Systems Engineering: When Knowledge and Technology Are the Product

Larry A. Young
Aeromechanics Branch
Flight Vehicle Research and Technology Division
NASA Ames Research Center
Moffett Field, CA 94035

Abstract

The interdependence of technology development, conceptual design, and system analysis is examined in the context of an overall systems engineering set of processes. In particular, the role of technology portfolio management – from initial investment decision-making all the way through technology maturation and transfer to industry – is emphasized. Additionally, the role of state of the art assessments is considered in terms of planning and tracking progress towards the development of enhanced predictive capabilities.

Introduction

Systems engineering is an essential technical discipline as applied to the whole of the aerial vehicle development life cycle. In turn, system analysis is a key element of systems engineering. But, unlike most industrial applications of systems engineering, the suite of end-products for rotorcraft research communities are not a product taken to market, or necessarily a vehicle achieving first flight, but are instead knowledge and the innovation/maturation of key technologies. This can be a decidedly different perspective from that of industrial experience. In many regards, systems engineering as a discipline is about the *requirements* for the development and operation of engineering systems (e.g. Refs. 1-2). How to accomplish this process for the rather intangible products such as knowledge and technological innovation is an important challenge for any engineering research organization.

The fundamental question posed, and partially answered in this paper, is: How might the conduct and application of aerospace research, in general, be improved? Where appropriate in this discussion, the specific relevance to rotorcraft research will be emphasized, though the majority of the discussion is of general utility. It will be argued in this paper, that the answer to this question lies in the performance of such research while embracing more fully key concepts from the systems engineering discipline. The objective of this paper, therefore, is to expand upon and consider in more detail the precept that systems engineering processes can be successfully and productively adapted to improve the conduct of aerospace research.

Systems engineering as a technical field, however, is broad in scope. It is beyond the scope of this paper to address all the potential implications of the systems engineering techniques and methodologies and how they might influence the conduct and application aerospace research. The focus of this paper is to describe how systems engineering (given its essential focus on requirements) might influence four aspects of aerospace research: conceptualization and conceptual design, system analysis trade studies, technical discipline self-assessments, and technology portfolio decision-making and tracking. Of the four areas, system analysis is perhaps the most important in that it significantly influences the other three areas, as well as systems engineering as a whole.

The work that follows is based solely on the author's personal opinions and expertise and should

Presented at the American Helicopter Society 64th Annual Forum, Montréal, Canada, April 29 – May 1, 2008.

not be construed as representing a NASA programmatic perspective. A generic perspective is provided in responding to important questions as to improving the definition and delivery of knowledge and technology end products.

Systems Engineering as Applied to Research

Every successful research institution must periodically answer certain key questions regarding their research portfolios. First, is the research relevant to the primary mission of the organization? In the case of public or governmental institutions this is equivalent to asking whether or not public good needs are being met by the research being conducted. Second, how is the knowledge gained from the research going to foster technological innovation? This question distinguishes engineering research organizations from other institutions engaged in natural science or other pursuits. A third key question for engineering research organizations is whether or not the knowledge gained helps enable improved efficiencies and confidence in the design process.

A key premise of this paper is that the adoption of a systems engineering perspective will help answer the above questions and also "engineer" better research processes.

In general terms, what is systems engineering? Reference 1 defines it as: "*Systems engineering is a robust approach to the design, creation, and operation of systems. In simple terms, the approach consists of identification and quantification of system goals, creation of alternative system design concepts, performance of design trades, selection and implementation of the best design, verification that the design is properly built and integrated, and post-implementation assessment of how well the system meets (or met) the goals. The approach is usually applied repeatedly and recursively…*" Reference 2 alternatively defines it as: "*Systems engineering is an interdisciplinary approach and means to enable the realization of successful systems. It focuses on defining customer needs and required functionality early in the development cycle, documenting requirements, then proceeding with design synthesis and system validation while considering the complete problem…*"

Figure 1 is a simple illustration of how the above generic definition – and key general tasks – of systems engineering can be applied to some of the specific tasks typical of engineering research, including that of rotorcraft research. Note that the general systems engineering tasks are in boldface font whereas specific research tasks are contained within parentheses and italicized. Many of these specific research-oriented tasks will be discussed later in the paper.

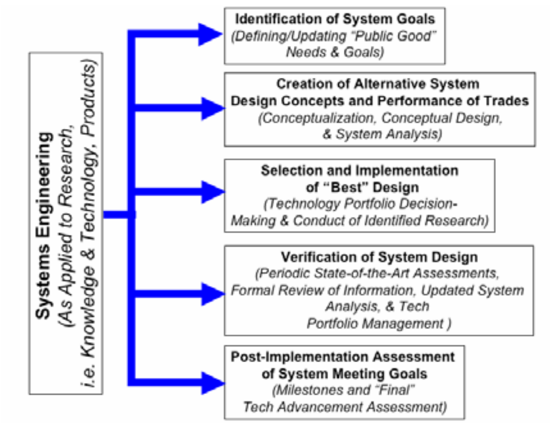


Fig. 1. How Systems Engineering Applies to Research Products

What is a "system" in this context? Can "products" such as knowledge and technology be considered outcomes of a "system" comprised of the resources/elements embodied in a research organization? Reference 1 defines it as: "*A 'system' is a set of interrelated components which interact with one another in an organized fashion toward a common purpose. The components of a system may be quite diverse, consisting of persons, organizations, procedures, software, equipment, and/or facilities.*" For the purposes of this paper, the "system" is the complete set of processes associated with conducting engineering research. Particular focus is given in this paper to those system elements that are critical to defining public good needs, the definition of technology goals to meet those needs, and the implementation of conceptualization, design, system analysis, and technology portfolio decision-making and overall portfolio management.

Figure 2 illustrates how a research-directed systems engineering effort might be decomposed into complementary tasks, such as those outlined in Fig. 1, that come into play at different times during the technology maturation effort, as denoted by different technology readiness levels (TRL). There is a spectrum of knowledge and technologies that result from engineering research. In particular, technology investigations that can be taken only to relatively low TRL may yield a considerable amount of data, and therefore knowledge, but not much in the way of technology with great utility.

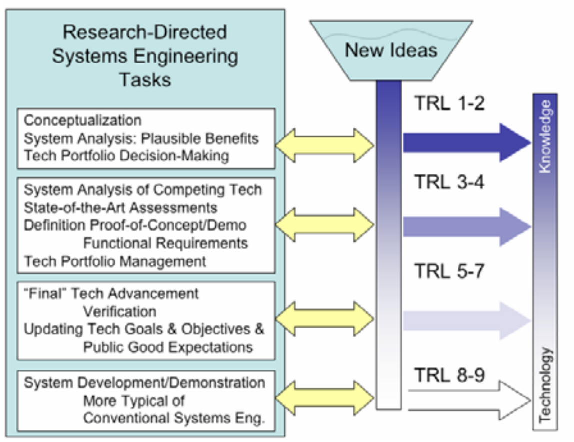


Fig. 2. Representative Systems Engineering Type Tasks Applied to Engineering Research Efforts

The remainder of this paper will discuss four important tasks/aspects of systems engineering as applied to research endeavors: (1) the role of conceptualization and design in engineering research; (2) the criticality of system analysis for the assessment of potential public good benefits stemming from a suite of technologies; (3) the potential role of state-of-the-art assessments in prioritizing technologies and gauging their development progress; and (4) various considerations and possible approaches to technology portfolio decision-making and overall research portfolio management.

Role of Conceptualization and Conceptual Design in Research

As described earlier, a key emphasis for systems engineering, in its typical context, has been on the *design* of systems. Even though the emphasis of this paper is to explore how systems engineering can be applied to and enhance the development of intangible products such as engineering knowledge, design remains an important and necessary component of the overall research process.

Design, almost by necessity, remains in large part an art rather than an exact science. This continues to be the case as long as innovation thrives within a particular engineering field. As an organization or industry matures, innovation slowly tapers off, knowledge and predictive capability steadily improves, and design practice appears to approach an exact, almost formulaic, science. Fortunately, the rotary-wing engineering field is far from this state of industry maturity. Therefore, a medium does still exist between innovation and analysis, or between design as art and design as science.

The importance of synergy between technology investigations and advanced vehicle concept development cannot be over-emphasized. Advanced vehicle concepts are, in general, drivers for developing new suites of technologies. Conversely, the development of one or more key technologies could potentially have a critical role in whether an advanced vehicle concept is viable.

Design paradigms have to continuously evolve to encompass not only new technologies but also new analytical tools, theoretical advances, and changing societal needs. One example of this necessary and ongoing evolution is the recent advances in vehicle design and design methodologies in response to advances in vehicle automation and other information technologies. For example, Refs. 3-6 address the challenges of accounting for autonomous system technologies in system analysis studies. Recent advances in rotary-wing predictive capability, as a consequence of the general trend towards the use of higher-fidelity physics-based computational tools, has profound implications for rotorcraft design. Yet, a crucial balance between design- and analysis-centric perspectives must be preserved. Even in these modern times, design is not solely analysis. Experienced practicing design engineers should collaborate with rotary-wing analysts and computer science specialists in defining this emerging new design paradigm. Further, and most importantly, the design experience in this collaboration should be grounded in not only conceptual design but vehicle detail design and system integration as well.

System Analysis in Support of Research

Reference 1 notes that: "*The role of systems analysis and modeling is to produce rigorous and consistent evaluations so as to foster better decisions in the systems engineering process. By helping to progress the system design toward an optimum, systems analysis and modeling contribute to the objective of systems engineering. This is accomplished primarily by performing trade studies of plausible alternatives.*"

The specific knowledge and technology products for an aerospace research organization are: test and evaluation of technologies and systems (embodying those technologies) at various levels of maturation; technological innovation; advances in theoretical and predictive capabilities; innovation in vehicle concepts; predicting and gaining insight into aerospace technological trends; identifying emerging mission or application requirements and critical enabling technologies.

It is essential for any technology investment decision-making process to not unduly inhibit either the creativity of researchers or technological innovation as a whole. Ideally, the opposite should occur. Technology portfolio analysis should help engender new ideas, highlight unexpected technologies, and suggest alternate approaches to conducting research campaigns. Such portfolio decision-making has to be inevitably influenced by both the emergence of new technology discipline areas, such as autonomous or intelligent systems, as well as the increasingly multidisciplinary (and increasingly higher-fidelity) nature of vehicle conceptualization and conceptual/preliminary design. Ultimately, technology portfolio analyses must capture a sense of the public good of the pertinent technology or mission/application in order to be relevant to a governmental research organization. Having stated this ideal, it is a challenging task to quantify public good metrics and to integrate, or account for, them into robust system analyses. Various past attempts at this type of effort can be found in Refs. 7-12.

Conceptualization and vehicle conceptual design is an essential element in the planning of new technology investigations. System analysis and the conceptual design process have always been intrinsically linked for aerospace applications. However, system analysis, as a discipline, is more than just performing trade studies using vehicle sizing, or preliminary design, codes. System analysis is also critical in assessing the potential impact of emerging, and otherwise elusive-to-quantify, technologies on vehicle/mission capabilities. For example, consider the work to incorporate vehicle autonomous system technologies into system analyses as detailed in Refs. 3-6.

The following are postulated attributes for an "ideal" system analysis capability:

1. Ease of use. Easy to use system analysis tools should allow, for example, a subject matter expert (SME) in aerodynamics (but not having any particular expertise as a system analyst) an opportunity to assess the impact of a new aerodynamics concept or technology on vehicle/mission performance and, in more sophisticated tools, the overall public good metrics.
2. Augment rather than hamper creativity and innovation – i.e. the tools are easily extensible to new configurations and analyses.
3. Enable widespread user community access (where appropriate).
4. Generally applicable architecture for multiple application domains, and not just rotorcraft system analysis, to maximize technical interchange.
5. Adjustable fidelity tools that can support complementary or competing analysis modules and models.
6. Embody a rigorous methodology for defining, and adhering to, their anticipated confidence or uncertainty levels and range of application.
7. Have a comprehensive analysis architecture that addresses the full scope of rotorcraft system analysis tools in an integrated manner. The tools should provide for conceptualization, sizing, mission analysis and simulation, public good metric estimates, and mission requirements definition and refinement, etc.
8. Have a robust means of validation with higher fidelity codes and reconciliation among competing analysis modules and models.
9. Capable of integrating new and/or hard to quantify technologies (e.g. autonomous system technology).
10. Capable of accommodating or reflecting multi-mission, multi-scenario, and/or multi-modal requirements.
11. Capable of adjustable or variable levels of design automation.
12. Capable of interfacing to CAD (Computer Aided Design) and CAE (Computer Aided Engineering) software as well as rotorcraft-specialized engineering analysis tools.
13. Have robust self-documentation that reflects potential rapid evolution of the analysis tools and models.
14. Capable of being a pre-processor tool for high-fidelity analysis tools such as rotorcraft comprehensive analyses, coupled CFD/CSD (Computational Fluid or Structural Dynamic) codes, or MDAO (Multidisciplinary Design, Analysis, and Optimization) analyses.

15. Capable of aiding in making and/or managing technology portfolio decisions.

These attributes cannot be achieved solely by utilizing the resources of the rotary-wing research community but must draw upon the whole of the aerospace community. Further, rotorcraft research – or research into any large and complex engineering system for that matter – cannot be conducted as an end in itself. In the case of governmental research organizations public good considerations must also ideally be taken into account.

From a global perspective, some of the anticipated benefits stemming from advancements in rotorcraft system analysis are:

1. Improved confidence in trade studies and “best” design candidate selection early in the design process.
2. Shortened design cycles and reduced development costs.
3. Ability to address advanced technology impacts on public good metrics/goals or, vice versa, to enable robust assessment and definition of reasonably attainable and/or cost-efficient public good target metrics. Among these many possible public good metrics are noise reduction, emission, and airspace congestion targets.
4. Enhanced vehicle/system innovation through earlier introduction of powerful analysis tools.
5. A powerful interactive medium to preserve and impart engineering design knowledge to the next generation of aerospace workers and academics.
6. Identify new mission and application opportunities.

Some of the problems with current system analyses as applied to rotorcraft research efforts are:

1. Technology investment decisions can potentially be made in an informal and/or ad hoc manner.
2. The difficulties in dealing with the use of “legacy” software design tools/analyses (see Refs. 13-15, for example).
3. The incorporation of new technologies and/or radically different missions or applications into analyses is extremely difficult to accomplish with the system analysis tools currently available.
4. Current system analysis tools/processes are inadequately automated, not tailored for distributed computational architectures, and do not reflect modern programming and computer science advances.

There is a substantial body of literature on both capital and technology investment decision-making, from an industrial and/or tangible product development perspective, whereby techniques such as cost-benefit analysis can be employed to aid in decision-making. The situation is quite different when such investments are made from the perspective of maximizing the benefits stemming from intangible products such as knowledge and technology innovation. The risks and benefits of knowledge acquisition and technology development, and their associated uncertainties, must be accounted for in quantitative decision-making methodologies. The following list summarizes some of the key considerations in defining these risks and benefits.

1. Is the proposed data or technology unique?
2. Will the proposed effort result in data/knowledge of general or focused/specialized application?
3. Will the investigation/effort yield a more accurate or definitive set of results or assessment than current data supports?
4. Is the proposed effort relevant to the research organization’s goals and/or public good needs?
5. Will the resulting data/information be timely?
6. Will the information and/or knowledge acquired (or methodology employed or developed) have long-term value or will it quickly depreciate?
7. How susceptible is the value of information or knowledge acquired to changing programmatic priorities and/or precepts?

This overall question of investment decision-making with regards to knowledge acquisition and technology development and/or investigation will be discussed in considerably more detail later in the paper. Next the potential role of state-of-the-art technical discipline assessments on the definition and guidance of research priorities will be discussed. Further, a brief discussion regarding the challenges in assessing the accuracy and applicability of rotorcraft system analysis, or rather vehicle-sizing tools, will be provided.

State-of-the-Art Assessments and their Potential Implications for Research Requirements and Prioritization

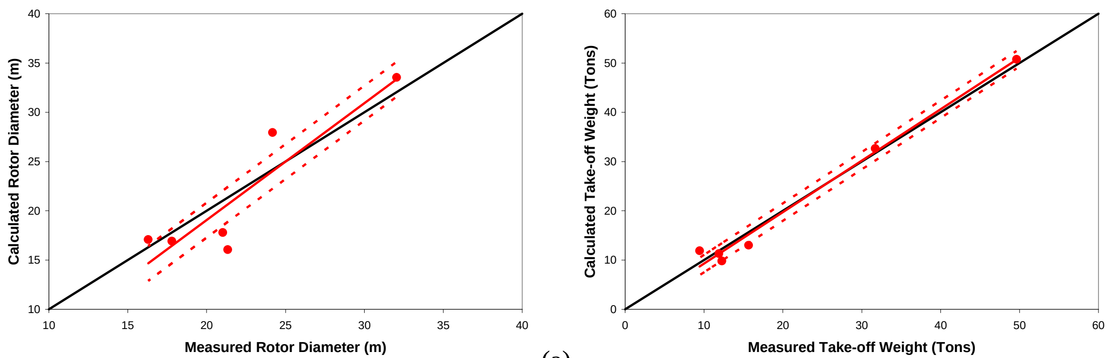
A state of the art (SOA) assessment for rotorcraft research is in the process of being completed (Ref. 16). In this study quantitative metrics are defined and evaluated to assess the current predictive capability for a wide spectrum of rotary-wing disciplines. Not surprising, for certain vehicle systems and operating ranges overall predictive capability is quite good. However, Ref. 16 has also identified areas where there are still major shortcomings with respect to the analytical tools currently available. A key outgrowth of this assessment effort is the complementary assessment of design confidence to meet specific functional requirements for rotorcraft. Design confidence has implications for the definition, and preservation, of weight margins during the vehicle development, as well as other comparable techniques such as tech factor assignment, to insure that the final design will meet user requirements.

For a rotorcraft research organization, system analysis and overall system integration and demonstration efforts can be categorized as follows:

1. Aid in the technology portfolio management of overall research efforts.
2. Investigate the systemic — and public good implications — of not meeting, meeting, or exceeding planned/anticipated individual technology and discipline metric goals.
3. Help define future requirements for integrated system demonstrations whether by means of focused wind-tunnel tests, simulator facilities, or flight experiments. Such tailored demonstrations would emphasize the integration of complementary technologies and build/leverage off of prior tests looking at individual technologies.

There are very few published studies assessing the relative accuracy of rotorcraft sizing codes against a wide spectrum of actual vehicle data. To some degree this is not too surprising for three reasons: first, a significant fraction of such data is proprietary or sensitive; second, most vehicle sizing codes are highly tuned using empirical data; and, third, predicted versus actual design trend data are not typically archived adequately and made accessible even to internal organizational designers and developers. One important exception is the work of Refs. 17-18 which examined the predictive accuracy of then existent rotorcraft weight estimation methodologies (weight equations). Even though the three different sets of weight equations studied were at the time well-known and widely used, and, further, were empirically tuned for a spectrum of vehicles, the estimation results showed that there were significant discrepancies in predicted versus actual vehicle weight groups. This was the case for all three sets of statistical weight equations studied, though all three methods performed best when applied to vehicles similar to those employed in their empirical heritage.

One possible option for assessing system analysis SOA, given the limited accessible data available, is to compare the sizing tool performance estimates against estimates from higher-fidelity tools. However, this is not an easy or necessarily satisfactory option for two reasons. First, in many cases, the analysis tools are “calibrated” or “tuned” against the very data sets that they could be evaluated against. Second, sizing tools are typically updated as the vehicle design matures with data and information from higher-fidelity design and analysis tools. Therefore such tools, and associated vehicle models, cannot be considered “static” instantiations that can be definitively evaluated for their accuracy and range of application. The study results from Ref. 19 provide some limited insight into vehicle sizing accuracy at the early stages of conceptual design. This work is perhaps unique in that the vehicle sizing methodology studied was developed primarily in Soviet-era Russia but was in this study partially validated against vehicle data for US/Western-developed helicopters. The limited results shown in Fig. 3 illustrate the difficulties in accuracy assessments of rotorcraft system analysis tools in general. Note in Fig. 3 that the linear regression analysis slope, m, is in general indicative of the relative under- or over-prediction of the particular design sizing tool being employed in the Ref. 19 vehicle sizing methodology. Further, S_e is the standard error of estimate for the regression data. The format of presentation for Fig. 3 is consistent with the SOA analysis methodology presented in Refs. 16 and 20.



(a) (b)

Fig. 3. Assessing system analysis accuracy: example based on Ref. 19 data/analysis: (a) main rotor diameter (m=1.1871 and S_e=±1.76902249) and (b) take-off weight (m=1.0445 and S_e=±1.266980765)

Figure 3 represents a limited example of the type of assessment of system analysis capability — in terms of accuracy and applicability — that ideally should be performed and reported more frequently in the technical literature. Whether the above results are representative for other vehicle sizing parameters predicted by the Ref. 19 analysis tool is indeterminable. To perform a comprehensive and definitive state-of-the-art assessment of system analysis capability for the rotorcraft community as a whole is an extremely difficult task given the very real concerns about data rights and dissemination. Such an exercise, though, might be the kind of challenge that a technical society design or systems engineering technical committee might consider sponsoring.

The advantages of such a community-wide assessment would be many: (1) improvements in current tools and advances in the development of new tools; (2) improved design confidence; (3) improvements in design innovation; (4) improvements in design engineering education.

There is also considerable value in analyzing publicly available historical rotorcraft design information. For example, Ref. 21 presents a number of examples of the design evolution in terms of system component weights for the Russian Mi-26 helicopter, from preliminary design to production aircraft. Another example of using historical data to assess the current state of the art in vehicle design and development is Ref. 22, where a number of factors potentially implicit in vehicle cost growth were studied in relation to a comparison of the CH-47 and V-22 aircraft development programs. However, as a whole, only very limited historical design data is generally accessible. Studies similar to Refs. 21 and 22 are examples of the type of quantitative design trend analysis that should be actively encouraged within the rotorcraft community.

Technology Portfolio Decision-Making

Systems engineering, as a discipline, is primarily concerned about defining, documenting, and tracking the adherence to requirements. System analysis, a key element of systems engineering, comprises the body of tools and analysis methodologies used to accomplish the tasks of defining, documenting, and tracking engineering requirements for the systems/products being developed. In the case of research institutions, these primary products are knowledge and technology. For such institutions, defining, documenting, and tracking "requirements" in the systems engineering context is conceptually equivalent to the processes for investment decision-making, and the demonstration/quantification of progress towards maturing, technology portfolios. Accordingly, some of the potential methods and approaches to technology portfolio decision-making will now be discussed.

There are many different ways in which technologies can be selected for development. Most of these approaches are quite informal and are not necessarily efficient or effective. One common example of why an individual technology is nurtured is "innovator advocacy," wherein the originator of a given technology is an impassioned and successful advocate of a given technology. This approach is not strategic in nature because it does not directly consider the alternate technologies that might be affected by pursuit of the advocated technology. Further, a good innovator is not necessarily a good advocate. Table 1 summarizes several approaches to technology investment decision-making.

Table 1. Technology Portfolio Decision-Making

Method	Description	Strengths & Weaknesses
Innovator Advocacy	Originator of a given concept or technology is its chief advocate to gain funding and/or other resources	An "entrepreneurial" spirit is often essential for successful introduction of new concepts or technologies. But, a good innovator is not necessarily a good advocate. A hierarchical structured organization is resistant to this type of advocacy.
Communal Advocacy	External/internal research communities are polled as to research prioritization within the purview of a given research organization. E.g. "Decadal Studies."	Brings in a diverse set of inputs from a broad community. Can devolve, if care is not taken, into a form of apportionment for the more influential "technical areas" being represented in the polling.
Workshops & Committees	A semi-formal process by which "grass roots" subject matter expert input is distilled and filtered through multiple levels of vetting (through a sequential series of workshop sessions) till a final set of recommendations is made to programmatic decision makers.	A well-known and frequently employed approach. Chief weakness of the approach lies in "hidden agendas" and "jockeying for resources" when performing the successive filtering/distillation of information and priorities steps.
Apportionment	Resources are apportioned in some manner not directly influenced by the particular technologies being pursued. Examples include fixed research stipends per individual researcher, proportional organizational funding relative to number of technologists in a given organization, etc.	The "strength" of an apportionment strategy is that "everybody," to some level, gets resources to perform at least a modest amount of tangible research. The chief weakness of this approach is that there is no strategic direction for the research.
Advisory Panels	Primarily to gain independent experience and historical perspectives not readily apparent or palatable to programmatic decision-makers.	Chief strengths are the independent viewpoints and insight from advisors with well-established credentials. The chief weakness of this approach is that time does change the circumstances sometimes and what was once a successful strategy to pursue in the past may not be as relevant today.
Preferred-TRL/Discipline Investing	Organizations may explicitly or implicitly target technologies that are within certain ranges of technology readiness level (TRL).	Chief strength of this approach is that it is responsive to organizational values and heritage. Chief weakness is that the organization is inherently dependent on other organizations to either incubate or pick up via technology transfer technologies that fall outside the preferred range of TRL or disciplines.
Predictive Capability	Use state of the art assessment(s) to identify weakest areas of predictive capability and invest accordingly, in terms of low accuracy ranking, into analysis tool development that seeks to address that weakness.	Chief strength of this approach is that it can be implemented in a quantitative manner (through periodic SOA assessments). Additionally, the underlying philosophical argument that new technological advancements need strong (new and improved) tools to aid their development is at least a plausible one. The chief weakness in this approach is that synthesis and analysis (innovation and prediction) may not be strongly coupled.
Sponsored Studies or Solicited White Papers	Areas of interest are defined, studies are awarded, or requests for information are made, and responses generate new ideas/technical approaches.	Brings in a diverse set of inputs from a broad community. A potential catalyst for innovation. Responses, though, potentially may not address the key questions being raised.
Internal or External Competitions	Requirements are defined and proposals are solicited to meet requirements. Proposals are then formally reviewed by decision-makers.	"Fair" competition is always good for innovation. Weakness is that quality and number of proposals is dependent upon perceived probability of award success.
Formal Portfolio Analysis	Sundry decision-theory, or macroeconomic, derived analysis techniques have been applied, e.g. Refs. 23-27.	Quantitative, defensible, and robust. Unfortunately, the resulting analyses are often opaque to programmatic decision-makers.

Various formalized technology portfolio investment strategies or approaches have been detailed in the literature (e.g. Refs. 23-27). It is unclear which, if any, of these analyses might be the best strategy to employ for rotorcraft technology portfolios. The objectives of portfolio analysis must first be defined. The following is a list of possible portfolio analysis objectives:

1. Validate and, as appropriate, prioritize current technology portfolio.
2. Identify critical missing technologies. Rank in priority these identified technologies against existing portfolio.
3. Highlight technologies with highest utility/commonality against a suite of missions, applications, and vehicle-types.

4. Identify unique technologies that are singular in application to certain missions or vehicle-types. Assess relative importance of these unique technology investments versus other technologies weighted more towards greater commonality of application.
5. Perform periodic reassessment of technology portfolio, as an engineering and project management tool, in light of technical progress, unanticipated innovations, shifting programmatic focus, and new opportunities.

State-of-the-art predictive capability assessments can also influence technology portfolio decision-making. Areas in which the predictive capability is relatively poor could be potential areas for investment – investments in both refined analyses as well as in individual technologies whose development is dependent on improved predictive capability. This, of course, cannot be the sole criterion by which technology investment decisions are made. For research organizations where knowledge is a key product, predictive capability or deficiencies therein must be an important consideration in investment decision-making. Figure 4 takes the state of the art assessments made for the aeromechanics discipline, Ref. 20, using non-CFD-based analysis tools, and recasts the error, or inaccuracy, estimates into an analysis tool development priority ranking — if lack of predictive capability were the primary criterion for establishing such a prioritization. A similar exercise can be performed for other rotorcraft disciplines and other categories of analytical tools. Figure 5 uses data from the Ref. 20 aeromechanics SOA assessment — and using cited standard errors of estimate as guiding metrics — illustrates how various experimental measurement categories and data sets could possibly be ranked in priority for enhancement or improvement for future correlation/validation efforts. In actuality, numerous factors have to be considered in defining technology investigation priorities, not just predictive capability accuracy and the collective standard errors for classes of measurements. The important point is that periodic technical discipline state-of-the-art assessments potentially enable inclusion of predictive capability considerations into research portfolio decision-making process (though, of course, not exclusively so).

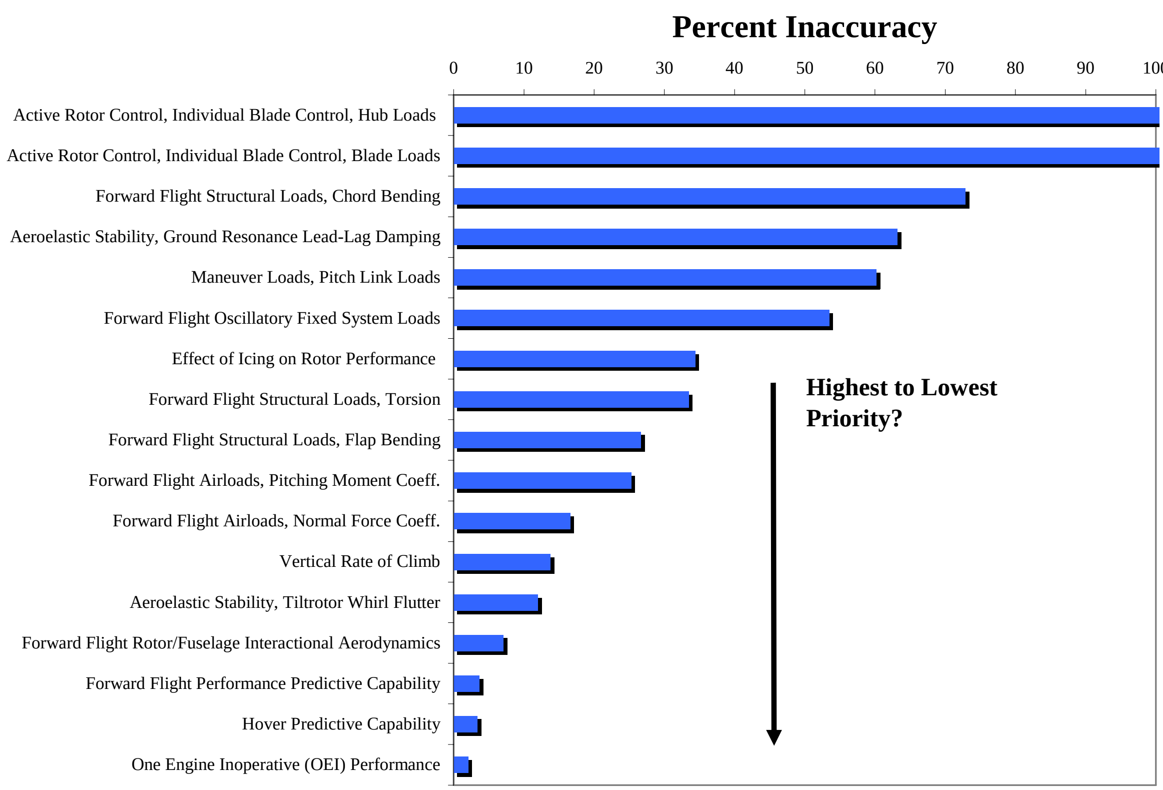


Fig. 4 – Relative Ranking If (Lack Of) Predictive Capability Were the Primary Criterion for Prioritizing Aeromechanics Analysis Development (based on Ref. 20 SOA assessments)

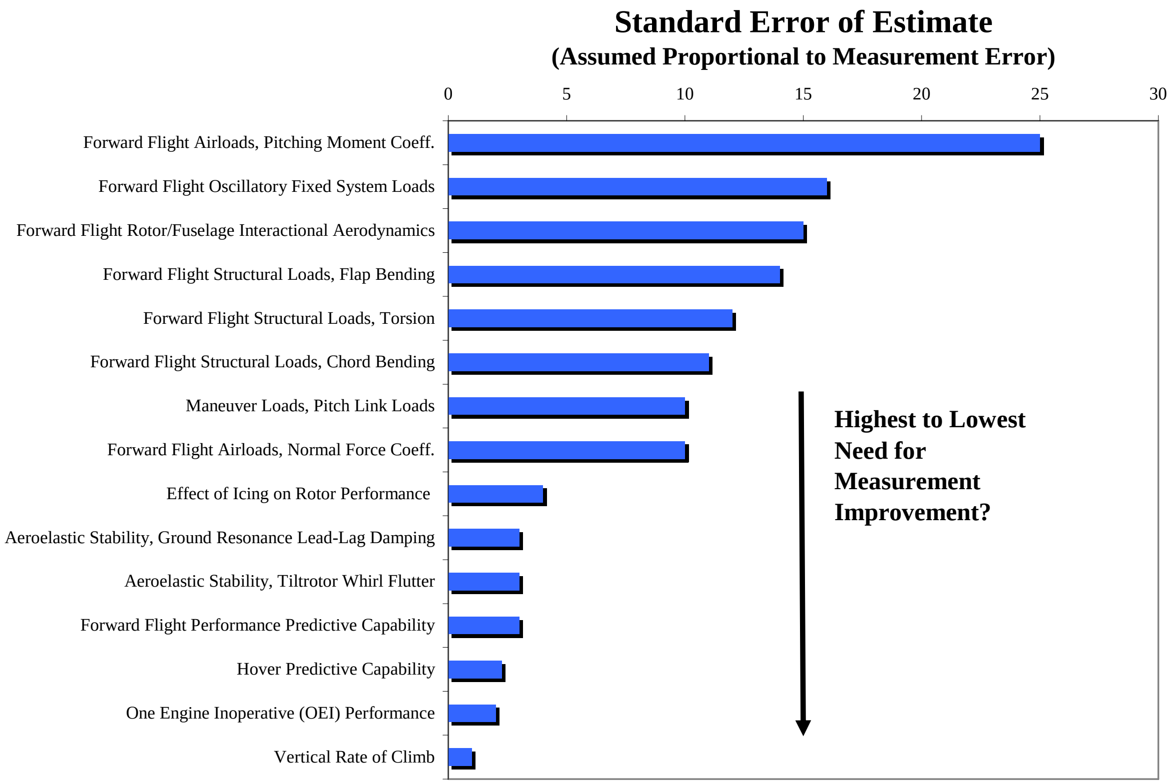


Fig. 5 – Relative Ranking If Standard Error Estimates from SOA Assessment was the Primary Criterion for Prioritizing Aeromechanics Experimental Measurement Improvements

Alternate approaches to technology portfolio analysis will now be discussed. In the aerospace industry, there is never really a clean sheet of paper when it comes to defining and assessing technology portfolios. In many cases, certain technologies have slowly been percolating up from low to high TRL for years if not decades. Therefore, two hypothetical rotorcraft technology portfolios spaced apart by a few of years might in fact look very similar to each other, with only the relative TRL levels perhaps evidencing much change. This observation perhaps overstates the problem, but it does raise important questions as to what is truly innovative versus what is generally accepted "conventional wisdom" regarding technologies that should be pursued. If innovation is to be truly fostered, care must be taken not to accidentally suppress viable new ideas because they do not conform to the conventional wisdom viewpoint.

Therefore, the challenge lies in encouraging design and technological innovation while simultaneously taking into account the inherent uncertainty, in terms of risks and benefits, associated with them. Unnecessary expenditures on infeasible or low-pay-off technologies should be avoided. The temptation for a large organization might be to avoid the lowest TRL technologies and let smaller organizations or academia nurture/incubate this category of technologies. Such conservatism perhaps unnecessarily restricts innovation. However, overly focusing on low TRL technology is also probably undesirable. Ideally improved analysis methodologies are needed that take into account large degrees of uncertainty in a low TRL technology's future potential when performing technology portfolio investment analysis.

Table 2 illustrates a partial list of some of the many rotary-wing technologies that have been or are being currently pursued by many organizations. This list is a synthesis of information from a variety of sources, including, for example, Refs. 7-12 and 28. These technologies are influenced by a number of perceived public good needs. These needs include improved safety, improved community and passenger acceptance, improved environmental effects, and a beneficial influence on aviation-system capacity and operation. For example, Refs. 7, 8, and 11 detail some of the advantages and challenges of developing large, high-speed rotorcraft platforms that might ultimately become a major aviation component of commercial passenger transport. This public good is further decomposed into engineering objectives such as noise, vibration, and emission reductions, as well as crashworthy lightweight structures and efficient high-speed rotors, among others. Additionally, in this paper, new test and analysis capabilities are considered technologies in themselves and, therefore, included in Table 2. Given this interpretation, the development of new test techniques and analysis tools can also be subject to technology portfolio assessments.

Populating Table 2 are numeric values assigned to several different "rating" parameters. The author solely on the basis of his personal opinion and rotorcraft expertise prescribed these "rating" parameter values. The information provided in Table 2 enables the introduction of yet another potential methodology for technology portfolio analysis. Table 2 is also intended to act as a strawman assessment of a suite of technologies currently being pursued by many different rotorcraft research organizations It is hoped that this strawman assessment will help provoke some much-needed critical discussion of the relative merits of these technologies.

Table 2 contains well-considered assessments by the author of not only TRL ratings, but other new "rating" parameters, as well, such as: technical stretch; the value of the technology; the level of analysis fidelity possible for a given technology; and organizational heritage. These parameters were first introduced in Ref. 5 to examine technology issues related to vehicle concepts. These same parameters have been adapted and adopted in this paper to help outline analysis approaches to rating individual technologies for possible inclusion in a research organization's technology portfolio.

In Table 2, the "stretch" parameter is be used to indicate the degree of difficulty in technologically achieving the anticipated individual performance levels for a given technology. Note that it is possible to have a high TRL rating but at the same time a low "stretch" value, as this would represent the situation where a technology has achieved some level of maturation but has reached a performance plateau that currently falls short of its original promise. The "value" parameter quantifies the anticipated applicability of a given technology in meeting some public good goal. The level of analysis "fidelity" parameter is intended to embody in one metric the relative accuracy, range of applicability, and inherent first-principles nature of the existent suite of predictive tools that could be applied to a given technology. This definition is somewhat different than that employed in Ref. 5, above and beyond its application to technologies rather than vehicle concepts. The maximum predictive capability is defined or assessed in this case, rather than indicating relative placement in a spectrum of predictive capabilities as suggested in the work of Ref. 5. Finally, the organizational "heritage" parameter helps gauge a research organization's past interest, or expertise, in a particular technology. In other words, the heritage parameter helps assess whether or not a given organization is uniquely suited to pursue a particular technology versus the research being conducted by some other organization/entity.

As a whole, such a system of parameters as noted in Table 2, and their associated ratings, are essential to methodologies seeking to guide new technology investment decision-making. For it is only through this general type of SME input can the relative risk and benefits of these technologies be assessed. Other rating parameters can perhaps be devised but the parameters noted in Table 2 are proposed as a generic minimum set required to perform satisfactory technology assessments.

Identifying valuable new technologies for investments is only the first step in the overall problem. Such approaches should also ideally be used to track progress towards the development of individual technologies as well as monitor their synergistic effect on vehicle high-level customer/end-user requirements, system functional requirements, or overall potential future public good benefits. Further, such technology portfolio analysis tools should respond to changes in requirements, unexpected and unintended results during detailed design and system integration, and failures to meet expectations during test and evaluation.

Table 2. Representative List of Potential Rotorcraft Technologies for Investment

Candidate Rotorcraft Advanced Technologies:	Technology Readiness Level (TRL)	Technical "Stretch" to Develop (0 easy to 10 hard)	"Value" of Technology (0 low to 10 high)	Level of Analysis Fidelity (0 low to 10 high)	Org. "Heritage" (0 none to 10 high)	Comments and Key Cited Past Work
Rotor Blade Related --						
Advanced Blade Planforms and Airfoils						
Advanced tip shapes	9	3	3	7	9	Tangler, Ogee-Tip work mid-70's
Vane tips and stub-wings	6	3	3	7	9	Tangler, 1978; Lau, 1997
Tip edge treatment/tailoring	3	3	6	5	3	
Variable Twist Blades						
Active control via smart material actuators	4	6	5	5	4	Prahlad &Chopra, 2003 ...
Passive control via aeroelastically tailored blades	4	7	5	5	6	Nixon, 1987 …
Dynamically-tuned, structurally-sound, rotor blades for multi-speed rotor systems	2	7	7		5	
Active Flow Control						
Periodically deployed devices to effect circulation and tip vortex core size changes	3	7	7	3	5	
Weak Ionized Gas Plasma Actuators	3	6	7	3	4	Post & Corke, 2005 …
"Zero Mass" Synthetic Jets	3	6	7	3	5	Hassan, 1998 …
Steady spanwise tip blowing	4	8	5	5	5	Lim, 1994 ; Duraisamy, 2005 …
MEMS-based surface-devices for enhanced BL mixing/energizing (e.g. active VG's)	3	6	7	5	4	Barrett & Farokhi, 1993
Variable camber airfoils						
Drooped leading-edge	4	7	6	5	4	Chandrasekhara, et al, 2004
Fixed/Deployable slats/slots	4	6	7	7	5	Yeo, et al, 2002; Han, 2005 …
Jet-flaps	6	7	1	6	3	
Circulation control airfoils	6	8	1	6	5	
Individual Blade Control (IBC)						
Hydraulic Blade-Root Actuators -- Hydraulic Sling Ring	9	4	8	6	9	
Electromechanical Actuators	3	7	8	6	7	
Active Blade-Embedded Control Surfaces						
Torsionally-soft, dynamically-acceptable rotor blades	9	7	7	6	7	
Embedded flaps/elevons						
Electromagnetic actuators	3	8	5	6	7	Fink, et al, 2000
Electromechanical actuators	5	6	3	6	6	
Piezoelectric actuators	5	8	8	5	5	Sirohi, 2000; Straub, 2001 …
Nitinol/smart-material-based actuators	4	8	3	5	4	Straub & Merkley, 1997 …
Active trailing edge tabs	4	6	3	5	2	Kobiki, et al, 2003
Active (pitching) tips	4	7	5	6	6	Bernhard & Chopra, 1998 …
Rotor Hub/Mechanical-Control-System Related --						
Proprotor Hubs for More than Three Blades per Rotor	7	7	9	7	8	
"Swashplateless" Rotor Primary Flight Control	3	8	7	7	8	Ormiston, 2001; Shen, et al 2004
Higher Harmonic Control via Swashplate						
Flightworthy actuators	9	5	5	5	8	
Control Law development	8	5	5	5	7	
Avionics and flight control system architecture development and integration	8	5	5	5	7	
Airframe Related --						
Ultralightweight Crashworthy Structures	3	4	5	4	9	
Multifunctional Structures Embodying Enhanced Cabin Acoustic Attenuation	3	6	7	4	7	
Hub Drag Reduction						
Advanced (passive) aerodynamic fairings	6	4	5	7	9	Young, 1987; Martin, et al, 1993
Active flow control for enhanced drag reduction	3	7	5	3	4	Ben-Hamou. 2007
Propulsion/Drive-Train Related --						
Ceramic Components for Turbo-Shaft Engines	4	6	7	5	9	
Multi-Speed Efficient Rotor and Propulsion Systems						
Variable-Speed Transmissions	3	8	7	5	3	D'Angelo, 1995
Tip-Jet-Driven Rotors						
Hot-gas cycle	9	6	1	5	3	
Cold-gas cycle	7	6	1	5	5	Mavris, et al, 1994
Avionics and Flight Control Related --						
Low-Cost Portable Precision Guidance/Navigation Aids	7	1	7	N.A.	9	Schmitz, et al, 2007
Flight Control Algorithms to Accommodate Multi-Speed Propulsion	2	5	7	5	3	Litt, et al, 2007
Flight Control Algorithmns to Accommodate Active Rotor Control Systems	4	7	9	5	5	
New Load-Limiting and Health-Monitoring Systems for Enhanced Inflight Safety	9	4	7	5	5	
Test and Evaluation Capability Related --						
External Flowfield Measurements						
Stereoscopic wide-field 3-D PIV	N.A.	3	9	N.A.	10	Heineck, et al, 2000
Internal Flowfield (Propulsion) Sensors						
High-temperature thermal/pressure sensors	N.A.	4	5	N.A.	6	
Image-based Techniques for Wind-Tunnel Blade Displacement Measurements	N.A.	5	9	N.A.	8	
Predictive Capability Related --						
Improved CFD/CSD Coupling for Rotor Aeromechanics Prediction	N.A.	6	9	8	7	
Application of Unstructured Flow-Solvers to Rotorcraft for Improved CFD Efficiency	N.A.	6	8	7	8	
New turbulence models for rotary-wing CFD applications	N.A.	8	9	7	7	
New internal Cabin Noise and Vibration Analysis Methodologies	N.A.	6	7	4	5	
Flight dynamics analysis and design tools for mult-speed & active control rotor systems	N.A.	8	9	5	7	
New computational aeroacoustics analysis and noise propagation tools	N.A.	6	9	7	10	

Several preference strategies can be devised base on the type of assessment information contained in Table 2. For example, a preferred TRL-range could be defined to prioritize technologies. One organization might prefer to invest in low- to mid-TRL technologies, whereas another organization might only want to invest in high TRL technologies. Alternatively, it is not uncommon to make technology investment decisions based on the perceived organizational heritage. Thus there may be a focus on only "core mission" research efforts. Similarly, investment decisions could also be made on any combination of the above as well as accordingly the perceived value, technical stretch, and assumed current predictive capability (i.e. level of analysis fidelity of existent tools).

Table 3 is an example of how an organization's "culture" can influence the relative weighting of these "rating" parameters. Without a keen sense of the global values of an organization's engineering culture it would be extremely difficult to successfully advocate and gain support for proposed technology investment decisions.

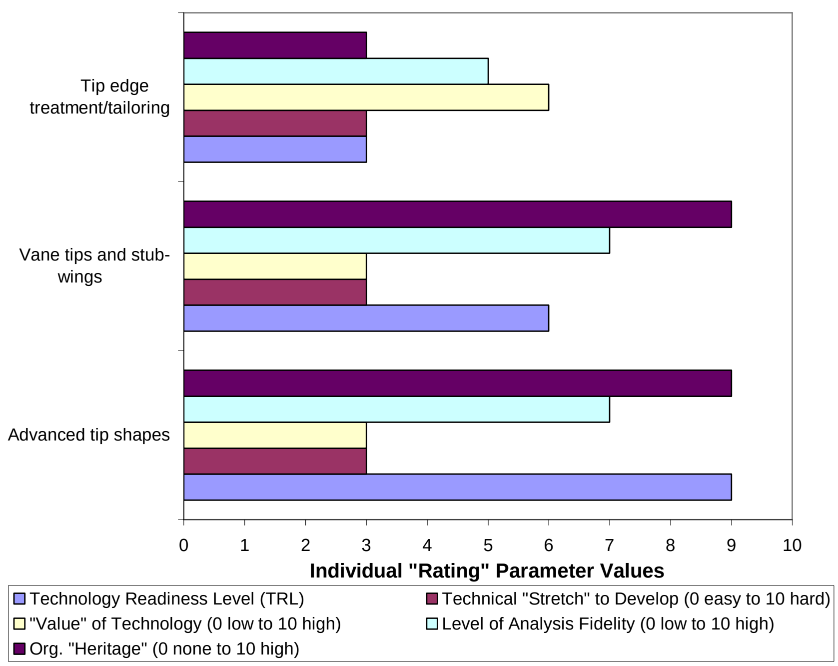
Table 3. Influence of Organizational Culture

	Weighting				
	TRL	Stretch	Value	Level of Analysis Fidelity	Heritage
Core Mission Focused	0.8	0.2	0.8	0.8	0.8
Diversif-ying	0.5	0.5	0.8	0.5	0.2
Risk Adverse	0.8	0.2	0.5	0.8	0.8
Entrepr-eneurial	0.2	0.8	0.8	0.2	0.2

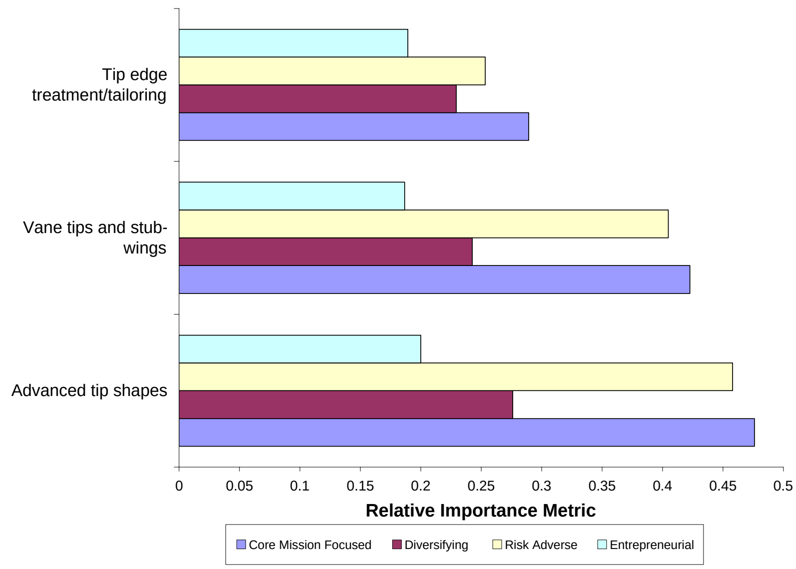
This organizational cultural influence can be captured in a relative importance metric, I. In determining this relative importance metric, N_P is the number of rating parameters being considered in the relative importance metric, W_i is the weight for the ith rating parameter (the numeric values from Table 3, for example), R_i is the non-weighted numeric value assigned to the ith rating parameter (e.g. Table 2), and $R_{\max_i}$ is the maximum possible rating value for ith parameter (also from Table 2) used to normalize the overall result. Note that, by definition, $0 \le W_i \le 1$.

$$I = \frac{1}{N_P} \sum_i W_i R_i \big/ R_{\max_i}$$

Figure 6a-b illustrates, for a few of the technologies noted in Table 2, how these organizational culture weightings can shift the relative importance of individual technologies.



(a)



(b)

Fig. 6. Relative Importance: (a) Initial Rating Parameters and (b) Influence of Organizational Culture

An alternate approach, based on a QFD- (Quality Functional Deployment) inspired methodology, e.g. Refs. 3-6, to effecting technology investment decision-making will now be discussed. A general QFD-like matrix is shown in Fig. 7. A tailored QFD-matrix to the rotorcraft technologies problem is illustrated in Figure 8, where the QFD matrix is partially populated by a subset of the Table 2 technologies. The numerical ratings contained in Fig. 8 are based solely on the author's personal opinions and expertise. The sum of the ratings in a single row must equal unity. In addition to a suite of technologies it is also necessary to define some nominal technical goals and objectives to which the technologies are ideally intended to help address. The sum of the ratings in individual columns ranks the relative influence of a given technology on the overall engineering objectives, which in turn must be identified with and support the public good goals, which are also noted. There are three "goals" that are identified (again provided only to illustrate the methodology) to which individual technologies can be classified in terms of being most responsive/directed towards a given goal or subset of goals. The first public good "goal" is the introduction of large commercial passenger transport rotorcraft (see Ref. 7 for example). The second "goal" is to reduce overall design cycle time, risk, and costs, doing so by primarily improving predictive capability. The third "goal" is the development of an environmentally benign, community and passenger friendly aircraft.

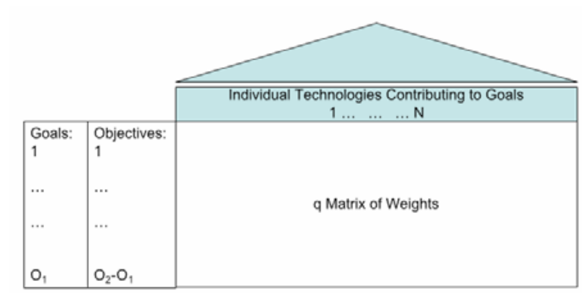


Fig. 7. General Format of QFD-Inspired Tabular Matrix

In this QFD-inspired approach technology investments are made in proportion to the relative cumulative scoring of given technology (by adding up the numerical values in a given matrix column) as to its anticipated applicability (given subject matter expert input) on one or more technical objectives supporting one or more goals. The more technical objectives a technology is applicable towards, and the more profoundly the technology influences those objectives, the higher the priority that should be given to investing in that technology.

A QFD-inspired matrix also provides a good visual confirmation of whether or not a technology portfolio is "well-balanced" in the sense that: all goals and objectives are satisfactorily addressed and that a reasonable number of technologies can be applied to meeting those goals and objects; and that there are not too many or too few technologies being applied to a given technology goal or objective.

		Rotor Blade Related						Rotor Hub/Mechanical-Control-System Related			Airframe Related			Propulsion/Drive-Train Related			Avionics and Flight Control Related				Test and Evaluation Capability Related			Predictive Capability Related					
		Advanced Blade Planforms and Airfoils	Variable Twist Blades	Dynamically-tuned rotor blades for multi-speed rotor systems	Active Flow Control	Individual Blade Control (IBC)	Active Blade-Embedded Control Surfaces	Proprotor Hubs for More than Three Blades per Rotor	"Swashplateless" Rotor Primary Flight Control	Higher Harmonic Control via Swashplate	Ultralightweight Crashworthy Structures	Multifunctional Structures Embodying Enhanced Cabin Acoustic Attenuation	Hub Drag Reduction	Ceramic Components for Turbo-shaft Engines	Multi-Speed Efficient Rotor and Propulsion Systems	Tip-Jet-Driven Rotors	Low-Cost Portable Precision Guidance/Navigation Aids	Flight Control Algorithms to Accommodate Multi-Speed Propulsion	Flight Control Algorithmns to Accommodate Active Rotor Control Systems	New Load-Limiting and Health-Monitoring Systems for Enhanced Inflight Safety	External Flowfield Measurements	Internal Flowfield (Propulsion) Sensors	Image-based Techniques for Wind-Tunnel Blade Displacement Measurements	Improved CFD/CSD Coupling for Rotor Aeromechanics Prediction	Application of Unstructured Flow-Solvers to Rotorcraft for Improved CFD Efficiency	New turbulence models for rotary-wing CFD applications	New internal Cabin Noise and Vibration Analysis Methodologies	Flight dynamics analysis and design tools for mult-speed & active control rotor systems	New computational aeroacoustics analysis and noise propagation tools
Enable Large Commercial Transport Rotorcraft	Develop approach and identify concepts for variable ratio mechanical power transmission that enables large speed changes with minimum weight penalty	0	0	**0.08**	0	**0.08**	**0.08**	0	0	**0.08**	0	0	0	0	**0.08**	**0.08**	0	**0.08**	**0.08**	**0.08**	0	**0.08**	**0.08**	**0.08**	0	0	0	**0.08**	0
	Demonstrate lightweight but robust structural concepts for non-rotating and rotating vehicle components	0	0	0	**0.17**	0	0	**0.17**	**0.17**	0	**0.17**	**0.17**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0.17**	0	0
	Improved turbo-shaft engine efficiencies with increased engine reliability	0	0	0	0	0	0	0	0	0	0	0	0	**0.25**	**0.25**	0	0	0	0	**0.25**	0	**0.25**	0	0	0	0	0	0	0
Reduced Design Cycle Time and Improved Design Confidence	Demonstrate integrated model with engine and drive-system dynamics with improved accuracy of prediction	0	0	**0.17**	0	0	0	**0.17**	0	0	0	0	0	0	0	0	0	**0.17**	0	**0.17**	0	**0.17**	0	0	0	0	0	**0.17**	0
	Improve CFD accuracy relative to wind tunnel test data for all flight conditions.	**0.08**	**0.08**	0	**0.08**	**0.08**	**0.08**	**0.08**	**0.08**	**0.08**	0	0	**0.08**	0	0	**0.08**	0	0	0	0	0	0	0	**0.08**	**0.08**	**0.08**	0	0	0
	Improve experimental accuracy & comprehensiveness of rotor and aiframe measurements, particularly acquiring new data for new designs and unexplored operating conditions/flight regimes	**0.08**	**0.08**	0	**0.08**	**0.08**	**0.08**	**0.08**	**0.08**	**0.08**	0	0	**0.08**	0	0	**0.08**	0	0	0	0	**0.08**	**0.08**	**0.08**	0	0	0	0	0	0
Enable Environmentally-Benign and Community/Passenger Friendly Rotorcraft	Model mid and high frequency velocity response of relevent rotorcraft structure within 5dB of exp. data	0	0	0	0	0	0	0	0	0	0	**0.33**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0.33**	0	**0.33**
	Improved source noise prediction while accounting for large RPM variations and/or active rotor control inputs	**0.06**	**0.06**	**0.06**	**0.06**	**0.06**	**0.06**	**0.06**	**0.06**	**0.06**	0	0	0	0	**0.06**	**0.06**	**0.06**	0	0	0	0	0	0	**0.06**	**0.06**	**0.06**	0	0	**0.06**
	Develop improved noise scattering and propagation capability; to predict within 5dB at 150ft altitude under temperature inversion weather conditions	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0.5**	0	0	0	0	0	0	0	0	0	0	0	**0.5**

Fig. 8. An Example of a QFD-Inspired Technology Portfolio Assessment of Advanced Rotorcraft Technologies

Technology investment decisions are only the first step in the engineering management of technology portfolios. Ideally, the system analysis tools used to support investment decisions could also be used to track progress in developing individual technologies, to evaluate systemic effects on technical goals and objectives by underperforming technologies, and to refine the portfolio complement to reflect not only technical progress but evolving programmatic requirements. Further, the information flow regarding technology portfolio decisions should not be one-way, i.e. from technologists to system analysts to engineering and programmatic managers. Indeed, considerable value could be accrued if the information flows in both directions. Technologists should be better informed on systemic and societal benefits implications of their work. It is rare that individual technologists have an adequate background in system analysis and systems engineering. Therefore, an ideal situation would be that technology portfolio analysis tools be sufficiently transparent in their utility to provide technologists timely feedback on the value, in public good terms, of the specific technologies that they are investigating.

Ultimately, establishing and managing a robust technology portfolio is essential to meeting the key goals of many engineering research organizations: to better address current and emerging public good needs, to foster technological innovation, and to improve the efficiency and confidence of the design process. To define and maintain a high-quality technology portfolio requires a well-thought conceptualization process, judicious application of technical discipline assessments, the essential and integral requirement for high-fidelity system analysis to aid in technology investigations, and well-considered technology investment decision-making processes. In short, research, as a pursuit or process, can benefit from adaptation and adoption of many of the practices of systems engineering discipline.

Concluding Remarks

This paper has discussed systems engineering in the context of research organizations where the products are knowledge acquisition and technology development. Arguments were presented that key aspects of system analysis and systems engineering were important components throughout the research and technology development life cycle. A number of ideal attributes for rotorcraft system analysis tools and methodologies were advanced in the paper as well. The discussion specifically focused on the related issues of technology investment decision-making and how that might be positively influenced by periodic state of the art assessments and rotorcraft system analysis studies.

The initial technology investment decisions are only the beginning of a continuous process of tracking the progress and assessing the successes and failures of the complete technology research and development cycle, as well as the required management of the transfer of these technologies into vehicle development efforts. In this regards, system analysis is an essential element of aerospace systems engineering.

References

1. Shishko, R., et al, "NASA Systems Engineering Handbook," NASA SP-610S, June 1995.
2. International Council on Systems Engineering website: http://www.incose.org/
3. Young, L.A., "Future Roles for Autonomous Vertical Lift in Disaster Relief and Emergency Response," Heli-Japan 2006: AHS International Meeting on Advanced Rotorcraft Technology and Life Saving Activities, Nagoya, Japan, November 15-17, 2006.
4. Young, L.A., "System Analysis Applied to Autonomy: Application to Human-Rated Lunar/Mars Landers," AIAA-2006-7516, AIAA Space 2006, San Jose, CA, September 19-21, 2006.
5. Young, L.A., "Aerobots as a Ubiquitous Part of Society," AHS Vertical Lift Aircraft Design Conference, San Francisco, CA, January 18-20, 2006.
6. Young, L.A., Yetter, J.A., and Guynn, M.D., "System Analysis Applied to Autonomy: Application to High-Altitude Long-Endurance Remotely Operated Aircraft," AIAA Infotech@Aerospace Conference, Arlington, VA, September 2005.
7. Johnson, W., Yamauchi, G.K., and Watts, M.E., "NASA Heavy Lift Rotorcraft Systems Investigation," NASA TP-2005-213467, December 2005.
8. Johnson, J. et al, "Evaluation of the National Throughput Benefits of the Civil Tilt Rotor," NASA CR-2001-211055, September 2001.

9. Wilkerson, J.B., et al, “Technology Needs for High-Speed Rotorcraft, Vol. 1,” NASA-CR-177585, May 1991.
10. Scott, M.W., “Technology Needs for High-Speed Rotorcraft, Vol. 2,” NASA-CR-177590, August 1991.
11. Clay, B., et al, “Civil Tiltrotor Missions and Applications,” NASA-CR-177452, July 1987.
12. Bauchspies, J.S., et al, “Tradeoff analysis of technology needs for public service helicopters,” NASA-CR-3927, August 1985.
13. Davis, S. J., Rosenstein, H., Stanzione, K. A., Wisniewski, J. S., “HESCOMP. The Helicopter Sizing and Performance Computer Program. User's manual, revision 2,” NASA-CR-168697, 1979.
14. Schoen, A. H., Rosenstein, H., Stanzione, K., Wisniewski, J. S., “VASCOMP 2. The V STOL Aircraft Sizing and Performance Computer Program. Volume 6 User's manual, revision 3,” NASA-CR-163639, 1980.
15. Hirsh, J., Wilkerson, J., and Narducci, R., “An Integrated Approach to Rotorcraft Conceptual Design,” AIAA-2007-1252, 45th AIAA Aerospace Sciences Meeting and Exhibit, Reno, Nevada, Jan. 8-11, 2007.
16. Yamauchi, G.K. (Ed.), et al, “A State of the Art Assessment for NASA Rotary-Wing Research,” Soon to be Published NASA TM.
17. Stepniewski, W.Z. and Shinn, R.A., “Soviet Vs. U.S. Helicopter Weight Prediction Methods,” 39th Annual Forum of the American Helicopter Society, St. Louis, MO, May 9-11, 1983.
18. Stepniewski, W.Z., “Some Weight Aspects of Soviet Helicopters,” 40th Annual Forum of the American Helicopter Society, Arlington, VA, May 16-18, 1984.
19. Tischenko, M.N., Nagaraj, V.T., and Chopra, I. "Preliminary Design of Transport Helicopters." Journal of the American Helicopter Society, 48:2, April 2003.
20. Bousman, W.G. and Norman, T.R., “Assessment of Predictive Capability o Aeromechanics Methods,” AHS Specialists Meeting on Aeromechanics, San Francisco, CA, January 23-25, 2008.
21. Tischenko, M.N. "Mil Design Bureau Heavy-Lift Helicopters." Journal of the American Helicopter Society, 42:2, April 1997.
22. Streich, E.G., “A Development Program Comparison: CH-47 and the V-22,” 57th Annual Forum of the AHS International, Washington, DC, May 9-11, 2001.
23. Roth, B. and Mavris, D. “Technology Portfolio Assessments Using a Modified Genetic Algorithm Approach,” AIAA-2002-5424, 9th AIAA/ISSMO Symposium on Multidisciplinary Analysis and Optimization, Atlanta, GA, Sept. 4-6, 2002.
24. Maier, M.W., Singleton, G., and Fishenden, J., “Selecting System Portfolios,” 2004 IEEE Aerospace Conference, Big Sky, MT, March, 2004.
25. Elfes, A., Lincoln, W.P., Rodriguez, G., Weisbin, C.R., and Wertz, J.A., “Risk-Based Technology Portfolio Optimization for Early Space Mission Design,” IEEE Transactions on Aerospace and Electronics Systems, Vol. 42, No. 1, January 2006.
26. Some, R.R., Weisbin, C., Neff, J., and Witz, J., “XML Based Tools for Assessing Potential Impact of Advanced Technology,” 2004 IEEE Aerospace Conference, Big Sky, MT, March, 2004.
27. Mavris, D.N., Baker, A.P., and Schrage, D.P., “Implementation of a Technology Impact Forecast Technique on a Civil Tiltrotor,” 55th Annual Forum of AHS International, Montreal, Canada, May 25-27, 1999.
28. Anon. “Rotorcraft Research and Development Initiative 10-Year Plan (in response to Vision 100 – Century of Aviation Reauthorization Act),” FAA Report to Congress – House Committee on Science and Senate Committee on Commerce, Science, and Transportation, 2004.
30. Rand, O. and Khromov, V. "Helicopter Sizing by Statistics." Journal of the American Helicopter Society, 49:3, July 2004.