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AN ANALYSIS PROCESS FOR AFFORDABILITY

AND THE RELATIONSHIP TO COST

by

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ABSTRACT

This paper explores the generic concept of affordability analysis, and then discusses the attributes of one method in particular, the Integrated Product and Process Development (IPPD) process. Affordable means obtainable with the means available. Affordability is that characteristic of a system that it does what the customer wants it to do—that is, meets or exceeds the customer's needs—for a price that the customer is willing to pay. An overview of the IPPD process is presented, with emphasis on the desirability optimization methodology for multivariable, multicriterial optimization. An example problem involving material specification and selection of the forming process is used to illustrate the technique. It is seen that different "Best-Value" solutions can be achieved at various levels of investment or product cost. The IPPD process will continue to yield advantages to those who use it. This systems engineering approach to Affordability is a discipline to which the Department of Defense (DoD) is committed. The Affordability process provides metrics that support making good decisions, understanding ramifications of each option, and drawing upon the collective knowledge of the project team in a structured way. There is now a methodology and associated tools that guide one through the process of creating higher value at a lower cost.

INTRODUCTION

During the past decade, customers of aerospace technologies and products have placed ever-increasing emphasis on Affordability. They continue to demand stellar performance, innovative solutions, reliability, and the highest standard of safety—and expect that all will be achieved through a more efficient design process within bare budgets and on tight schedules. This paper explores the ramifications of the concept of Affordability in general and describes a methodology that is particularly applicable to design engineering in the aerospace industry and to materials development and optimization. Because the complex issues in aerospace design require the work of multidisciplinary teams pursuing a common set of goals, the authors describe the systematic, powerful, proven methodology for developing affordable systems and technologies efficiently.

The Integrated Product and Process Development (IPPD) process, developed by the Air Force Research Laboratories (AFRL) and James Gregory Associates (JGA), has been applied early in design or technology development to generate systems or technologies representing the best value among the set of alternatives considered. The "end game" in the IPPD process is improved by constructing and exploring the multidimensional response surface that is the system or technology design space. SynGenics has promulgated the use of desirability functions, having assisted developers with multivariate, multicriterial optimization of products and processes for thirteen years. The powerful desirability optimization methodology has been part of the IPPD process since 1998. Systems and technologies are enhanced using the IPPD process, desirability analysis, and multicriterial optimization.

This process has been applied successfully to a number of aerospace programs, including the Next-Generation Transparency (NGT) program, the Composites Affordability Initiative (CAI), and the Metals Affordability Initiative (MAI), to name a few. AFRL/VA programs currently employing the IPPD process include NGT, the Automatic Air Collision Avoidance System (Auto ACAS), Space Operations Vehicle (SOV), Sensor Craft, Control of Multi-Mission UAV Systems (CMUS), and Structurally Integrated Compact Inlet Technology (STRICT) Demonstration. Other directorates within AFRL continue to apply the process to numerous other programs, with excellent results. The Army and the Navy also advocate the process. A 2002 publication describes how the U.S. Army Multi-Role Armament and Ammunition System (MRAAS) munition-suite program is currently using the IPPD process[1].

The research that formed the basis of this paper was directed toward illustrating how Affordability does not necessarily mean cheapest but, rather, comprises achieving the optimal combination of levels of performance, supportability, and cost criteria. By achieving the proper balance, the best-value solution emerges from the development process. Use of a systems engineering process facilitates the recognition and pursuit of best-value alternatives in the face of numerous competing criteria that aerospace systems typically must meet.

What is new is the degree to which embryonic concepts are evaluated against a complete set of carefully specified criteria to make early decisions that one might otherwise tend to make almost subconsciously when deciding which of the many possible paths to pursue early in a development program. That decision precludes outcomes that might have provided greater value. Careful analysis often helps the team recognize the potential and make a better choice—the one that provides best value. It is the sense of risk, typically unquantified, that often sways subconscious judgment. But the IPPD methodology, which helps quantify risk and support informed choices, often leads to better decisions early in the program to produce better final results.

An important contribution of this paper to the design process is the capability to satisfy multiple criteria by making appropriate decisions in the presence of limited information using the techniques described.

It's About Cost—or Is It?

If one asks what Affordability is, the answer is typically given without hesitation, and most often it focuses on cost. Statements like the following resulted from a survey conducted by the authors. "It's the cheapest." "It is something that costs what you are willing to spend…or less." "It can be purchased within the amount budgeted." Upon further reflection, some respondents incorporated the concept of value: "I think I know what I want. If I can get it for what I am willing to pay, then I will buy it." "If I like it and it means something to me, then I will buy it, no matter what it costs."

The Science and Technology (S&T) view of Affordability was stated by Dr. Lance Davis[2] in his keynote address at the Air Force Affordability Transition Conference, 6 April 1999. He said, "[Affordability is] a style of program management that includes an Integrated Product and Process Development (IPPD) methodology, a mechanism to establish mature processes, an empowered Integrated Product Team (IPT), measures of program effectiveness, and a window of opportunity for technology insertion and transition." The general view of affordability is that something is affordable if it is the least expensive choice that gives one most of what he or she seeks.

The term "Best Value" is often used with the assumption of inherent, universal meaning. But Best Value, like beauty, is in the eye of the beholder. It may represent something different from the perspective of the producer of the product versus that of the user community. The IPPD process and the tools that support it enable the capture of criteria that describe value from each different relevant perspective and facilitate the synthesis of these definitions of value into a set of criteria for the technology or system under development.

Different Best-Value solutions exist at various levels of investment. Hence, the quest for Best Value not only incorporates the concept of a good Return on Investment (ROI) but also an understanding that, as investment cost varies, so does ROI. The resulting function for Best Value is most decidedly nonlinear, as capability response values do not necessarily change in direct proportion to variations in S&T investment or end-item purchase price. Instead, peaks, valleys, and plateaus emerge in the response surface as design and cost parameters vary. Thus, the perception of Best Value is not necessarily a first-order function of cost. Sometimes there are large increases in perceived value as incremental alterations to the budget are considered. These response measures may be continuous functions or may contain discrete steps. A true Affordability analysis must include the concept of investment cost and therefore is enhanced by the use of a cost modeling tool to estimate investment costs.

PROSPECTING FOR POTENTIAL

This paper presents innovative techniques for characterizing and exploring the multidimensional response surfaces for specific capabilities and costs, illustrated with a simplified example, development of a structural component for aerospace applications.

This IPPD process is rooted in industry best practices—Quality Function Deployment (QFD), Balanced Scorecard[3], statistical design of experiments[4], and six sigma techniques[5]—adapted for S&T as described in Brink *et al.*[6] applied to the early stages of design.

A high-level overview of the IPPD process is available in a Quick Reference Manual[7]. The process has been applied to numerous programs sponsored by the Air Force Research Laboratory's Vehicle Aeronautics Directorate (AFRL/VA), resulting in a vast improvement in technology maturity and the potential for transition of technologies emerging from S&T programs. Although the process requires serious commitment of time early in the program and at intervals thereafter, program managers have found repeatedly that the investment pays off in better technology, a higher likelihood of transitioning the technology to fielded systems, and a more efficient, cohesive development program.

The process, by its nature, encourages team participation and synergy among the diverse disciplines represented on a typical project team. Consensus is achieved through the rigor of the process, rather than by virtue of rank or persuasiveness of individuals. The process entails systematic and traceable inputs, in fact requiring them, and provides a framework for "what-if" exercises.

The process is scalable, in that meaningful results will be produced at a level of effort commensurate with the magnitude of the project at hand. This, rather than a one-size-fits-all method, makes it manageable and beneficial for part, component, subsystem, technology, or complex-system development. The level of documentation is similarly flexible and relates directly to the traceability desired.

The forced focus on a single criterion at a time causes practitioners to avoid the necessity of leaping to conclusions concerning what is best given the competing nature of the criteria they intend to achieve. Completing the framework enables an assessment of the sensitivity of measures for each criterion both to design variables and to other criteria.

Not only is the method scalable in terms of size of project, but also, analysis is beneficial at all stages of knowledge within a project, from preliminary understanding and initial concept through availability of detailed data. The metrics within the process reflect the maturity of the information available. The methodology applies to the entire product-realization cycle, from concept development through full-scale production.

IPPD PROCESS

Figure 1 presents the S&T IPPD process, with its six activities represented horizontally in the middle of the figure. All activities are performed by the multidisciplinary project team. The process begins with the identification of needs, defined in the form of formal requirements documents or less formally presented customer desires, and the availability of potential or actual solutions. The purpose of the process in the view of the AFRL S&T

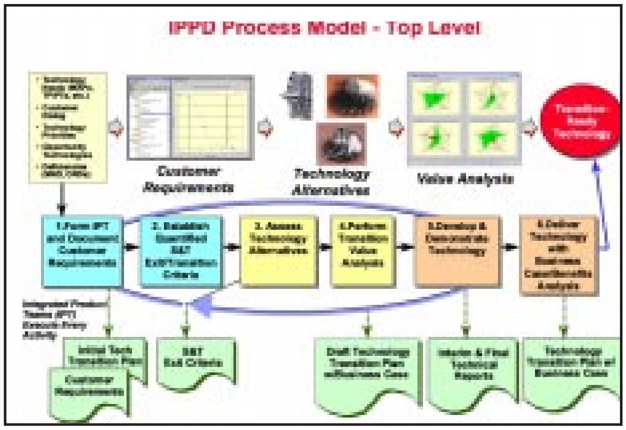

Figure 1. Process Model

community is to generate a technology that is sufficiently mature to transition to the next program element or to the target system.

Information flow among the steps generally feeds forward, but feedback loops and reiterations enhance the benefits of applying the process. The artifacts at the top of the figure allude to the following:

- Requirements tree and desirability curves as a means of capturing the "voice of the customer"
- Technology alternatives and Worksheets, which capture the detailed data for each alternative
- Value Analysis graphics and the Value Scorecard, which summarize data formatted for ease of use by decision makers.

CUSTOMERS AND CRITERIA

The first activity of the IPPD process involves identifying customers and stakeholders and establishing a set of criteria by which each would evaluate the system or technology being developed. Once a set of criteria is established for each customer/stakeholder, a synthesized set for a "Composite Customer" is created. This set is used for managing the program.

The terms "requirements" and "criteria" are used somewhat interchangeably in this discussion; however, more rigorous usage might reserve the term "requirements" for those formally specified by the user community of the Department of Defense (DoD). Requirements in that sense would be a subset of the criteria for a program. Critical to the success of IPPD applications is the effort devoted to capturing criteria.

One set of criteria should be documented, one requirement at a time, for each identified customer. Engineers tend to compound metrics, specifying mathematical operations on individual measures of performance and cost. Ratios and more complex formulae are commonly used as figures of merit. Using desirability methodology permits the luxury of treating criteria individually, giving careful consideration of each one without the need for creative mathematical relationships that sometimes lead to simultaneously representing several program goals, necessarily relegating other important ones to the status of constraints.

A requirements spreadsheet or a method such as the House of Quality (HOQ) may be used as the structure for requirement documentation. How requirements are captured is less important than *that* they are captured with appropriate detail. Each criterion should be measurable on a scale agreed to by the project team. Attributes of the documented criteria include

- Name and description
- Unit of measure
- Customer
- Priority
- Objective
- Threshold(s)
- Desirability function
- Type
- Weighting factor within type.

The objective is the "ideal" criterion value that the customer would like to see achieved—the value that, when exceeded, often results in diminishing returns. It may be established with recognition of real-world constraints, but it should represent the best outcome envisioned from the current program.

A threshold value is that value established for each criterion that must be met. It is the boundary of the range of acceptable values for a criterion.

Organizing requirements into types is convenient, especially if the number of criteria exceeds a dozen. The construct of Type supports the natural tendency to categorize criteria into performance measures, supportability criteria, cost metrics, etc. Each criterion is assigned a numerical weighting factor commensurate with its importance relative to the others within the same type.

Measures of Merit

The process provides two new measures of merit: desirability and risk. These augment the typical set of engineering metrics, costs, human-factors assessment results, and other measures by which, absent application of the IPPD process, one would normally analyze the effectiveness, appropriateness, and value of the thing under development.

Desirability is a measure of "goodness" on a zero-to-one scale. Zero is defined as unacceptable, while one connotes complete customer satisfaction. When desirability is one, there is no benefit in seeking further improvement.

Risk, also measured on a zero-to-one scale, is the probability of failure to meet a threshold. Risk is expressed as "zeta" (ζ). Both desirability and risk values are specific to a customer or stakeholder.

Desirability and risk each may be calculated at three levels: the criterion level, the type level, and overall. These measures of merit retain their meaning at each level. Desirability remains a measure of customer satisfaction; zero continues to denote the unacceptable and one continues to signify complete customer satisfaction with no benefit for further improvement. The risk measure for a single criterion is the probability of failure to meet the threshold(s) for that criterion. The risk for a set of criteria organized by type (e.g., Performance) is the probability of failure to meet one or more of the thresholds for criteria within the type. Overall aggregated risk is the probability of failure to meet one or more thresholds of criteria of any type.

Desirability and Exit Criteria

The desirability function used in the IPPD process was documented by Derringer and Suich[8] for use in the simultaneous optimization of several response variables. Denoted d_i for i^{th} criterion, it is a mathematical function that maps the criterion measure, in its units, to the nondimensional desirability scale. Like the Taguchi Loss Function[9], desirability functions may assume three forms: *more is better*, *less is better*, or *nominal is best*. For the first two, $d = 1.0$ at some point, typically the objective, and beyond; $d = 0.000$ at some other value, and beyond. Aside from the fact that the desirability curve must be monotonic between these two points, only the rate of change of customer satisfaction with respect to the criterion value determines the shape of the curve. When some nominal value is best, a two-sided desirability curve is used. It is constructed in two parts, as if one each of the first two types were created and joined at the objective, where $d = 1.0$.

Once the set of criteria is established for a single customer, accomplishing the same for additional customers typically flows easily. Name, description, and unit of measure define a requirement class. An instance, defined for each customer, has its own objective, threshold(s), desirability function, and weighting factor. The "constructed" set of requirements for the "Composite Customer" is determined by examination of the customer-specific instances of each criterion, organizational goals, and programmatic issues. Once again, objective, threshold(s), desirability function, and weighting factor within type is specified for each criterion. "Exit Criteria" comprise that subset of the constructed set; meeting the Exit Criteria defines program completion. Thus, some "nice-to-have" criteria would be omitted from the exit criteria.

Value Analysis

Data required for value analysis include the assessment of each alternative under consideration against each criterion. Required is a prediction of the response, in the unit of measure of the criterion, not as a point, but as a distribution of future outcomes. Often, the normal distribution is assumed and the prediction is characterized by an expected value and a standard deviation. Once a prediction is generated for each criterion class, the most difficult part of the value analysis is completed. These predictions are generated by a variety of means, depending upon the availability of data and the maturity of the technology involved. Methods ranging from expert estimation and engineering judgment to detailed cost modeling and statistically designed experiments are used. The predicted distribution of the response and the attributes of the criterion permit the calculation of d_i and ζ_i.

A Worksheet covers a single alternative evaluated against one type of criterion for a single customer. Desirability and risk for the criterion type are the bottom-line measures on a Worksheet. Aggregation of desirabilities from a lower level is accomplished using a weighted geometric mean as described by Ventresca[10], computed as in Equation 1:

$$D_T = \left(\prod d_i^{w_i} \right)^{1/\Sigma w_i} \qquad (1)$$

where D_T is the composite desirability for type T, d_i is the desirability for criterion i within type T and w_i is the weighting factor for criterion i within type T.

The risks are aggregated into a ζ in accordance with the Poisson formula:

$$\zeta_T = 1 - e^{-\Sigma \zeta_i} \qquad (2)$$

where ζ_T is the probability of failure to meet one or more thresholds for criteria within type *T*, and ζ_i is the probability of failure to meet the threshold(s) for criterion *i* within type *T*.

Value Scorecard

The Value Scorecard consists of one "Type Scorecard" for each type of criterion and one "Affordability Scorecard", which presents top-level results. Like the Worksheet, the Value Scorecard is customer-specific.

The Type Scorecard presents multiple alternatives for all criteria of the given type for a single customer. The metrics for each criterion come from the corresponding Worksheet for each alternative presented. They include expected value, d_i and ζ_i , as well as D_T and ζ_T . The Type Scorecard facilitates identification of risk drivers and technical challenges. Type Scorecard results might lead one to redirect program funding to reduce risk or suggest fall-back strategies and the formulation of rules concerning when the strategy should be invoked.

The Affordability Scorecard presents multiple alternatives for all types of criteria for a single customer. It contains a column for each type of requirement and displays D_T and ζ_T for all alternatives. The top-level metrics are presented in the rightmost "Affordability" column. These are Customer Satisfaction Index (*CSI*) and aggregate risk (ζ_A). A weighting factor (W_T) is assigned to each type of criterion to signify its importance in comparison to other types. *CSI*, being a composite desirability function, is computed as the weighted geometric mean of the composite desirability for each type:

$$CSI = \left(\prod D_T^{W_T} \right)^{1/\Sigma W_T} \qquad (3)$$

The aggregate risk (ζ_A) is calculated using the Poisson formula in Equation 4.

$$\zeta_A = 1 - e^{-\Sigma \zeta_T} \qquad (4)$$

The Value Scorecard for each customer may be used to communicate directly with that customer concerning the benefits of the technology or system under development. It may also be used to identify risks. The Value Scorecard for the Composite Customer is used to influence program-management decisions, to identify risks and interdependencies, and to redirect program resources.

Decision Support

Applying this process early in a program permits the team to zero in on the alternatives most likely to lead to success. Having codified the definition of success, the team is more likely to be unified in pursuit of the goals. The process is typically revisited every quarter to revalidate the criteria and to refine the assessment of alternatives.

This process applied to disparate alternatives leads to selection of the most promising and sometimes to generation of different alternatives, because the Value Analysis highlighted the strengths and weaknesses of those under consideration. Often, the decoupling of criteria and the viewing side by side of alternatives that might have been disqualified out of hand along with others that were thought to be leading contenders inspires ideas for new alternatives that would not have been generated absent the rigorous analysis of the IPPD process.

Optimizing the Alternative of Choice

Once the focus has turned to a particular solution principle, the remainder of the project becomes refining it to meet the program objectives (Exit Criteria). The multiattribute desirability optimization methodology was described by Ventresca[10] in 1991. Jaggers *et al.*[11] describe a materials optimization using the methodology. The optimal formulation for a material was derived to achieved the physical properties desired, as well as producibility and cost criteria. Moreover, two very different optimal formulations were discvered for two customers, one of whom emphasized low price while the other was willing to pay a much higher price for vastly improved physical properties. After numerous attempts using other methods, the manufacturer was extremely pleased to be able to satisfy a high-volume, albeit low profit-margin customer. More importantly, he was ecstatic to have discovered, at no extra investment in research, a high-margin product for another customer whom he thought could not be satisfied.

This method involves identifying design variables that relate to one or more criteria and generating relationships between the response measures and the design variables. The levels of the design variables are evaluated in different combinations to produce predictions of response values, typically using statistically designed experiments and response-surface methodology[12]. Regression analysis is performed on the response values generated through modeling or experimentation to produce functional relationships that predict the response value at any combination of values of the design variables. A composite desirability function is maximized to determine the optimal values of the design variables. The example in the next section illustrates this technique.

Example

The process described in this paper applies to multicriterial problems of this magnitude, as well as larger ones. As a means to illustrate the technique, a simplified example was created based on experience with AFRL/VA programs in structures.

This example development project involves both material specification and selection of the forming process. Specifics of the material composition and manufacturing process are hypothetical because of the proprietary nature of the work from which the example was drawn, but sufficient information is provided to explain the analysis process.

The material must be strong, light weight, durable, nonporous, thermally conductive, corrosion resistant, and easy to repair. Parts produced should possess required surface-quality characteristics and should be easy to form, easy to inspect, resistant to warpage during manufacturing, etc. In the actual program, nine alternatives were evaluated against fourteen criteria. These alternatives included steel, aluminum, numerous alloys, and ceramics.

As is typical, the options included solutions that differed qualitatively; the influential factors were different, and the physical principles that determined their properties were distinct. This is typical of design alternatives, and the Value Analysis process provides the means to select the most promising of the disparate options for further analysis. A Value Analysis was performed to select the alternative with the best chance of satisfying the criteria. “Obtainium 4” was found to be the best-value solution. This alloy was then optimized to maximize its capability to meet the objectives of the program.

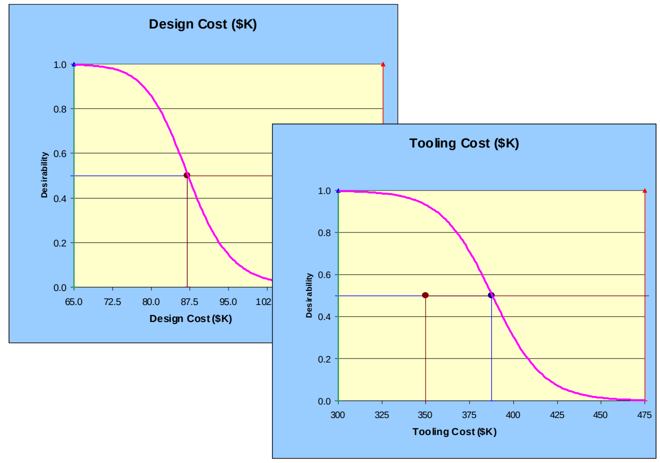

Figure 2. Desirability curves for two cost criteria

Responses

Criteria chosen for multivariate optimization are those affected by one or more of a set of factors that can be manipulated. Also, the response value for each can be quantified in the presence of varying levels of factors, either by empirical means, computer modeling, first principles analysis, or other means. They may be a subset of the criteria used in the down-select, or they may include other metrics that reflect the goals of the detailed design process. Often, engineering and process variables are included at this stage.

This example involves six criteria:

1. Design Cost, measured in thousands of dollars, representing the nonrecurring cost of all the design activities resulting in the design of the part and its forming process using the material selected

2. Tooling cost, measured in thousands of dollars, a nonrecurring cost that includes the cost of the tool material, any hardware, fittings, connectors, heating or cooling lines, buildup of the tool block, machining or polishing the tool surface, if required—all costs associated with making the tool available for production

3. Time to form part, measured in minutes, is process cycle time for part formation

4. Warpage, measured as microinches of deflection per inch of longitudinal part dimension.

5. Surface defects, measured as the probability of rejecting a part due to the presence of specified surface defects and the quality inspection standard

LinearPlusInteraction

Dependent Variables	Composition (Independent Variables)	Processing (Independent Variables)	Response	Standard Deviation	Goal	Desirability	Robustness	Lower Threshold	Objective	Upper Threshold	Zeta
Design Cost ($K)	0.00000	10.40678	75.13559	10.27000	Minimize	0.955	0.954		65	125	0.0000
Tooling Cost ($K)	0.00000	46.93220	353.14407	53.46000	Minimize	0.407	0.393		300	400	0.1904
Time to Form Part (min)	-10.71250	1.61483	28.19475	4.74000	Minimize	0.859	0.843		24	36	0.0498
Warpage (10-3 in per in)	1.96875	-0.13455	1.44618	0.77200	Minimize	0.429	0.422		0.2	4.5	0.0000
Surface Defects (Pr)	-1.05882	0.00000	2.70626	1.09800	Minimize	0.811	0.808		0	8	0.0000
Thermal Conductivity	0.46250	0.01130	0.69498	0.18600	Maximize	0.744	0.738	0.1	0.9		0.0007

	Composition	Processing		
Design Set Point:	-0.389241785	-1	Overall Desirability:	0.626
Robustness:	0.626	0.619	Overall Robustness:	0.622
Lower Limit:	-1	-1	Sum of Zeta:	0.24093
Upper Limit:	1	1	Probability of Success:	0.785897

Figure 3. Design space exploration

6. Thermal conductivity, measured in Watts per square centimeter per degree Kelvin (W/cm^2-K).

For criteria 1–5, less is better. For the sixth, more is better, because high thermal conductivity enables the part to dissipate heat. After the criteria and their units of measure were specified, objectives and thresholds were established for all. A desirability function was created for each criterion. Two of the six are shown in Figure 2. The figures in this section are screens from a software tool, SynGenics.com, created to facilitate multivariate, multicriterial desirability analysis directed toward product and process optimization.

Analysis

The behavior of the material composition and processing approach was evaluated in seven trials, during which data were collected on all six responses. For design cost and tooling cost, analysis was performed to estimate for each of the seven cases the expected cost and the uncertainty, expressed as the standard deviation of the cost estimate. Formation time, warpage, and surface defects could have been determined experimentally. In fact, for this illustration, values were derived from data from a structures development program, modified to prevent disclosure of proprietary data. Thermal conductivity was calculated based on published thermal properties of materials.

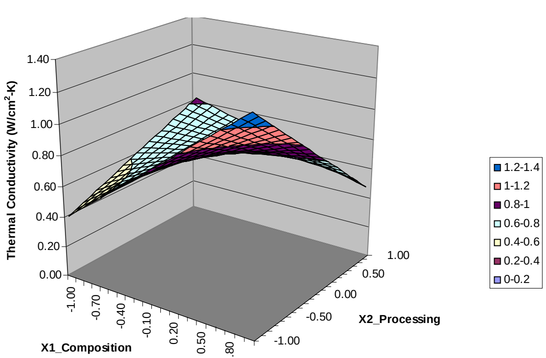

Figure 4. Surface plot of thermal conductivity as a function of the factors

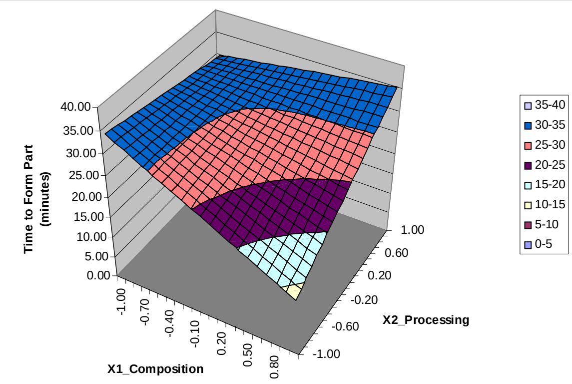

Figure 5. Surface plot of time to form part as a function of the factors

The factors are chosen for analysis because, alone or in combination, they are hypothesized to have a causative effect on at least one response of interest. The design variables, *X1_Composition* and *X2_Processing* are coded variables, simplified for the purposes of this illustration and coded, again, to protect the proprietary nature of the work on which example is based.

Results

Figure 3 shows the predicted responses for each criterion and the optimal values of the design variables, which were derived by maximizing composite desirability. The surface plots of Figures 4–6 depict, respectively, the behavior of thermal conductivity, forming time, and warpage over the range of interest for the independent variables (factors). Figure 7 is a contour plot of surface quality. The competition among criteria is evident from the plots.

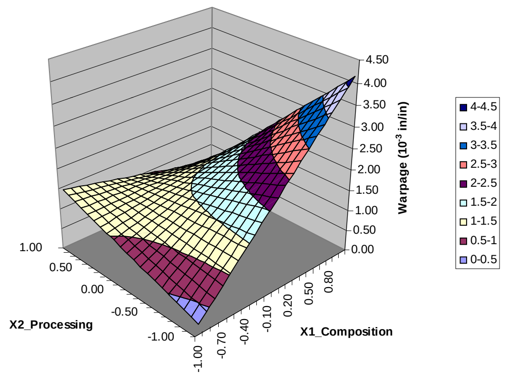

Figure 6. Surface plot of warpage as a function of the factors

The response surfaces illustrate the 3-dimensional predictive models generated during the analysis. (In a typical problem, there would be many more factors, and the response surface would be (*n*+1)-dimensional, *n* being the number of factors.)

The models were exercised to predict a mean response for each criterion, as shown in the "Response" column of the Design-Space table. The composite desirability response surface is shown in Figure 8, which corresponds to the data in Figure 3. The optimal design set point (*X1* = -0.389 and *X2* = -1.000) is located at the top of the desirability hill.

To investigate the effect of level of investment, the design cost threshold was increased from $125K to $325K, and the tooling cost threshold was increased from $400K to $475K. In addition, the cost desirability curves were modified to reflect the changes. Repeating the optimization process resulted in a different optimal design set point of (-0.295, -0998). (See Figure 9.) It is seen that tighter or looser constraints on investment in design activities or tooling result in different optimal solutions.

Sensitivity Analysis

What-if analyses produced some interesting results. To explore optimality with respect to physical and quality criteria in the absence of cost constraints, the weighting factors for tooling cost and design cost were set to zero. The optimal design set point moved to the opposite quadrant of the *X1*-*X2* design domain, to (0.58, 0.32). See Figures 10–12.

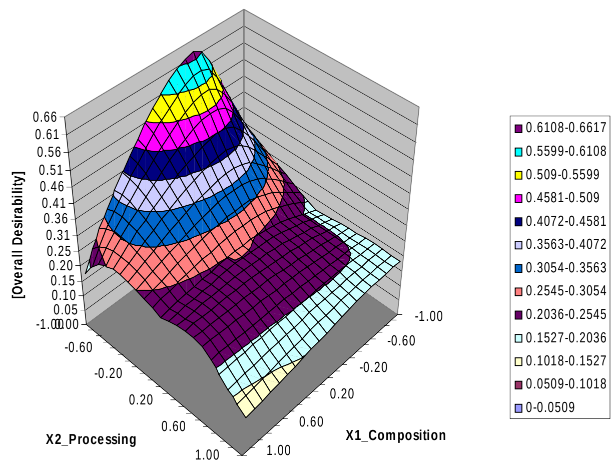

Figure 8. Surface plot of composite desirability

Finally, an analysis of cost versus risk was performed. Figure 13 illustrates the results for seven cases. The lowest risk options were the fourth and fifth most costly, not, as one might have presumed, the most expensive. The "sweet spot" was found at $95K design

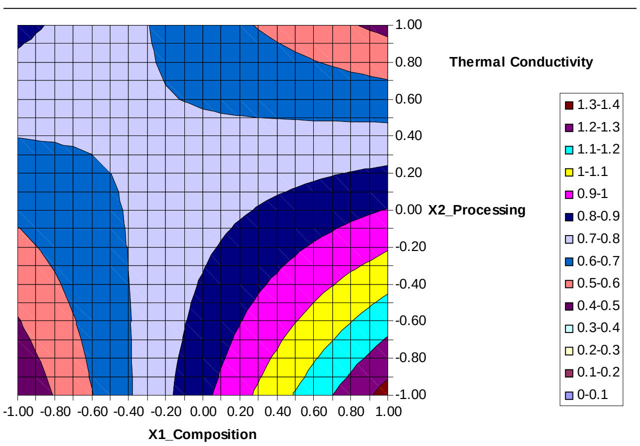

Figure 7. Contour plot of surface quality as a function of the factors

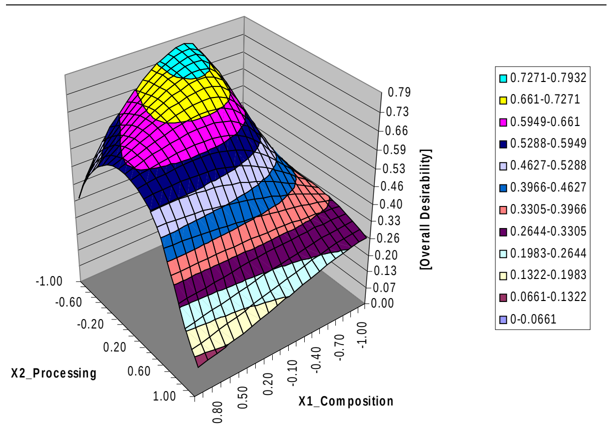

Figure 9. Surface plot of composite desirability under loosened cost constraints

LinearPlusInteraction	Independent Variables					
	Composition	Processing	Response	Standard Deviation	Goal	Desira-bility
Dependent Variables						
Design Cost ($K)	0.00	10.41	88.90	10.27	Minimize	0.389
Tooling Cost ($K)	0.00	46.93	415.24	53.46	Minimize	0.009
Time to Form Part (min)	-1.90	8.09	28.49	4.74	Minimize	0.820
Warpage (10-3 in per in)	0.37	-1.31	1.63	0.77	Minimize	0.367
Surface Defects (Pr)	-1.06	0.00	1.68	1.10	Minimize	0.961
Thermal Conductivity	0.04	-0.30	0.75	0.19	Maximize	0.810
Design Set Point:	0.58	0.32		Overall Desirability:		0.661
Robustness:	0.661	0.660		Overall Robustness:		0.660
Lower Limit:	-1	-1		Sum of Zeta:		0.6693
Upper Limit:	1	1		Probability of Success:		0.5121

Figure 10. Design space page after optimization absent the influence of cost criteria

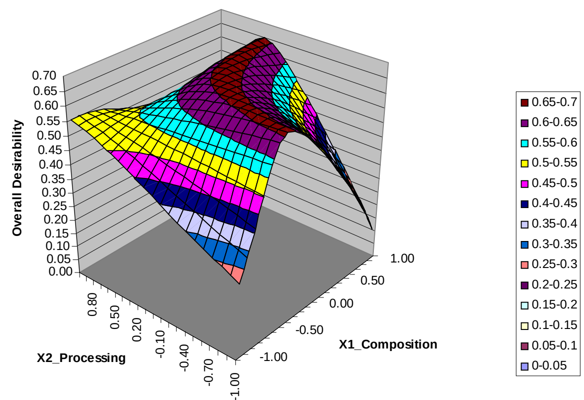

Figure 11. Surface plot of response surface of composite desirability without the influence of cost criteria

cost budget. This kind of analysis supports the DoD initiative, “Cost as an Independent Variable” (CAIV).

Conclusions

Affordable means obtainable with the means available. Affordability is that characteristic of a system that it does what the customer wants it to do—that is, meets or exceeds the customer’s needs—for a price that the customer is willing to pay. The customer will to pay only (1) if the price is within his/her means and (2) if the perceived value is commensurate with the price. The IPPD process enables project teams to make good investment decisions, to understand the ramifications of each decision, and to draw upon the collective knowledge resident within the project team. The structure of the process facilitates meaningful communication among developers, producers, and customers. Of crucial importance in achieving the benefits of applying this process is taking the time to capture the criteria, including definition of “the ideal” for each stakeholder group.

The authors have presented an overview of the IPPD process and some tools that are available to support its execution. An Affordability tool set, to be complete, must include cost modeling capability to estimate investment cost and affordability assessment metrics for the assessment of ROI. Use of these tools will result in consistent delivery of best value from product, process, and technology development investments.

Because best value may meean something different to the producer of the product than it does to the user community, an important aspect of the process and its tools is the ability to capture different sets of criteria, manage the development process to meet a set of crite-

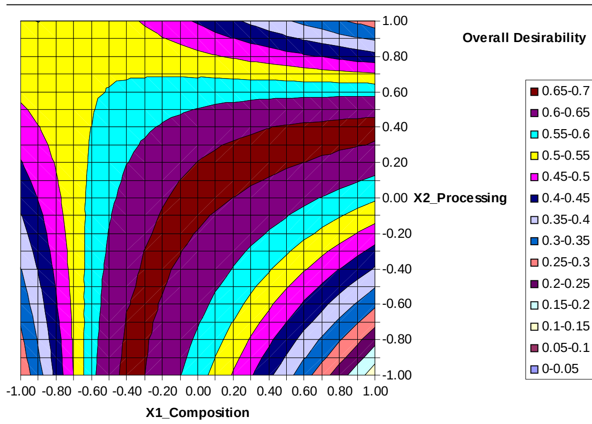

Figure 12. Contour plot of response surface

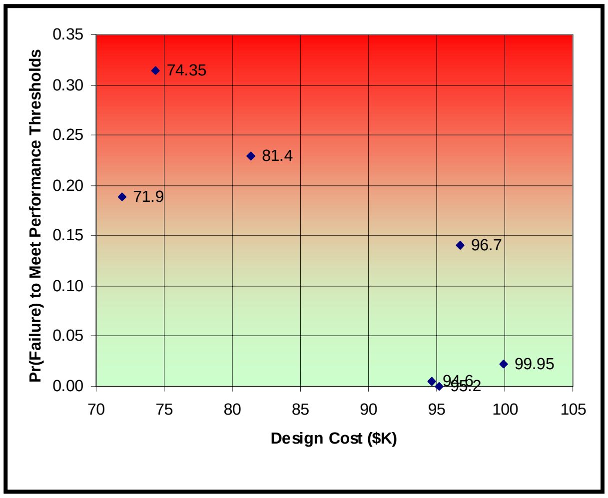

Figure 13. Risk versus design cost for 7 cases, showing the "sweet spot" at $95K

ria that synthesizes the interests of the various stakeholders, and evaluate the results with respect to each of the stakeholder's interests, as well as the synthesized criteria. This latter facility constitutes a valuable communication mechanism and capability.The paper illustrates that best value is a function of ROI and investment. In other words, varying levels of investment result in different solutions that provide best value. Cost modeling allows the exploration of the solution space to support decisions concerning the level of investment to be recommended, given the varying cost plateaus and the best ROI.

Best Value is a function of investment cost. Different Best-Value solutions can be achieved at various levels of investment, various levels of product cost, and at various levels of life-cycle cost. Cost models allow the exploration of investment cost plateaus yielding the best ROI.

This systems engineering approach to Affordability is a discipline to which the DoD is committed. The discipline of Affordability will continue to be applied because of the advantages to those who use it. The Affordability process provides the metrics needed to make good decisions, to understand the ramifications of each option, and to draw upon the collective knowledge of the project team in a structured way. There is now a methodology and associated tools that guide one through the process of creating higher value at a lower cost.

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