

Simultaneous Assessment of Requirements and Technologies in Rotorcraft Design*

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Abstract

Recent emphasis in the design and acquisition of complex systems has focused on the requirements that drive the design process. Most fundamental to the rotorcraft designer is the effect that requirements have on the system design. Requirements drive initial design studies, procurement decisions, and ultimately operational effectiveness and cost. However, it is often the case that design processes (and designers) overlook the impact of changes and/or ambiguity in requirements and fail to understand the relationships between requirements, technologies, and the design space. Increasingly, the decisions made early in the design time line involve the choice of new technologies or combinations of new technologies that will ensure the system meets customer requirements. Providing the designer/decision maker with knowledge of these relationships enhances the ability to find a technically feasible, economically viable, robust solution for the customer. In this paper, the authors present a design environment for the simultaneous assessment of technologies, requirements and design space. The creation of this environment is described along with the tools for its implementation. Examples of the various design spaces are presented for a civil tiltrotor. The requirements space for the civil tiltrotor is further examined. Finally, the benefit of applying this environment to the Joint Transport Rotorcraft is discussed.

Introduction

Recent emphasis in the design and acquisition of complex systems has focused on the requirements that drive the design process. This is particularly true of the acquisition community in both the commercial and government sectors. In the commercial sector, the term “requirements engineering” is coined to explain the process of requirements’ elicitation, analysis, negotiation, validation, documentation and tracing.¹ This “new”

process has risen primarily as a result of the experiences with designing large complicated software products in the midst of a changing technological environment. Since there is no requirements standard in the commercial sector, requirements engineering is applied through the indigenous systems engineering approach. Many would argue that requirements engineering is not a new process but a re-emphasis of the requirements analysis and allocation processes inherent in the systems engineering approach.^{2,3} Whatever the means for its application, the need to capture and meet the customer’s requirements remains at the heart of the designer’s task.

In the defense acquisition sector, there is guidance given for the acquisition of complex systems that addresses the requirements issue and provides broad guidance for the requirements process.^{4,5,6} Perhaps some of the best guidance is summarized in Section 2.3, Requirements Evolution, of Reference 5. “In the process of refining requirements, key concepts that shall be adhered to include:

1. keeping all reasonable options open and facilitating trade-offs throughout the acquisition process;
2. avoiding early commitments to system-specific solutions, including those that inhibit future insertion of new technology and commercial or non-development items;
3. defining requirements in broad operational terms; and
4. using minimum acceptable operational performance (thresholds) to establish operational test criteria.”

These broad guidelines allude to other concepts being emphasized in DoD Regulation 5000.2 including Key Performance Parameters and Evolutionary Acquisition. These guidelines and concepts motivate the research presented in this paper towards the creation of an environment for design in the early stages of design.

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In the design community, the emphasis on customer requirements is exemplified by the increased use of brainstorming techniques such as Quality Function Deployment (QFD) to turn the often vague qualitative requirements of the user (“voice of the customer”) into appropriate quantifiable design metrics (“voice of the engineer”). Even more telling is the move toward Integrated Product and Process Development (IPPD) with its reliance on the multi-faceted, multi-disciplinary Integrated Product Teams. Certainly, a major purpose of these teams is the focusing and refining of the product requirements whether they are from a performance, operational, cost, maintenance, etc. point of view. The inclusion of members from each life-cycle discipline during the requirements definition phase increases the probability that the final product will meet the original requirements as perceived by the customer.

The research presented in this paper draws from the needs and guidance described above. The need to provide an environment that justifies decisions and documents their effect on the product is borrowed from the commercial acquisition community. The broad guidelines expressed in the defense acquisition community point to the need for an environment that keeps the design space open and allows for trade-offs as well as establishing key metrics with appropriate targets to aid in the decision making process. Finally, the design community, which is most closely associated with the product of this research, emphasizes the need for a modern design environment that incorporates the ability to address ambiguous requirements and minimizes the rework of previous design studies.

With this general background, it is clear that the most fundamental issue for the rotorcraft designer is the effect that requirements have on the system design. Requirements drive initial design studies, procurement decisions, and ultimately operational effectiveness and cost. However, it is often the case that design processes (and designers) overlook the impact of changes and/or ambiguity in requirements and fail to understand the relationships between requirements, technologies, and the design space. Increasingly, the decisions made early in the design time line involve the choice of new technologies or combinations of new technologies that will ensure the system meets customer requirements. Providing the designer /decision maker with knowledge of these relationships enhances the ability to find a technically feasible, economically viable, robust solution for the customer.

In References 7 and 8, the authors described in detail a probabilistic design environment that allows for design in the presence of uncertainty/ambiguity as well as the possible infusion of new technologies. This environment is an essential part of a design methodology referred to as the Technology Identification, Evaluation and Selection (TIES) method developed at Georgia Institute of Technology. In this paper, the authors will present an extension of this methodology to include the simultaneous assessment of technologies, requirements and design space. The creation of this environment is described along with the tools for its implementation. Examples of the various design spaces are presented for a civil tiltrotor. The requirements space for the civil tiltrotor is further examined. Finally, the benefit of applying this environment to the Joint Transport Rotorcraft is discussed as well as future research directions.

Technical Approach

Creation of Overall Environment

Discussion to this point has dealt with requirements in a general fashion. An examination of the design process at the system level will further specify the meaning of requirements in this research and provide definition of the responses and variables. When decisions are made during the design process, they are based on three categories of criteria: requirements, desirements and constraints. Desirements are metrics which are desired to be maximized (or minimized) to delineate between competing alternatives which satisfy the requirements. Constraints are limits externally imposed by nature, government regulations, communities, etc. Requirements in this context are thresholds on performance or cost metrics that must be satisfied. This includes, for example, mission radius, mission payload, etc. In traditional design environments, such mission requirements are prescribed and the analysis results in a limited design environment, if not a single design, early in the design timeline. This traditional environment does not anticipate the variability of mission requirements nor can they easily assess the impact on the system in real-time. The environment proposed here treats the mission requirements as inputs to the analysis instead of responses.

Response Surface Methodology

In this research, Response Surface Methodology (RSM)⁹ is used to mathematically

represent the combined requirements-technology-configuration space. RSM is a process that allows one to model the behavior of a complex system using a simplified equation. RSM includes:

1. Design of Experiments (DOE)¹⁰ for determining the appropriate number and combination of simulation cases;
2. running prescribed analysis cases and collecting appropriate response data; and
3. performing multivariate regression analysis to build the response surface equations (RSEs)

Generally, the exact deterministic relationships that govern the behavior of the measured responses to the set of design variables is either too complex or unknown. Therefore, an empirical model is constructed which captures the system response as a function of the design variables. The empirical model used in this methodology is assumed to be second order with k number of design variables. This second-degree model is assumed to exist and can be expressed in the following form.

$$R = b_o + \sum_{i=1}^k b_i k_i + \sum_{i=1}^k b_{ii} k_i^2 + \sum_{i=1}^{k-1} \sum_{j=i+1}^k b_{ij} k_i k_j \quad (1)$$

where:

b_i = regression coefficients for linear terms

b_{ii} = coefficients for pure quadratic terms

b_{ij} = coefficients for cross product terms

x_i, x_j = design variables

The coefficients of this regression curve (surface) are determined by applying a least squares analysis to the responses generated by the set of simulations identified through a Design of Experiment. When this model fails to accurately predict the behavior of the complex analysis code, other methods found through independent or dependent variable transformations or artificial neural networks can be used.

As mentioned above, the coefficients of the RSE are determined utilizing a carefully planned design of experiments or simulations. This approach ensures that the resulting RSE will be applicable in a sufficiently large design space without requiring an unrealistic number of simulation runs (or cases) to provide the response data for the regression analysis. The DOE chosen will dictate the number of simulation runs required based on the number of

levels considered, the number of interactions modeled and the number of variables prescribed. By employing a fractional factorial DOE the required cases are manageable with higher order effects neglected. Fractional factorial designs neglect third or higher order interactions and, in the case of RSE generation, account for linear and all second order interactions including the quadratic effects (see Equation 1).

The three levels of inputs are then mission requirements as described above, design / economic variables which control vehicle geometry / economics and technology k-factors which provide a change in disciplinary metrics to simulate the step change in a response associated with technology insertion. Thus, the problem is broken down into snapshots of the system (Figure 1). The snapshots shown in Figure 1 are visual representations of the response surface equations that mathematically relate the responses (desirements / constraints) to the appropriate variables for each individual snapshot. These snapshots provide “deltas” in responses with respect to baseline values. This approach allows for the combination of the effects of mission requirements and applied technologies along with the geometry of the vehicle on the decision making space. The assumption for this environment is that interactions between k-factors, design variables and requirements do not occur across design spaces. As mentioned earlier, interactions within one of the three design spaces is captured through the RSE model and the appropriate DOE. Future research will explore this correlation issue. The effect on the system is then represented as:

$$\text{Response (i.e. } \Delta \text{GW)} = \text{function (Requirements, Vehicle Characteristics, Technology k-factors)}$$

Snapshot 1 de-emphasizes the geometry of an aircraft, and instead focuses on the mission requirements. However, it does require a baseline vehicle configuration. A baseline geometry and a baseline technology level set are fixed, while top level requirements (*req*) are allowed to vary. Each vector of top level requirements maps to a specific mission. Thus, the effect of primary mission requirement changes on alternate missions can also be tracked. For example, the primary mission range (which sizes the vehicle) can be included as an input variable with the secondary mission range as a fallout response.

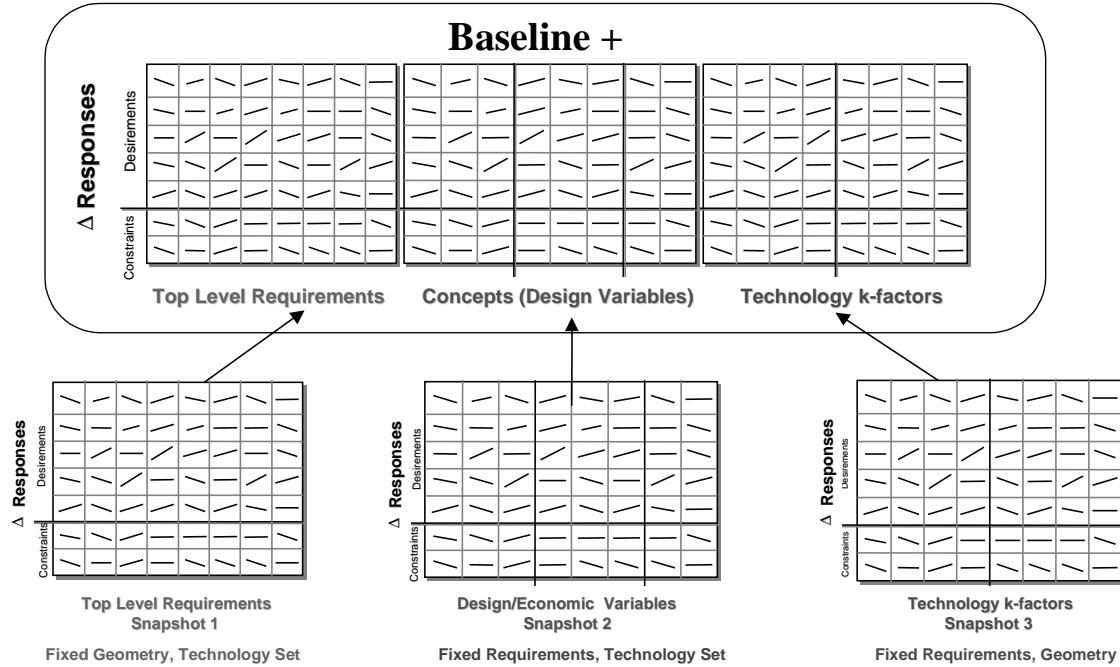


Figure 1: Additive Creation of Overall Environment¹¹

In Snapshot 2, the baseline vehicle is once again fixed with regards to mission requirements and applied technologies, but the vehicle characteristics are allowed to vary. Each vector of design variables (*DV*) and economic variables (*EV*) maps to a specific geometry of a configuration.

In Snapshot 3, the requirements and the vehicle are fixed, but the technologies are allowed to vary. The technology k-factors (k_{TProd} , k_{TManuf}) used during the creation of this space act as techno-dials allowing the manipulation of various disciplinary metrics to simulate the insertion of individual technologies or combinations of technologies. Each vector of technology k-factors maps to a specific combination of applied technologies. More detailed information on the creation and use of Snapshot 2 and 3 can be found in References 7 and 8.

The overall effect on the system is the summation of these three snapshots and can be written (for example):

$$\begin{aligned}
 \text{Response} = & (b_0)_{\text{overall}} + \Delta \sum (req_1, req_2, req_3, \dots) + \\
 & \Delta \sum (DV_1, DV_2, \dots, EV_1, EV_2, \dots) + \\
 & \Delta \sum (k_{TP1}, k_{TP2}, \dots, k_{TM1}, k_{TM2}, \dots)
 \end{aligned}$$

The intercept is thus the combination of the baseline vehicle plus the “delta” contributions from the changes made to requirements, vehicle attributes and technology k-factors. By representing the three design spaces with response surface equations, the designer /decision maker has created explicit relations between the desirements / constraints and the various inputs. These surfaces represent a powerful tool for probing the decision space. These response surface equations represent a non-linear set of equations that can be manipulated to:

1. search for alternatives (configuration changes plus technology infusion) that satisfy requirements and constraints
2. simultaneously, optimize on desirements within this feasible space (continuous) or set (discrete) then, perform sensitivity studies to show the perturbation of the solution due to possible changes in requirements and design variables.

Thus the customer / decision maker has information with regards to the choice between a relaxation in requirements or accepting achievable performance levels.

The graphs shown in Figure 1 are called prediction profiles and are interactive visualizations created from the response surface equations with the aid of a commercial software package named JMP¹².

Application of Method

In this application, the reader is introduced to the individual design spaces, the input variables and the responses tracked. The baseline vehicle for this study is NASA's Short Haul Civil Tiltrotor (4/95 Baseline). The design mission consists of a 600 nm design range at a cruise speed of 350 knots with a 50 nm and 45 minute reserve mission¹³ (1962 U.S. STA ATM Cond - Zero). Note that all responses presented are normalized with respect to the baseline values except where specifically mentioned.

In order to create the environment needed to analyze the various concepts, technologies and requirements the synthesis/sizing code VASCOMP II¹⁴ was enhanced. This enhancement provided the ability to properly model the baseline vehicle. In order to address economic concerns, the Tiltrotor Aircraft Life-Cycle Cost Analysis (TRALCCA) code was developed using NASA Ames' ALCCA as a framework. Newly developed modules for research, development, testing and evaluation (RDT&E) and production cost were incorporated and this analysis capability was integrated into VASCOMP II including the passing of all relevant outputs (weights, block speed, block time). This combined code allows economic analysis for the design mission and/or subsequent economic missions. Capabilities include manufacturer and airline cash flows, operating costs (DOC, DOC+I), required average yield per revenue passenger mile (\$/RPM), acquisition cost, internal rate of return, break-even units, etc. The tracking of all desirements and constraints is done using this combined analysis code.

Table 1: Design Variables & Ranges

Design Variable	Minimum	Maximum
Wing Aspect Ratio	6	8
Wing Loading (lbs/sq ft)	110	130
Tip Speed (fps)	650	750
Propeller Diameter (ft)	38	45
Blade Loading	0.125	0.151
Economic Range (nm)	200	600
Engine Scale Factor (MCP, deg F)	2220	2400
Production Quantity	400	600
Utilization (hrs/yr)	2000	3500
Manufacturer ROI (%)	10	20
Airline ROI (%)	5	15
Fuel Cost (\$/gal)	0.55	1
Load Factor	0.6	0.95
Hull Insurance Rate (%)	1	10
Learning Curve	0.82	0.92

Table 2: Desirements & Constraints

Gross Weight
Empty Weight
Installed Power
Propulsive Efficiency
Disk Loading
Wing Area
500 Ft Sideline Noise
Direct Operating Cost (DOC)
Price / Installed Power

After conducting a screening test (2 level DOE) for thirty design/economic variables, the variables shown in Table 1 are retained as the most influential and all other variables are set to their baseline value. Table 2 shows the desirements and constraints that are tracked in this application.

In Figure 2, prediction profiles are presented which show the relationship between the desirements /constraints (ordinate) and the design variables (abscissa). This screen is an interactive representation of the design space as captured by the design space RSEs. When the hairlines (light gray vertical lines) are moved to indicate the changing of a design variable value, the desirements/constraints are automatically updated through the RSE. Thus, one can investigate the design space by manipulation of the design variables to determine if an objective can be met. The slopes indicate the relative effect each variable has on the objectives. On a more practical note, this screen is often helpful as a debugging tool since trends can be verified and potential mistakes located.

The technology space is generated using the aforementioned technology k-factors. This environment is created in the most generic manner to allow flexibility when used in a stand-alone mode. This generality allows for the implementation of individual technologies, combinations of technologies (assuming, for the time being, the additive property of technology "k" vectors) or simply the identification of metric improvements that will provide the best solution. These metric improvements are then used as targets to identify potential technologies or combinations of technologies. In the overall environment, this technology space allows for assessment of technologies with regards to desirements or constraints. The technology k-factors used to create the technology environment are presented in Table 3.

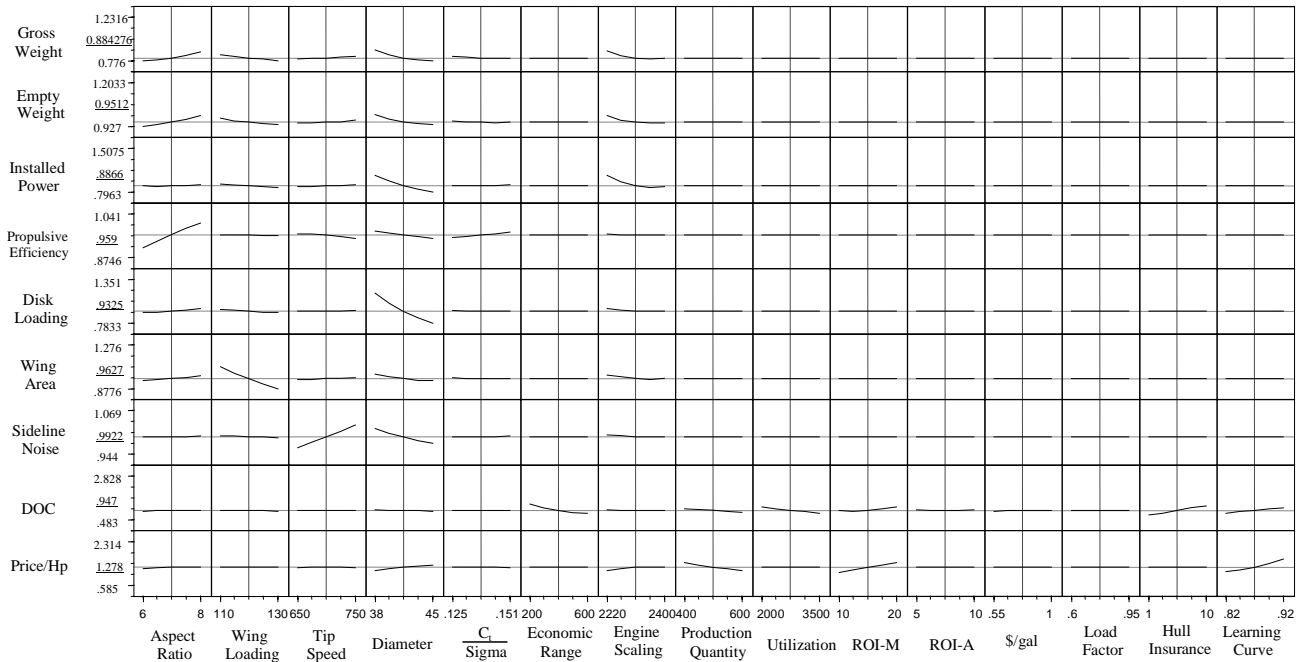


Figure 2: Concept Design Space

The ranges for each factor reflect both benefit and degradation with respect to the baseline or nominal metric value. This formulation ensures that technology modeling can handle both the primary benefit and secondary degradation of appropriate metrics. The technology space is shown in prediction profile format in Figure 3.

Table 3: Technology k-Factors

Technical Metric "k" Factors	Minimum (%)	Maximum (%)
Fuel Flow	-40%	+10%
Hover Efficiency	-5%	+10%
Propulsive Efficiency	-5%	+10%
Download	-50%	+5%
Contingency Power	11.9%	31%
Fuselage Drag	-20%	+5%
Wing Weight	-20%	+10%
Fuselage Weight	-30%	+5%
Rotor Weight	-20%	+10%
Drive System Weight	-10%	+10%
Engine Weight	-50%	+10%
Electrical System Weight	-10%	+50%
Utilization	-20%	+20%
RDT&E	-20%	+20%
Production costs	-20%	+20%
O & S costs	-20%	+20%

For this application, mission requirements are chosen to include payload (i.e. passengers), cruise range and cruise speed. These are chosen for illustrative purposes and do not represent the limit of applicability for this environment. For a military rotorcraft, one can certainly see the inclusion of rate of climb requirements, additional fuel tank requirements, stealth requirements, etc. in addition to the mission radius, payload and speed requirements. For this application, the mission range is varied from 200 to 700 nautical miles (nm), the mission cruise speed is varied from 275 to 350 knots and the payload is varied from 19 to 45 passengers.

The requirements design space is shown in Figure 4. The wing loading and blade loading are included as inputs in this study for illustrative purposes. They provide some information in prediction profile format but are most useful when displaying the requirements design space as contour profiles (see Figure 5). As mentioned earlier, this format can be used as a debugging tool since trends are easily verified. In Figure 4, one could question the trend for direct operating cost versus payload if the DOC was displayed in units of dollars/trip. This trend would not make sense and could indicate a

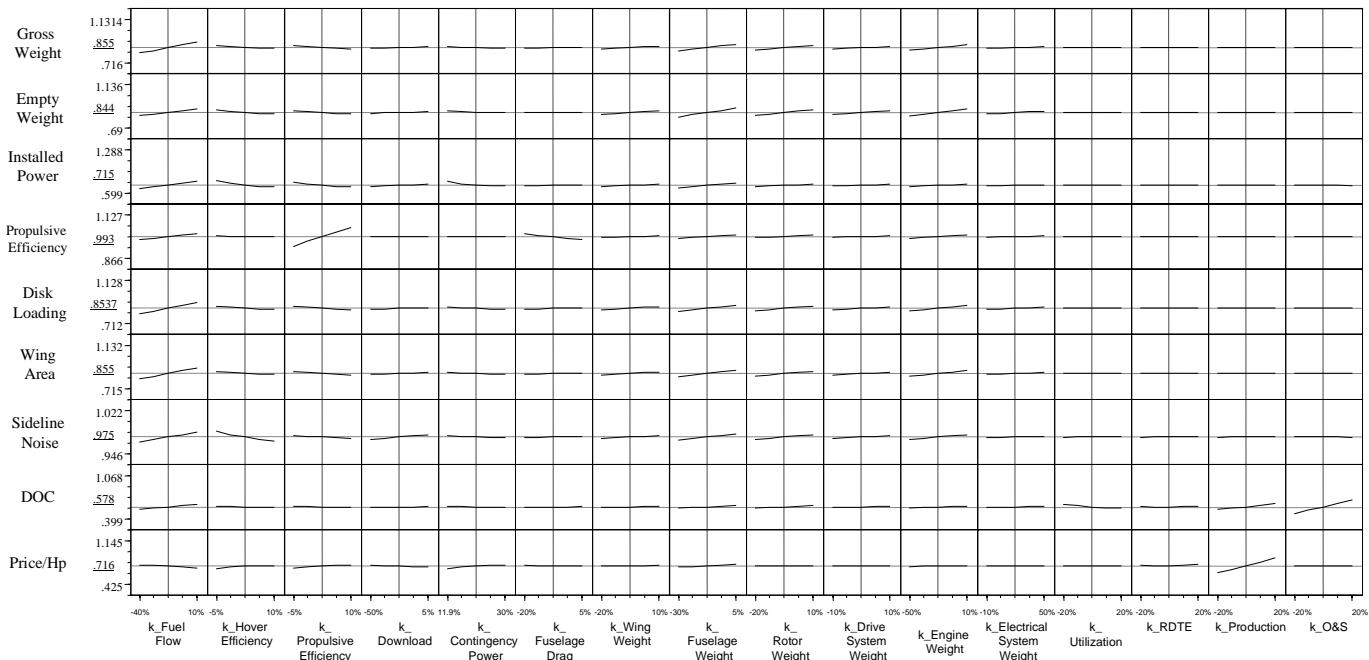


Figure 3: Technology Design Space

problem with the analysis. However, the DOC is displayed in units of cents per available seat mile (\$/ASM) (normalized) which is a common commercial airline metric. The anticipated trend is not seen since the number of passengers appears in the denominator of the metric and masks the increasing fuel costs expected when carrying more passengers. This trend does indicate the need to carefully scrutinize metrics comprised of the ratio of two analysis responses (e.g. Price/Horsepower).

Another way to visualize the design space is through carpet plots in the form of dynamic contour plots provided in JMP. To further study the requirements space, it is presented as a contour plot in Figure 5. This screen is interactive and has the power of the response surface equations behind it. It allows manipulation of requirements within the specified ranges and the placement of limits on desirements and constraints. Although difficult to see in grayscale, the display is shaded with the appropriate color for the desirement/ constraint that is being violated. By using the slide bars for the requirement variables, the design space can be searched, in real time, to determine if the constraints can be satisfied as requirements are changed. Feasible space in the contour plots is indicated by white (or unshaded) space. The slide bars for the desirements / constraints are useful in depicting the magnitude of the violation. When the dots fall within the shaded region the objective is violated and the

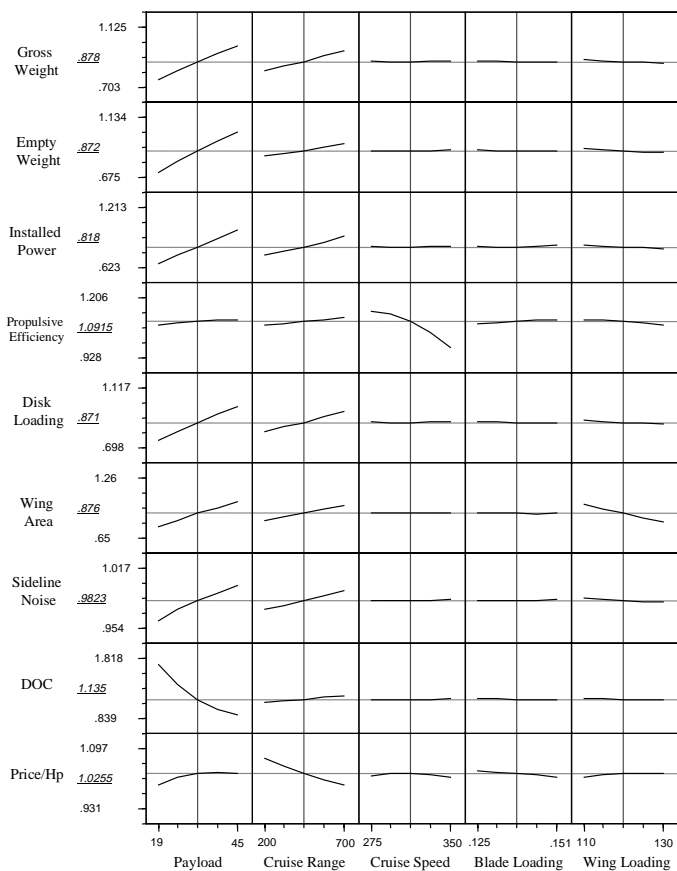


Figure 4: Requirements Design Space

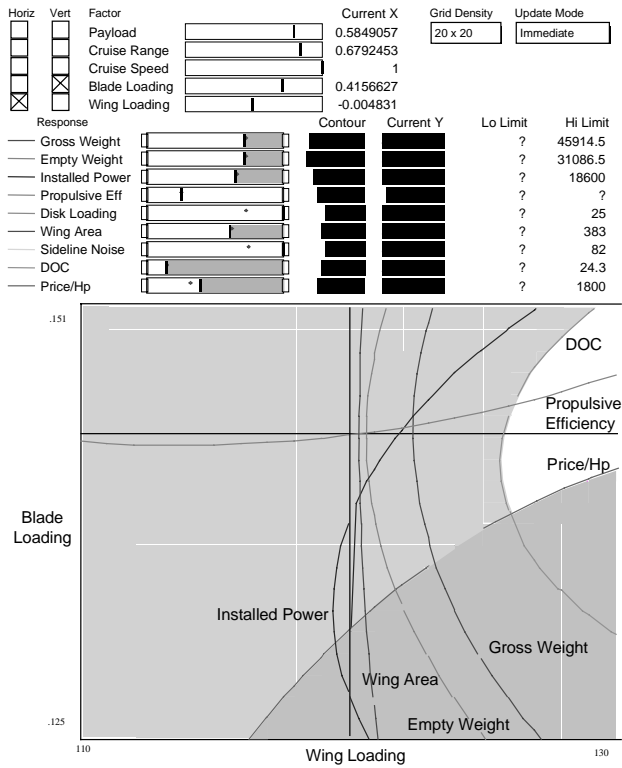


Figure 5: “What-If” Environment

distance to the unshaded region indicates the magnitude of the violation. The contour lines shown in Figure 5 are for illustrative purposes only. The placement of the contour lines is controlled by the designer and aids in performing sensitivity studies. Likewise, dots accompanying the contour lines (not viewable in this figure) indicate the direction of increasing objective value. The requirement variables in this plot are presented on a scale from -1 to 1 which correspond to the low and high limits, respectively, of the range assigned to that variable. The contour and current Y values are stricken for proprietary reasons

The contour plots in Figure 6 are constructed with the baseline requirements and the axes set at the values corresponding to the wing loading and blade loading of the baseline vehicle. The space is explored for a 40 passenger civil tiltrotor with an upper limit of 25 psi for disk loading, the sideline noise limited to 82 dB, the DOC limited to .243 \$/ASM and the Price/HP limited to 1800 \$/Hp. The contour a) indicates there is a feasible requirements space bounded by the DOC, Price/HP contours and the upper limit placed on wing loading. This contour indicates the feasible space includes the baseline vehicle, which is expected.

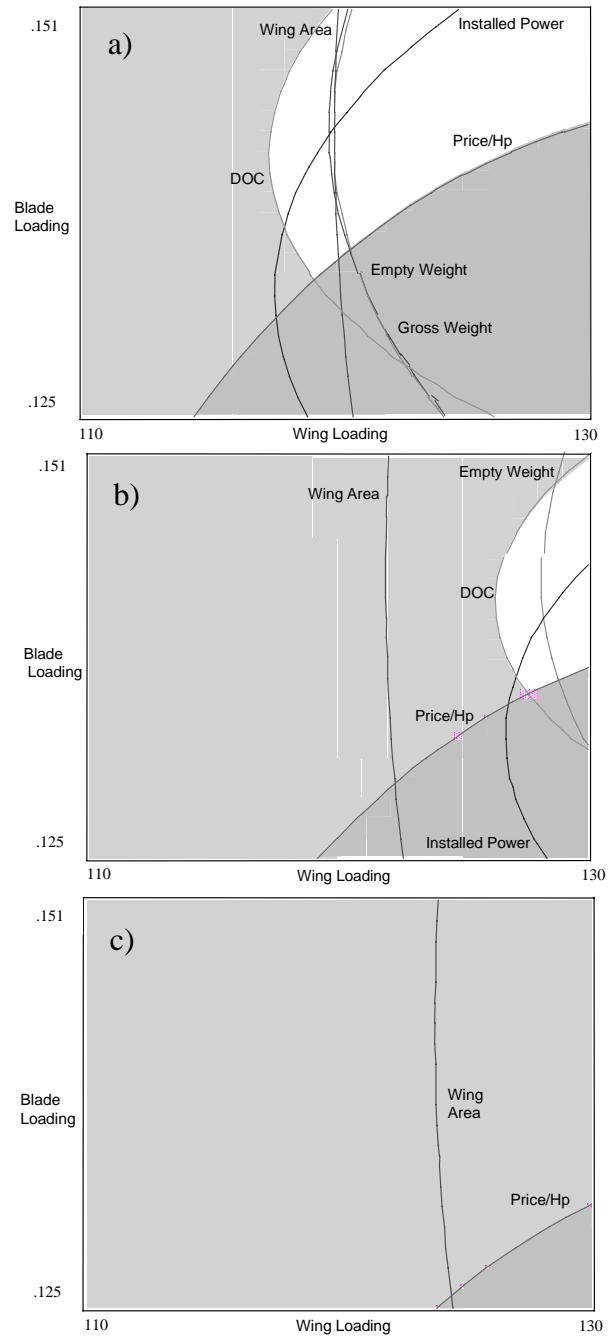


Figure 6: Effects of Increasing Mission Radius

The subsequent contours represent the feasible space when the mission radius is increased in 50 nm increments. At 650 nm (contour b)), feasible space exists but would require adjustment of the wing loading from the baseline value. Ideally, we would like to be at the upper right corner of contour b) at the highest wing loading and blade loading and within the

feasible space. If conducting a paper study, the blade loading could be adjusted in conjunction with wing loading to meet desriements/constraints. If the vehicle design has advanced beyond the drawing board and the blade loading is set, then wing loading (wing area) can be adjusted to place the design in a feasible space with opportunity for growth. In this case, the addition of a root plug for the wing would increase wing area and decrease wing loading. This adjustment would have effects on the whirl flutter speed of the tiltrotor and would indicate the need to include an appropriate constraint in this environment. Finally, contour c) shows no feasible space when the mission radius is increased to 700 nm. This scenario could indicate the need to relax other requirements, relax the limits place on DOC and Price/Hp, infuse new technologies or provide vehicle geometry changes. These types of “what-if” games can be accomplished with the simultaneous assessment environment described in this paper.

Benefits to the Joint Transport Rotorcraft

The design environment described in this paper can easily handle the re-design or derivative design of a rotorcraft. The baseline vehicle is known and the technologies and mission requirements being applied are “known”. However, the design of a new rotorcraft such as a Joint Transport Rotorcraft (JTR) or Joint Common Lift (JCL) allows the designer / decision maker to take full advantage of this environment. The mission requirements are ambiguous at this stage in the planning process as well as the technologies which must be matured to assure system success. This environment could be wrapped around three existing platforms such as a single main rotor helicopter, a tandem rotor helicopter and a tiltrotor which could be grown to meet the mission requirements. This environment would allow the trade-off between mission requirements and acceptable performance levels. It could also indicate if existing platforms could be grown with technologies and re-design to meet the fledgling JTR/JCL requirements. This environment is not only beneficial for tracking and applying requirement and technology changes and their impact on the vehicle. It could also provide the ability to choose the desirements and constraints (and their ranges) which will be given status as Key Performance Parameters. The selection of these evaluation criteria is no less important to the successful system design as the rest of the design process.

Concluding Remarks

The design environment presented in this paper attempts to give the designer added flexibility in dealing with ambiguous requirements and new technologies. Through the use of RSM, the design environment is represented mathematically to allow for increased manipulation and visualization. The method is built to accommodate the design tools and codes with which the designer is most familiar, providing confidence in the analytic results and thus the decision making process. It should not be viewed as able to provide “the” answer but provides the environment in which “what-if” scenarios can be examined and educated decisions made. Future research will concentrate on the interactions between the design spaces and the correlation between design variables. Future research also will apply probabilistic techniques to this environment to allow comparisons of anticipated requirements space with achieved requirements space. The achieved requirements space is built by forecasting the growth potential of the baseline aircraft in light of technologies and geometry changes. This method will also be implemented on a problem of common and current interest to industry and government, the JTR, in partnership with Boeing-Philadelphia and Sikorsky Aircraft Corporation.

Acknowledgments

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