by:

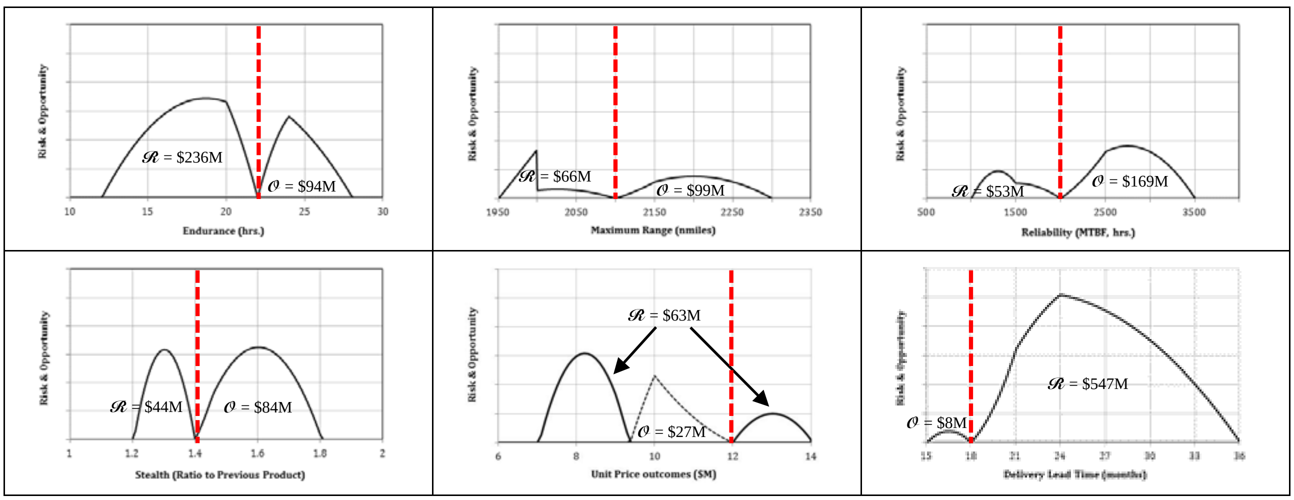
$$\mathcal{O}_{\hat{a}} = \sum_{\varphi=1}^{n} w_\varphi \mathcal{O}_\varphi \tag{23}$$

where the w_φ come from equation (7). Alternatively, using model $\hat{b}$:

$$\mathcal{O}_{\hat{b}} = \text{MAX}(\mathcal{O}_1, \mathcal{O}_2, \ldots, \mathcal{O}_n) \tag{24}$$

In both models, $0 \le \mathcal{O} \le V_{\text{MAX}} - V_G$.

Table 3: Risk and opportunity plots for each value attribute in the aircraft project.



For the aircraft example, $\mathcal{O}_{\hat{a}}$ = $86M (using the $\boldsymbol{w}_\vartheta$ given previously) and $\mathcal{O}_{\hat{b}}$ = $169M (due to the Reliability attribute). Model $\hat{a}$ expresses the expected gain in value (beyond the project's goal value) due to the rewards of the potential positive outcomes, while model $\hat{b}$ gives the expected opportunity from the single best attribute.

Using model $\hat{a}$, the overall risk and opportunity together determine the goal value gap (GVG):

$$\mathcal{V}_{\hat{a}} = \bar{V} - V_G = \mathcal{O}_{\hat{a}} - \mathcal{R}_{\hat{a}} \tag{25}$$

A similar relationship may be stated for each value attribute individually. For the aircraft example, recall that

$\mathscr{V}_{a} = -\$82\text{M}$ by equation (16) and that $\mathscr{O}_{a} - \mathscr{R}_{a} = \$86\text{M} - \$168\text{M} = -\$82\text{M}$ by equations (23) and (20). $\mathscr{R}$ and $\mathscr{O}$ provide greater insight than $\mathscr{V}$ alone, because $\mathscr{V}$ loses information through averaging, whereas $\mathscr{R}$ and $\mathscr{O}$ separate the value-weighted uncertainty in a project's capabilities into downside and upside components, respectively.

2.5 Summary of the PVRO Framework

Table 4 summarizes the PVRO framework's input and output variables. On its own, each of these components can be useful to a project manager. Integrated and analyzed together, they can provide many useful insights for project planning and management.

Table 4: A summary of the PVRO framework's input and output variables.

Inputs		Outputs*	
$\boldsymbol{\vartheta}$	vector of *n* project value attributes, φ	V_G	the project's overall *goal value*; the anticipated value of a project that meets all of its goals
$\mathbf{V}_{\vartheta}$	vector of *n* stakeholder value functions, V_{φ}	$\overline{V}$	the project's overall *likely value*
$\mathbf{w}_{\vartheta}$	vector of weightings of *n* attributes' relative importance, w_{φ}	$\mathscr{V}$	the project's overall goal value gap (GVG) relative to its goals; difference between goal and likely value
$\mathbf{G}_{\vartheta}$	vector of *n* project goals, G_{φ}	$\mathscr{R}$	the portion of the project's overall value at risk; the expected loss in project value due to uncertain outcomes that fail to meet the goals
$\tilde{\mathbf{P}}_{\vartheta}$	vector of *n* project capability distributions, $\tilde{P}_{\varphi}$, representing the prevailing uncertainty in the project's initial capability to provide a particular outcome for each value attribute	$\mathscr{O}$	the portion of the project's overall value at opportunity; the expected gain in project value due to uncertain outcomes that exceed the goals

*Although not shown explicitly, each output is available for each individual attribute, φ, as well as for the overall project.

3. Applications to Planning and Monitoring Project Value

This section presents two example applications of the PVRO framework, setting project goals and monitoring project progress, before concluding with a brief discussion of other types of applications.

3.1 Setting Project Goals

As described in the Introduction, for a given set of project capabilities, $\tilde{\mathbf{P}}$, difficult goals increase $\mathscr{R}$ (the portion of the project's uncertain outcomes that puts its value "at risk") while easy goals increase $\mathscr{O}$ (the portion of the project's uncertain outcomes with value "at opportunity"). This effect was illustrated in Figure 1, where raising the "bar" of goal value decreases the SVG while increasing the GVG. This effect can also be seen for the individual attributes in the aircraft example in Table 3, where the vertical, dashed lines represent the chosen goals. Taking the Endurance attribute for instance, relaxing the goal from 22 to 20 hours allows some of the most probable outcomes in $\tilde{P}_{\text{Endurance}}$ to meet the goal, thereby decreasing V_G and $\mathscr{R}$ while increasing $\mathscr{O}$. By working with the attributes individually and in combination, a project could select goals that provided a desired combination of risk ($\mathscr{R}$) and return (V_G). Focusing on the Endurance attribute, for example, Figure 2 shows $\mathscr{R}$ (solid line) and $\mathscr{O}$ (dashed line) as a function of G (holding $\tilde{P}_{\text{Endurance}}$ constant). When $G_{Endurance}$ = 22 hours (the original goal, indicated by the vertical, dashed line), $\mathscr{R}$ = \$236M and $\mathscr{O}$ = \$94M. As the bar is raised (i.e., as G increases), $\mathscr{R}$ increases. As the bar is lowered, $\mathscr{R}$ decreases but $\mathscr{O}$ increases. Interestingly, when $G_{Endurance}$ = 21.15 hours, $\mathscr{R}$ = $\mathscr{O}$ = \$155M and $\mathscr{V}$ = 0. Given the project's anticipated capabilities and the value function for the Endurance attribute, this setting for $G_{Endurance}$ balances the value at risk with the opportunity value and minimizes the value gap.

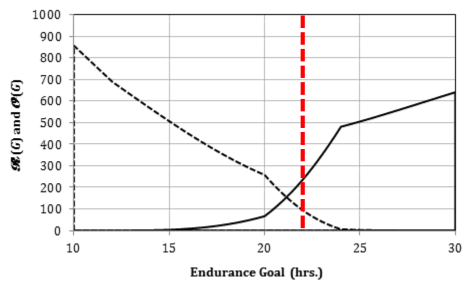


Figure 2: $\mathscr{R}_{Endurance}$ (solid line) and $\mathscr{O}_{Endurance}$ as functions of $G_{Endurance}$, along with an example value of G (vertical line).

Considering all six attributes at once, Figure 3 shows the aircraft project's goal value as a solid black line where an inner offset (red shaded area) indicates the portion of that value at risk ($\mathscr{R}$) and an outer offset (green shaded area) depicts the opportunity value ($\mathscr{O}$). By observation, $\mathscr{R}$ is driven primarily by Delivery Lead-time and Endurance, while $\mathscr{O}$ remains to be claimed primarily in the Reliability attribute. Hence, one way to reduce the project's initial risk is to relax the goal for Delivery Lead Time. Meanwhile, additional goal value could be claimed by increasing the Reliability goal.

Which goals should be changed and by how much depends on the project's risk attitude, as determined by the prominent stakeholders. A risk-neutral project would seek to balance risk and opportunity, whereas a project at a startup firm might be willing to take greater risks to increase the prospect for rewards (value). A conservative (risk-averse) project might seek to lower risks even at the expense of lost value. Yet, regardless of risk attitude, all projects would prefer to increase their goal value with the minimum increase in risk.

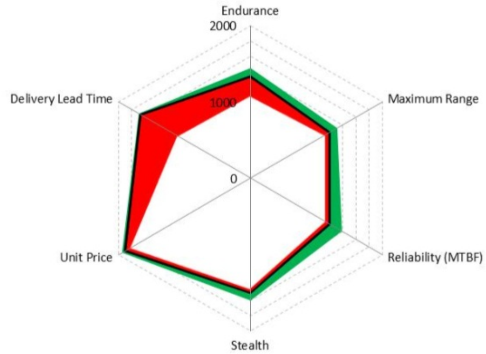


Figure 3: Goal value (solid black line) with offsets for $\mathscr{R}$ (inside) and $\mathscr{O}$ (outside) for each aircraft attribute.

Definition 14: An attribute's *risk-value ratio* is given by:

$$\rho_\varphi = \frac{\mathscr{R}_\varphi}{V_{G,\varphi}} \tag{26}$$

$\Delta\rho$ contrasts relative changes in risk and value as a function of G. For example, increasing $G_{Endurance}$ from 22 to 22.6 hours increases V_G by \$100M, of which \$66M is added risk ($\Delta\mathscr{R}$ = \$66M) and \$34M is claimed opportunity ($\Delta\mathscr{O}$ = –\$34M).[18] Thus, $\Delta\rho_{Endurance}$ = \$66M / \$100M = 0.66. When $\Delta\rho > 0.5$, most of the increased value comes from added risk, whereas when $\Delta\rho < 0.5$ most of the increased value is claimed opportunity. All else being equal, a risk-neutral party would increase G to seize the opportunity when $\Delta\rho < 0.5$. For the aircraft project, when the value of each goal is increased by \$100M (i.e., ΔV_G = \$100M $\forall\ \varphi$), $\Delta\boldsymbol{\rho}$ = [.66 .44 .34 .45 .73 .95]. Hence, the goals for Reliability, Maximum Range, and Stealth would be the best to stretch, while the goals for Delivery Lead-time, Unit Price, and Endurance would be the best to relax.

The implications of stretching or relaxing goals can also be considered in terms of changes in the opportunity to risk ratio.

Definition 15: An attribute's *opportunity-risk ratio* is given by:

$$\theta_\varphi = -\frac{\mathscr{O}_\varphi}{\mathscr{R}_\varphi} \tag{27}$$

$\Delta\theta$ compares changes in $\mathscr{O}$ and $\mathscr{R}$ and, like ρ, can be determined as a function of G. Continuing with the previous example, increasing $G_{Endurance}$ from 22 to 22.6 hours adds \$66M in risk and subtracts \$34M in opportunity. Thus, $\Delta\theta_{Endurance}$ = –(–\$34M / \$66M) = 0.51. When $\Delta\theta > 1$, more of the increased value is claimed

[18] $\mathscr{O}$ decreases by \$34M because $\Delta\mathscr{O} = \Delta\mathscr{V} + \Delta\mathscr{R}$ = –\$100M + \$66M = –\$34M (equation (25)).

opportunity than added risk, which again would indicate to a risk-neutral party that G could be reasonably increased. For the aircraft project, $\Delta\boldsymbol{\theta} = [0.51\ \ 1.27\ \ 1.95\ \ 1.23\ \ 0.36\ \ 0.05]$.

The optimal goals for a risk-neutral project would have $\theta = 1$, $\mathscr{R} = \mathscr{O}$, and $\mathscr{V} = 0$ for all attributes. Figure 2 shows this point for $G_{Endurance}$ = 21.15 hours. Setting $\boldsymbol{G^*} = [21.15\ \ 2116\ \ 2289\ \ 1.45\ \ 12.22\ \ 22.9]$ yields, by model $\hat{a}$, a goal value of V_{G^*} = \$1336M, $\mathscr{R} = \mathscr{O}$ = \$98M, and $\mathscr{V} = 0$. Note that $V_{G^*} = \overline{V}_{\hat{a}}$: *the ideal goals for a risk-opportunity-neutral project depend on its capabilities*. Stretching for goals beyond $\overline{P}$ increases risk at a greater rate than it seizes opportunity. However, capability estimates ($\tilde{\boldsymbol{P}}$) are imprecise, especially at the outset of a project, so they may not provide the full basis for setting goals, which are often influenced by other considerations, such as what is required to be competitive or to achieve a profit. Nevertheless, the PVRO framework can help managers understand the risks implied by any chosen set of goals.

The PVRO framework also supports considerations of whether a project should proceed given its amount of risk (especially if that amount of risk exceeds its goal value). For example, a large, risky project might be deferred until the completion of a smaller, exploratory project with the more limited goals of reducing the riskiness of the larger project. The anticipated costs of the earlier project could be weighed against the expected benefits in terms of risk reduction in the later project.

3.2 Monitoring Project Progress

Progress in projects, especially product design and development, is notoriously challenging to measure [51, 90-94]. However, a promising approach emerges from considering the value of information. Projects consist of activities that create information and knowledge. “Information reduces uncertainty” [95]. Project information has value when it decreases the risk of failing to achieve the project’s desired outcomes [51, 96]. This reduction in uncertainty (i.e., reduced variation in $\tilde{\boldsymbol{P}}$) reduces $\mathscr{R}$ *only when it obviates particular adverse outcomes*.[19] Thus, once goals have been set, the primary lever by which a project manager can decrease $\mathscr{R}$ is by the generation of information through the accomplishment of project work. The rate of information discovery indicates progress [97], which can be quantified in terms of risk reduction [51].[20] Doing project

[19] Merely reducing uncertainty does not necessarily reduce risk. Thus, standard deviation, variance, volatility, and probability alone are insufficient proxies for risk, added value, and progress in projects [51, 63].
[20] Unfortunately, many projects do not plan or track risk reduction [98].

activities is an effort to buy information at some price in project time and cost. All activities should thereby add value [21, 99] by decreasing a project's technical risk more than they increase its cost and schedule risk. "Progress is achieved when risk is successfully managed to create value" [100, p. 238]. The types of actions (including decisions) planned, the order in which they occur, and the results they accomplish all affect the returns on investments in risk reduction [41, 101, 102]. Several papers [3, 28, 43, 51, 65] have demonstrated the effects of activity type, mode, sequence, and outcomes on project cost, duration, and risk.

The PVRO framework supports this view of project value, risk, and progress. Over project time, activities are accomplished and information is produced and acquired that enables revisions of project capability estimates ($\tilde{\boldsymbol{P}}$). These revisions tend to reduce the difference between the best and worst case outcome estimates (*c*–*a* in equations (10)-(12)), thereby narrowing the distributions (q.v., Table 2). For example, Figure 4 shows the progression of Endurance capability estimates over the course of the aircraft development project. (Instead of showing the height of the triangle distributions on a *z*-axis, the base of each triangle is shown as points *a*, *b*, and *c*.) In this example, activity results revise $\tilde{P}_{\text{Endurance}}$ at weeks 10, 17, 19, and 27. Although some of the increased knowledge adjusts *b* downwards (weeks 10, 19, and 27), and other results revise *b* upwards (week 17), all four of these information infusions reduce the difference *c*–*a*.[21] (Indeed, reductions in *c*–*a* seem to be more predictable than changes in *b* [51].) Figure 4 also shows $G_{Endurance}$ (the thick, flat line at 22 hrs.) and $\mathscr{R}_{Endurance}$ (the dashed line) on the secondary *y*-axis. Note that the adjustment to $\tilde{P}_{\text{Endurance}}$ at week 10 has little effect on $\mathscr{R}_{Endurance}$ (it actually increases slightly) because the increase in *a* is more than offset by the reduction in *b*. The information at week 17 improves *a* and *b* and, despite also decreasing *c*, reduces $\mathscr{R}_{Endurance}$. The information at week 19 increases $\mathscr{R}_{Endurance}$ (mainly by lowering *b* and *c*), and the results at week 27 decrease it slightly (mainly by increasing *a*). By week 27, much has been learned about the aircraft's Endurance capability. In this example, the risk remains high because the chances of achieving the goal of 22 hours are very small, although it is also clearer that the Endurance will be fairly close to the goal (i.e., little

[21] Those familiar with the charts used to track the predicted paths of hurricanes know that the band of potential paths expands further into the future. Indeed, forecasts must use expanding confidence intervals the further they project into the future. However, without being able to predict *now* exactly where a hurricane will land in three days, we know that, three days from now, our confidence in such a prediction will be much greater than it is now. The decreasing uncertainty bounds over time in Figure 4 reflect this increased confidence, not merely because time is progressing, but because during this time project work is being done that is creating information that increases knowledge about the ultimate outcome.

chance of an outcome < 19 hours).

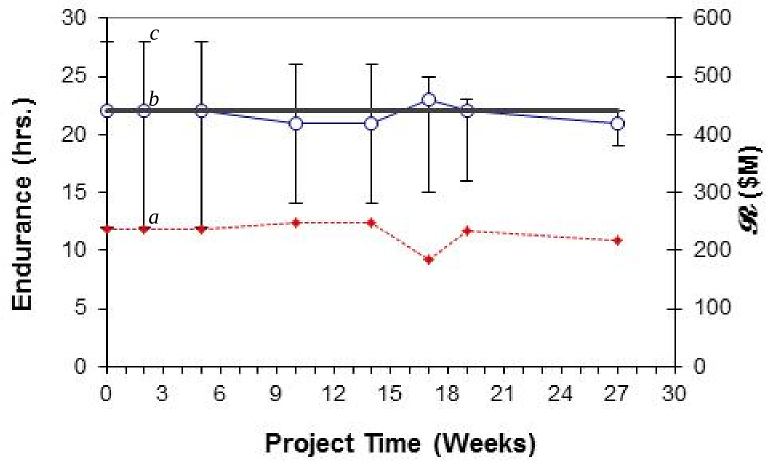


Figure 4: Example behavior of $\tilde{P}_{Endurance}$ and ℛ over project time.

Researchers and managers may also be interested in the amount of learning over the course of a project, particularly as it enables revised estimates of $\tilde{\boldsymbol{P}}$. It has been suggested that learning can be modeled as the rate at which uncertainty decreases [103]. In the PVRO framework, this rate would take the following form:

Definition 16: The amount of *learning* about an attribute's outcome at project time *t* is given by:

$$\lambda_{\varphi}(t) = \frac{\sigma_t}{\sigma_0} \tag{28}$$

where σ_i is the standard deviation of $\tilde{P}_{\varphi}$ (e.g., equation (12)) at time *i*.

For example, Figure 5 compares changes in σ for each of the six aircraft project attributes over time. None of the project's activities produce any information to increase knowledge of the aircraft's stealth capabilities, so $\tilde{P}_{\text{Stealth}}$ remains unchanged. Most of the learning occurs with respect to the aircraft's Maximum Range and Endurance. Because some of these attributes are more important than others to stakeholders, and because learning matters more when the uncertainty is more consequential (risk), it is important to look beyond the mere increase in knowledge to its implications for value.

Hence, a project's risk reduction profile provides additional insight into progress. Figure 6 plots $\mathscr{R}_a$ (equation (20)) for the aircraft project over 30 weeks of the preliminary design phase. As observed in Figure 4, $\mathscr{R}_{Endurance}$ does not change much (even though $\lambda_{Endurance}$ does in Figure 5), and $\mathscr{R}_{Stealth}$, although relatively small, does not change at all (cf. Figure 5). Substantial risk reductions occur with respect to Reliability and

Maximum Range, while the risks pertaining to Unit Price and Delivery Lead-time are only somewhat reduced. Overall, the preliminary design phase of the project reduces $\mathscr{R}_a$ from \$168M to \$109M.

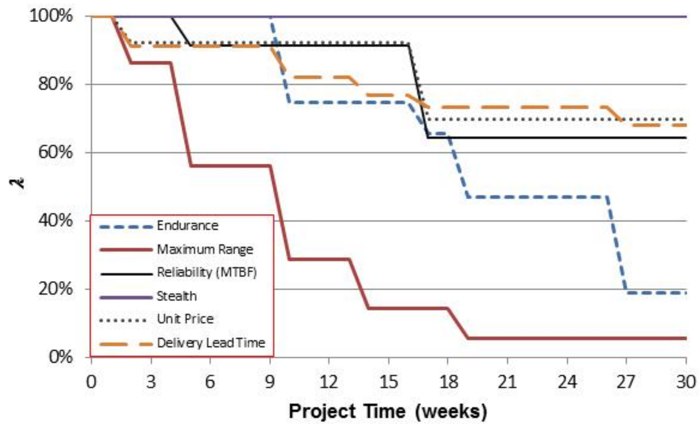


Figure 5: Amounts of learning (λ) about the outcomes of each of six attributes.

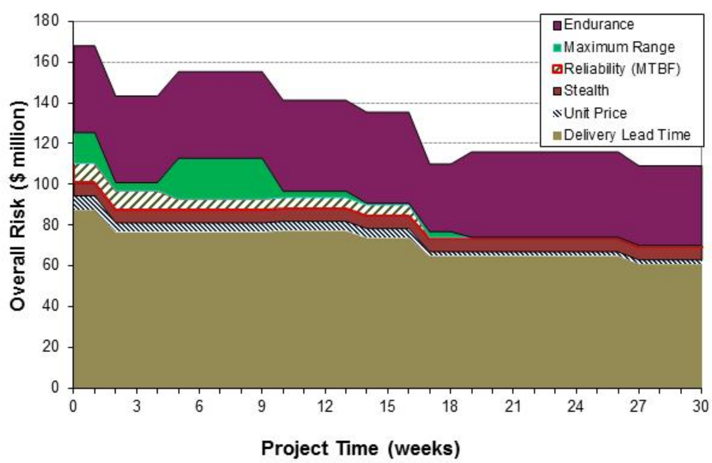


Figure 6: Risk reduction profile for $\mathscr{R}_a$ in terms of its weighted component attributes.

Figure 7 compares the $\mathscr{R}_a$ and $\mathscr{O}_a$ profiles with those of $\mathscr{R}_b$ and $\mathscr{O}_b$. The upper, dashed line in Figure 7 shows the overall risk reduction profile ($\mathscr{R}_a$) from Figure 6. In comparison, $\mathscr{R}_b$ drops from \$547M to \$381M, all due to the updating of $\tilde{P}_{\text{DeliveryLeadTime}}$. Meanwhile, $\mathscr{O}_a$ decreases from \$83M to \$52M—as reductions in *c* (for LIB attributes) and increases in *a* (for SIB attributes) eliminate the possibilities of some desirable outcomes—and $\mathscr{O}_b$ increases from \$169M to \$192M. Typical behavior is for both $\mathscr{R}$ and $\mathscr{O}$ to decrease over project time as $\tilde{\boldsymbol{P}}$ is revised in ways that tend to decrease its variation and bring each attribute's most likely outcome (*b*) closer to its goal (*G*).

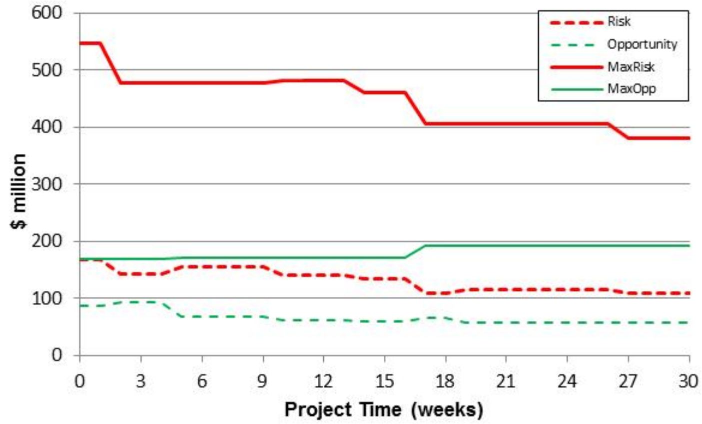


Figure 7: Minimum and maximum risk and opportunity profiles for the example aircraft project.

However, not all profiles that reduce $\mathscr{R}$ are equally desirable. Figure 8 shows three alternative profiles. Profiles B and C are fairly typical for many projects. In profile B, large amounts of risk are allowed to remain until late in the project. As a result of this persistent uncertainty, designs are kept more conservative, decisions are difficult to finalize, and rework is more likely. In profile C, risk is reduced in spurts by the results of particular activities over the course of the project. This profile is more realistic for the risk levels of individual attributes. The most desirable profile in this set is A, where risk is burned down rapidly at the beginning of the project (q.v., "front-loading" [65, 104]), enabling all subsequent activities to proceed with higher levels of confidence and assurance. The achievement of profile A requires the early scheduling of activities with the greatest likelihoods of reducing the most influential risks. "You cannot schedule innovation, but you can schedule arrival of answers to questions that define the utility of technology that's important to you" [105].

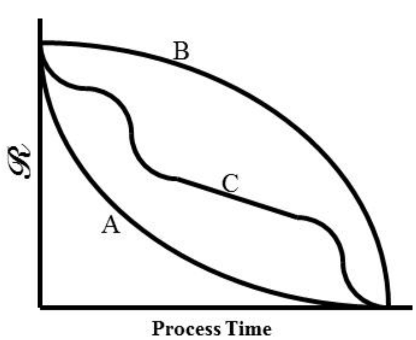


Figure 8: Generic, stylized, alternative profiles for the reduction of risk over project time.

Indices can help a project manager monitor an ongoing project. For instance, tracking the risk-value index (ρ, equation (26)) helps bring focus on the riskiest attributes. Figure 9 plots ρ_φ for each attribute in the aircraft preliminary design project, where the Delivery Lead Time and Endurance attributes continue to place relatively large amounts of the goal value at risk over the course of the project. (Since the goals and value functions are stable in this project, all changes in ρ are due to changes in $\tilde{\boldsymbol{P}}$.) If the risk reduction profile for any attribute does not match the planned profile (ideally something like profile A in Figure 8), then adjustments to the project plan may be necessary. Other indices (akin to those used in earned value management) could be developed to track risk reduction (i.e., "proven value") in terms of time and cost. A project manager could also compare actual progress against planned profiles and set thresholds for raising alarms about deviations.

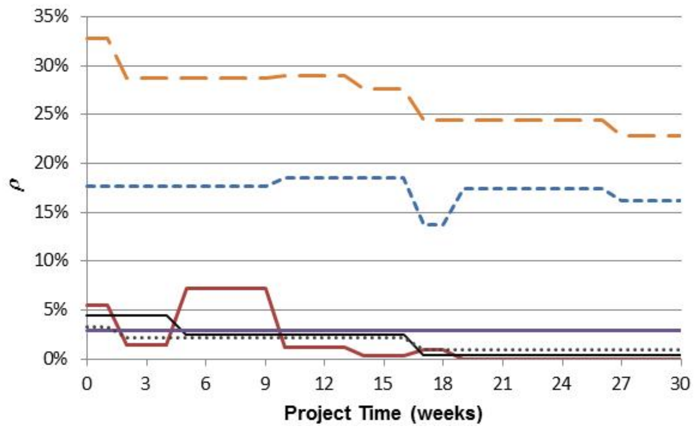


Figure 9: Risk-value ratios (ρ) over project time for each of the six example attributes (see legend in Figure 5).

3.3 Other Applications

The PVRO framework enables a variety of additional applications, many of which provide a way to compare the costs and benefits of managerial actions. All of a project manager's actions (reorganizations, redesigns, reallocation of resources, etc.) should reduce a project's overall risk and increase its value. Project control options—such as reworking existing activities, adding new activities, skipping some planned activities, expediting, delaying, etc.—can be evaluated in terms of their effect on overall project risk and value. Resources can be allocated based on maximizing value across the attributes and for the project overall [106]. The PVRO framework integrates well with approaches such as set-based design [56] and selectionism [107] that seek to manage risk by maintaining multiple paths to success.

Furthermore, the PVRO framework provides a basis for trading off time, cost, and technical performance/quality/scope. With a few exceptions [28, 108, 109, 110—most of which essentially treat these tradeoffs as an elaborated crashing problem], time-cost-quality tradeoffs have not received much attention in the literature, nor do current software tools for project management support such analyses.

The PVRO framework can also facilitate process improvement, where concepts such as lean have advanced the notion of "value-adding activities" [99, 111]. The value of activities can now be examined in terms of their collective effects on project time, cost, technical performance, value, risk, and opportunity. Potential improvements to a project in terms of its people, processes, or tools can be examined in terms of the project capabilities they might add versus the time and cost they might require (which will impact attributes such as Unit Price and Delivery Lead-time).

Although this paper focuses on pre-selected projects, the PVRO framework could also support project selection and portfolio analysis in terms of relative risk and value. And while the examples in this paper focus on product development projects, the framework could also be applied to many other types of projects. However, the framework is expected to apply best to projects that are not dominated by ambiguity and unforeseen uncertainty [107, 112].

4. Conclusion

This paper has presented an integrated framework for quantifying project value, risk, and opportunity. The PVRO framework serves as a basis for several indices that can be used by managers to plan and track projects and by researchers to operationalize important constructs. All of the factors derive from the key attributes that matter to a project's stakeholders. The framework has been demonstrated with a realistic, example project and used to select balanced goals and track progress. The framework is general enough to apply to a wide variety of projects and situations, although it is most useful for projects with a clearly defined set of performance attributes (even though the *outcomes* of each attribute are uncertain). Although novel projects may seem to have unclear attributes, this is usually a temporary situation that can be remedied through stakeholder research and understanding. It has been said that product development projects allow a firm's marketing and technical organizations and environments to co-evolve [113, 114]; the PVRO framework explicitly supports that process by integrating information about attributes of stakeholder value with information about a project's technical capabilities to deliver on those attributes. Much like concurrent engineering overlapped design and manufacturing activities to decrease the likelihood of designing something that could not be easily produced, "concurrent marketing" could furthermore overlap marketing and design to decrease the likelihood of developing something that the market will not want. By simultaneously considering stakeholder values and project capabilities, the framework provides a basis for balancing market pull with technology push.

Use of the PVRO framework forces project developers to define the important value attributes and confront critical uncertainties at the outset of the project. According to Gupta and Wilemon [115], the top two reasons for delays in new product development projects are (1) poor definition of requirements and (2) technological uncertainty, affecting 71% and 58% of projects, respectively. Characterizing the technology capability distribution ($\tilde{\boldsymbol{P}}$) at an early stage, and using it to help set goals ($\boldsymbol{G}$), addresses both of these issues. The framework focuses effort on choosing realistic goals, diminishing problematic uncertainties (risks), looking for ways to seize potentially beneficial outcomes (opportunities), and planning appropriate activities. The framework can be used for "gap analysis" [116]—i.e., assessing differences between a project's goal and likely values—as well as for preventing "surprises," which have been defined as differences between expected (likely) and actual value [117]. Because each decision made by a project manager should reduce the risk of the project not achieving its planned outcome, it has been said that project management *is* risk management [28, 51, 55]. More generally, *project management is value management*. The PVRO framework provides a basis for making this perspective more explicit. Because value is provided by eliminating anti-value (i.e., by reducing risk), this suggests an alternative to the classic definition of a project used to open this paper: *A project is the finite work done to decrease the goal value at risk in a unique product, service, or result* (where $\mathscr{R} = 0$ implies having achieved the chosen goals).

The PVRO framework has several current limitations, most of which provide opportunities for further research and development. Although aspects of the framework have been used successfully in several industrial applications (including projects at Tetra Pak [65], BMW [118], The Boeing Company [51], and a company in the data storage device industry), further applications and empirical investigations are needed. It would be interesting to test the empirical relationship between the shape of the risk reduction profile (Figure 8) and project performance. Models $\hat{a}$ and $\hat{b}$ as well as other potential models for multi-criteria optimization (e.g., multi-attribute utility [28, 119], geometric averages [2], and others [120]) could be compared for best fit to actual situations and managerial decision-making approaches (which may vary in practice). Explicit relationships could be derived for the value of information and maintained flexibility [121] in various circumstances. Further research could also explore situations where stakeholders have varying appetites for risk, or when adversarial stakeholders have competing perceptions of value [99, 112, 122].

Several opportunities exist to extend the framework. For example, explicit relationships could be developed between project duration and product delivery lead-time, project cost and product unit price, and overall life-cycle profitability—although such connections would require assumptions about factors such as production costs, support costs, upgrades, pricing, etc. (As mentioned earlier, however, firms are forced to make such forecasts all the time to support major decisions; such estimates should at least be used in an integrated and consistent way across the executive, marketing, engineering, manufacturing, and customer support functions.) This extension would enable study of and decision support for multi-phase projects, tradeoffs between design and production costs, and tendencies to push risks downstream (e.g., from design to production).

Another extension would be to allow the attribute weights and value functions to be uncertain and dynamic. This would be more realistic in some contexts, because it can be difficult to capture stakeholder values exactly, and they may change over the course of a project. Competitors may offer new alternatives that shift the relative value of meeting a project's goals. For example, the Iridium system met its goals but failed to provide desired value because the stakeholders' value functions changed during the course of the project [123]. The most likely value functions could be bounded by an envelope of higher or lower value functions and represented by a distribution over the intervening range. In such cases, it may make more sense to pursue reducing market uncertainties before worrying as much about uncertainties in the project's capabilities. Research could characterize the conditions under which it is more valuable to pursue decreasing market risk rather than project risk—i.e., when to focus externally versus internally, or when to explore versus exploit—and the value of options in such situations [e.g., 124]. Project value could also change based on other projects in a firm's portfolio: if they target the same market needs or use the same resources, then they could diminish the relative value of a project [125], essentially by altering the stakeholders' value functions.

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