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ELEMENTS OF AN EMERGING VIRTUAL STOCHASTIC LIFE CYCLE DESIGN ENVIRONMENT

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ABSTRACT

The challenge of designing next-generation systems that meet goals for system effectiveness, environmental compatibility, and cost has grown to the point that traditional design methodologies are becoming ineffective. Increases in the analysis complexity required, the number of objectives and constraints to be evaluated, and the multitude of uncertainties in today's design problems are primary drivers of this situation. A new environment for design has been formulated to treat this situation. It is viewed as a testbed, in which new techniques in such areas as design-oriented/physics-based analysis, uncertainty modeling, technology forecasting, system synthesis, and decision-making can be posed as hypotheses. Several recent advances in elements of this multidisciplinary environment, termed the Virtual Stochastic Life Cycle Design Environment, are summarized in this paper.

LIST OF ACRONYMS

AAW = Active Aeroelastic Wing
CDF = Cumulative Distribution Function
DOE = Design of Experiments
FPI = Fast Probability Integration
HSCT = High Speed Civil Transport
IMAGE = Intelligent Multidiscip. A/C Generation Env.
IPPD = Integrated Product and Process Develop.
ISE = Intelligent Synthesis Environment
JPDM = Joint Probability Decision Making
MDA = Multidisciplinary Analysis
POS = Probability of Success
RDS = Robust Design Simulation
RSE = Response Surface Equation
RSM = Response Surface Method
SBA = Simulation Based Acquisition
TIES = Technology Identification, Evaluation, Select.
TIF = Technology Impact Forecast
TIM = Technology impact Matrix
TOC = Total Ownership Cost
TRL = Technology Readiness Level
VSLCDE = Virtual Stochastic Life-Cycle Design Env.

INTRODUCTION

The intent of this paper is to describe advances in key elements of the Virtual Stochastic Life Cycle Design Environment (VSLCDE), introduced by the authors in Ref. [1]. The weaving together of a consistent, robust approach to complex systems design and engineering decision-making was motivated by numerous new initiatives in the government and industry sectors. Some of these proposed paradigms attracting proponents include multidisciplinary design optimization (MDO), Total Cost of Ownership (TOC) reduction, Design for Affordability, Cycle Time Reduction, Intelligent Synthesis Environments (ISE), Simulation-Based Acquisition (SBA), etc. A common thread amongst all of these appears to be an emphasis on using existing tools in new ways to create new and more reliable information for systems design, program management, and acquisition. MDO focuses on understanding and exploiting the interactions between traditional disciplines, primarily through integrated analysis and optimization techniques. Affordability (Ref. [2]) and TOC reduction (Ref. [3]) initiatives emanate mostly from the armed services and focus on understanding the interplay between system effectiveness, system life cycle cost, and the investment in advanced technologies required to achieve optimal results. Shifts in currents of commercial aviation and challenging goals from legislatures have evoked a response from the NASA in the form of the "Three Pillars for Success" program, described in Ref. [4]. A recent National Research Council report asserted that to achieve the goals set forth in the "Three Pillars" program, breakthrough technologies, in terms of both evolutionary and revolutionary developments, will be required (Ref. [5]). The ISE (Ref. [6]) is a new NASA endeavor centered on the creation of an advanced engineering environment that facilitates collaboration and efficiency in designing complex vehicles and their missions as well as achievement of the 10 goals called for in "Three Pillars". To facilitate this objective, a means to quantify and forecast the impact of emerging technologies or mix of technologies must be created. SBA, promoted by the Department of Defense, is being worked mainly by the defense industry and is focused on collaboration between contractors and the acquisition community. This collaboration intends to reduce time and cost while increasing the effectiveness of next generation military systems by employing modeling and simulation in Phase 0 and 1 of the acquisition process. The VSLCDE addresses many of the aims just described in one form or another, though it is clearly not THE answer. Instead, it should be viewed as a testbed for the examination of *individual research hypotheses* associated with its various elements.

The VSLCDE concept was initially formulated in 1997, representing a culmination of 5 years of research (sponsored primarily by NASA and the Office of Naval Research). The origins of this development began with the Integrated Product and Process Development (IPPD) concept (Ref. [7]), which proposed that downstream, manufacturing related issues must be considered in concert with product performance during early design phases. This was followed in subsequent years by the direct linking of design synthesis and economics (Ref. [8]), which facilitated IPPD studies. Also, the use of the Response Surface Method (RSM) for product and economic analysis approximation (Refs. [9, 10]) was a crucial advancement at that time. The recognition of uncertainty inherent in economic forecasting and engineering analysis prompted the development of Robust Design Simulation (RDS) (Refs. [11]). The most recent addition is the Technology Identification Evaluation Selection (TIES) technique (Ref. [12]), which specifically tackles the issues of new technologies in design evolution. All of these pieces are embedded and integrated in the VSLCDE. The overarching goal of the environment is to facilitate complex system design decision-making over time (at any level of the organization) in the presence of uncertainty.

Since the publication of the initial VSLCDE in 1998, advances have been made in various elements of this important research testbed. This paper describes some of those advances. Each of these research results characterizes an element in an overall research program directed towards further development, testing, and implementation of the VSLCDE.

A VIRTUAL STOCHASTIC LIFE CYCLE DESIGN ENVIRONMENT

The purpose of the VSLCDE is to facilitate design decision-making over time (at any level of the organization) in the presence of uncertainty, allowing affordable solutions to be reached with adequate confidence. The descriptors in the name attempt to capture the ambitious scope of the environment. Each term is in reality a new frontier for aerospace design methodologies, as summarized in Table 1. Further rationale behind this innovative engineering environment is described next.

Table 1 : VSLCDE Descriptors

Descriptor	Meaning
Virtual	Physics-based system life-cycle prediction
Stochastic	Time-varying uncertainty is modeled; temporal decision-making support is sought
Life-Cycle	The design, engineering development, test, manufacture, flight test, operational simulation, sustainment, and retirement of a system. The operational simulation includes virtual testing, evaluation, certification, and fielding of a vehicle in the existing infrastructure, and the tracking of its impact on the market environment.
Design	The environment's main role is to provide knowledge for use by decision-makers, especially for finding robust solutions.
Environment	Implies the support of geographically distributed analyses and people through collaboration tools and data management techniques

A conceptual depiction of the environment, as currently envisioned, has been formed and appears in Figure 1. A design project starts with activity in five elements. These are problem formulation/uncertainty modeling, physics-based modeling, integration, decision support, and decision-making, respectively. Each of these major elements is composed of detailed techniques and methods, several of which are exemplified in this paper. *Problem Formulation* consists of the identification of overall requirements, potential ambiguity in those requirements, uncertainties in the product's potential manufacturing and operating environment, potential technologies, etc. *Physics-Based modeling* consists of analysis derived from the fundamental engineering disciplines that provide the basis for design, along with techniques for approximating this complex set of analyses in a form and cost suitable for early design studies. *Decision support* functions both at the beginning and end of a project design iteration (in a sense, one cycle through the VSLCDE). Knowledge-bases, utility theory and other concepts are used in conjunction with the problem formulation information to create meaningful objectives to guide the process. The *Integration and Decision-making* elements operate on the knowledge produced by the first three to generate design options, characterize the relative merits of those options, and estimate the confidence of the results in light of uncertainty. Each of the five elements is described in more detail below, including a reporting of recent advances. The reader is referred to Ref. [1] for further explanations of the five elements.

RECENT RESEARCH RESULTS INVOLVING THE KEY ELEMENTS

Several important research efforts have been completed over the last two years concerning elements of the VSLCDE. While individual elements may be sound in themselves, validation of the integrated design environment proposed is difficult. Unlike the aerodynamics or structures fields, where new analyses can be validated against experimental data that is relatively easy to obtain, validation data for complex systems design methods is scarce at best. It is time-consuming and expensive to conduct an entire design exercise for the sole purpose of method validation. Instead, elements of this VSLCDE are to be examined first, and the results used to guide further, more comprehensive validation efforts.

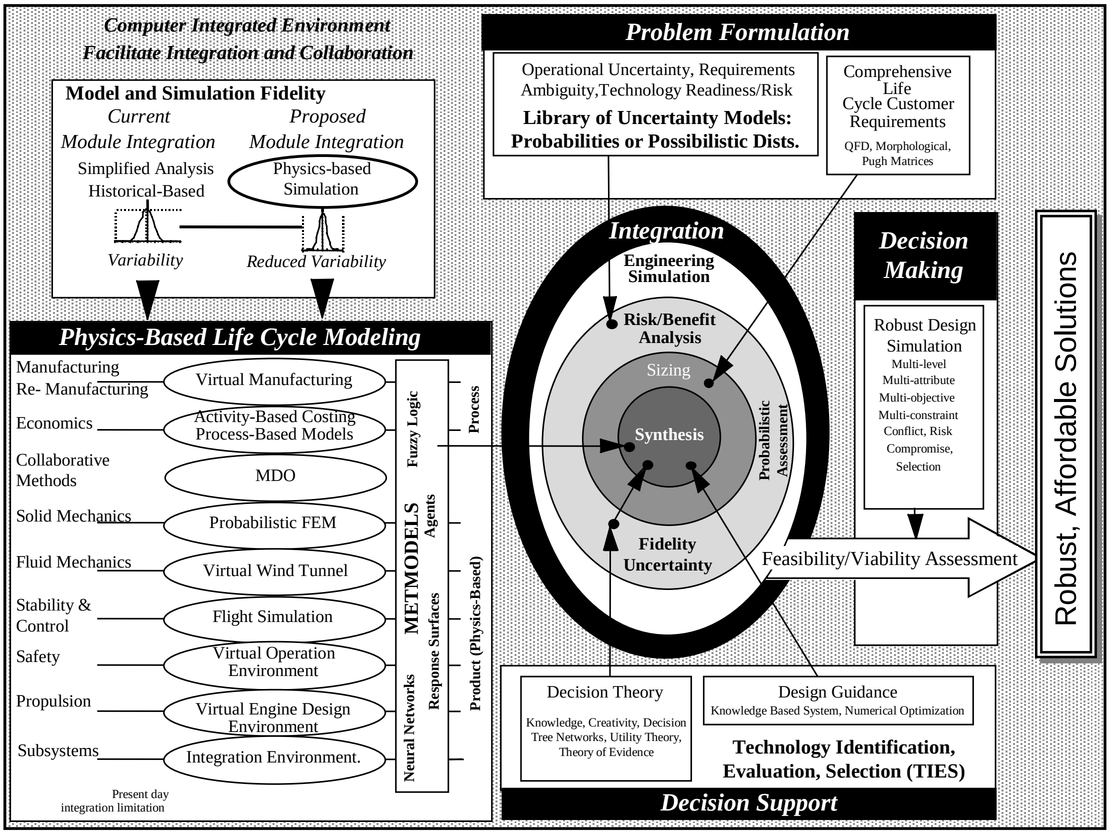


Figure 1: The Virtual Stochastic Life Cycle Design Environment (VSLCDE)

PHYSICS-BASED MODELING & SIMULATION; DESIGN-ORIENTED METAMODELS

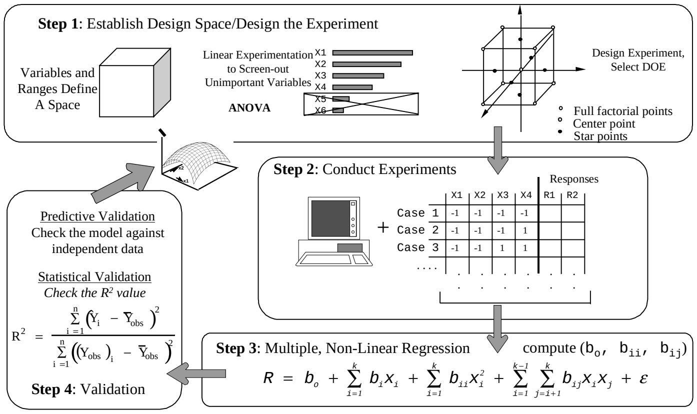
Role in VSLCDE

Information from the contributing disciplines is critical to successful design. In general, the most reliable source of such information is from historical data and context, i.e. ”In designing a wing for airplane model 2, examine the wing designed for model 1”. This reliance on historical data becomes untenable in two circumstances: a) components are envisioned which fall outside the nature of the database in some significant way (shape, composition, material, etc.), and b) down-stream attributes are to be considered which were not considered in previous designs. In these cases, physics-based analyses are employed to model revolutionary concepts (or any concept outside of the database) and attempt to capture life-cycle considerations, such as manufacturing, operation, and disposal. However, the classic “efficiency vs. accuracy” dilemma arises since these physics-based analyses often come at the price of computational complexity. Clearly, the design of a complex system using complex disciplinary analysis at each iteration becomes impractical. The use of metamodels addresses this dilemma by allowing higher-fidelity models to be represented (via “intelligent” approximation) and, consequently, reduces design cycle time. Through these metamodels, design-oriented analyses supply the needed information in a more efficient manner. Further, the error inherent in approximation is not discarded, but is quantified and carried through to system synthesis and decision making in the form of uncertainty.

The approach just described implies the existence of the physics-based models. Such models for an actual product are key to understanding the physical interactions among various components of a complex engineering system. These models often take the form of structural, thermal, fluid flow, or similar analysis capabilities that are based on natural governing equations. In contrast, process (both system and subsystem) models focus more on the processes by which the product is evolved, and they should capture the process impact on various design objectives. Such processes can encompass manufacturing, operational economics, maintenance, etc. Many of today’s existing product and process models were developed and have matured in a single, focused disciplinary area (e.g. legacy codes). They are often slow, require significant user interaction and expertise, and are difficult to incorporate into an integrated synthesis process. In other cases, physics-based models required for new technologies might not exist at all. Thus, a companion need to the design-oriented use of metamodels in the formation of VSLCDE is the development of physics-based models of key responses and/or constraints as a function of design variables. The scope of this need, of course, depends on the particular product and organization in question.

The nominal use of several metamodel techniques is now fairly well understood (Refs. [13, 14]) and increasingly accepted in the aerospace design community. The status of this element of the VSLCDE remains a function of the particular discipline in question. Barriers often include the incompatibility of existing physics-based tools with automated or repeated execution necessary for the creation of design-oriented metamodels. And, of course, accuracy of the approximation always remains an issue. The current, generic procedure employed by the authors for the generation and validation of metamodels is depicted in Figure 2. This procedure is often referred to as the aforementioned Response Surface Method (RSM), and it results in Response Surface Equations (RSEs). The usual form for the RSEs is a second-order polynomial shown in Eq. (1), where, b_i are regression coefficients for the first degree terms, b_{ii} are coefficients for the pure quadratic terms, b_{ij} are coefficients for the cross-product terms (second order interactions), and b_o is the intercept term. The $\mathbf{x}_i$ terms are the "main effects", the $\mathbf{x}_i^2$ terms are the "quadratic effects", and the $\mathbf{x}_i\mathbf{x}_j$ are the "second-order interaction terms". If a 2nd-order polynomial is found to be inadequate, other forms are possible, such as exponential or logarithmic, through a transformation of both the independent and dependent variables. The RSM is applied at numerous points in the VSLCDE. Two example applications using RSM are presented next.

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



$$R^2 = \frac{\sum_{i=1}^{n} \left(\hat{Y}_i - \bar{Y}_{obs}\right)^2}{\sum_{i=1}^{n} \left(\left(Y_{obs}\right)_i - \bar{Y}_{obs}\right)^2}$$

$$R = b_o + \sum_{i=1}^{k} b_i x_i + \sum_{i=1}^{k} b_{ii} x_i^2 + \sum_{i=1}^{k-1} \sum_{j=i+1}^{k} b_{ij} x_i x_j + \varepsilon$$

Figure 2: RSE Generation and Validation Procedure

Example 1: Integrated, Physics-Based Analysis for Drag Polar RSEs

The creation and utilization of accurate drag polars is one of the most essential components in the conceptual aircraft synthesis process. An improved general procedure to generate parametric drag polars in the form of RSE has been created and is reported in detail in Ref. [15]. Such sets of equations are used to facilitate and support aerospace system design studies in the VSLCDE. The RSEs replace the empirical aerodynamic relations often found in sizing and synthesis codes, especially when a configuration falls beyond the conventional realm. The accuracy of these RSEs can be tested to demonstrate the quality of their predictive capability. The improved approach is based on a statistical methodology (the RSM), which includes the use of Design of Experiments (DOE) (Ref. [16]). Computational aerodynamic codes based on linearized potential flow and boundary layer theory are employed. A major improvement over previous efforts is the development and use of an automated computational architecture that is capable of handling significant exchanges of data and information. Architectures of this type are envisioned for use throughout the VSLCDE.

As discussed, the physics-based analysis/metamodel approach is applied. Specifically, RSEs are produced by running cases derived from the DOE using actual aerodynamic analysis tools. The RSM was first applied to a High Speed Civil Transport (HSCT) design project at Aerospace Systems Design Laboratory (ASDL) of Georgia Tech in 1995. Since then, computational modeling and the DOE techniques have been improved spanning several years from 1996 to 1998. During this time, different linearized aerodynamic codes have been tested and used in the RSE generation, and their idiosyncrasies have been identified and solutions suggested and found. At the inception of this technique, the generation of drag polars in RSE format was inefficient requiring significant human intervention and monitoring. Since then, greater efficiency has been achieved in generating parametric drag polars, resulting in earlier completion time for aerodynamics facilitating other disciplines in the whole design project. The most recent research work in this regard is summarized in Figure 3. Details on the aerodynamic codes appearing in the flowchart can be found in Ref. [15].

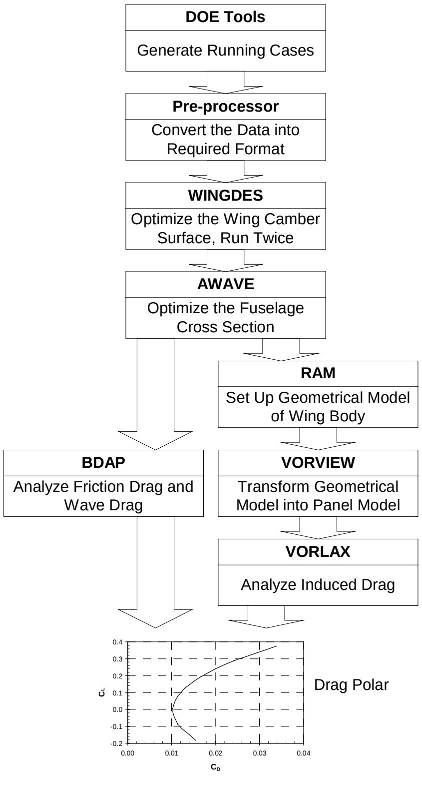


Figure 3: Analysis Integration for Aerodynamics (Ref. [15])

RSEs for HSCT drag polars were generated with satisfactory accuracy (confidence as high as 99% for subsonic flight and about 97% for supersonic flight) in the study in Ref. [15] and thus provide an efficient replacement for actual aerodynamic analysis. An example result is given in Figure 4, which is a plot of actual Lift-to-Drag ratios as computed from the actual analysis for 289 different aircraft versus the predicted ratio from the RSEs. Almost all the erros fall within a 5% error band. Appropriate computer codes, including wing design (WINGDES), area-rule optimization (AWAVE), parasite analysis (BDAP) and induced drag analysis (VORLAX), are selected and validated based on a compromise between required accuracy and desired efficiency. Thus, it is concluded that subsonic aerodynamic analysis can be represented very accurately by the RSM approach, though it was found that supersonic analysis is represented with less accuracy due to the sensitivity of Mach line to discretization of planforms, as discussed in Ref. [15].

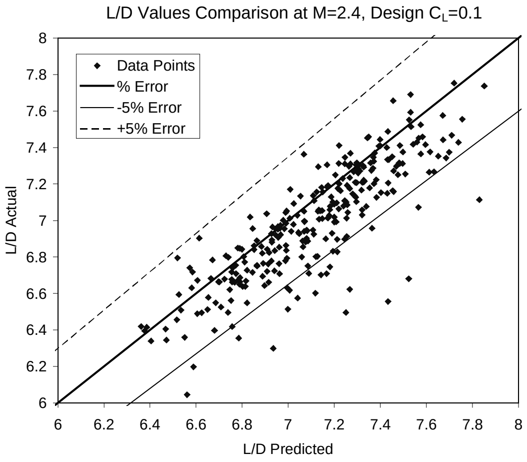


Figure 4: L/D Comparison for M=2.4 (Ref. [15])

Example 2: Aeroelastic Analysis with RSM for Design-Oriented Structural Optimization

In contrast to the previous example that involved a single discipline (aerodynamics), the next example illustrates the use of sophisticated, physics-based analysis in the VSLCDE involving multiple disciplines. Specifically, a multidisciplinary study considering the impact of Active Aeroelastic Wing (AAW) technology on the structural wing weight of a lightweight fighter concept was performed (Ref. [17]). The study incorporated multidisciplinary design analysis (MDA) and RSM to characterize wing weight as a function of wing geometry. The study involved the sizing of the wing box skins of several fighter configurations to minimum weight, subject to static aeroelastic requirements, using a finite element approach. In addition, the problem makes use of a new capability for trim optimization for redundant control surfaces to accurately model AAW technology. The RSM in this case uses the parametric definition of a structural finite element model in conjunction with an aerodynamic model to build RSEs of wing weight as a function of wing geometric parameters for both AAW technology and conventional control technology. The goal for this design study was to demonstrate a process by which some of the benefits associated with AAW technology could be quantified over the design space of wing geometry, so that future conceptual designers may make the best use of the technology.

In order to realize the maximum potential of AAW technology, a clear comparison between AAW and a conventional control approach over the wing geometry design space must be provided to the conceptual level designer. This guidance, in part, includes the influence of wing design parameters (e.g., aspect ratio, taper ratio, etc.) on structural weight, which can be expressed as polynomial equations for the synthesis and sizing of a new fighter concept. Traditionally, these equations were obtained through regression of historical data. *However, since AAW is a new technology and falls outside the range of validity of the historical data, one must rely on physics-based simulation to generate these relations.* Refs. [18] and [19] used finite element methods and equivalent laminated plate analysis, respectively, in conjunction with RSM to generate wing weight RSEs as a function of wing geometry for an HSCT concept. In addition, Ref. [20] demonstrated a procedure to develop wing bending material weight equations for a HSCT using finite element based structural optimization.

The task of representing AAW technology poses a similar challenge. Traditional weight equations used in the sizing of fighter concepts will not likely provide accurate estimates of wing structural weight. Instead, detailed aerodynamic and structural simulations, incorporating accurate modeling of AAW technology, must be used to understand the new relationships between wing weight and wing geometry. The process developed for this is depicted in Figure 5. Again, it is emphasized that the physics-based, metamodel approach is applied.

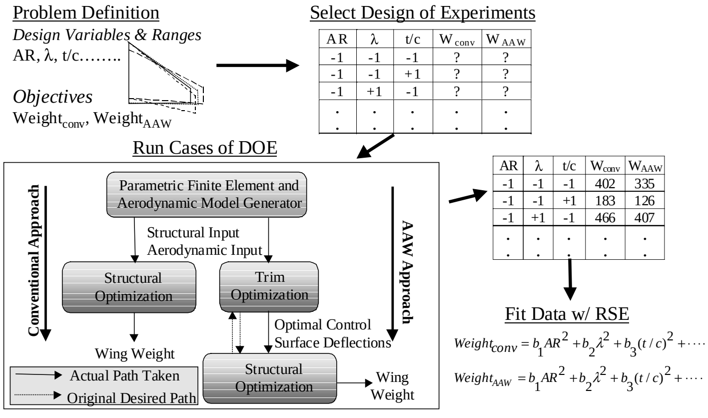


Figure 5: MDA Wing Design Process (Ref. [17])

For future design studies of advanced AAW-equipped fighters performed in the VSLCDE, these RSEs could be used to complement the historically based equations that are currently residing in standard synthesis/sizing codes. The study summarized here demonstrated the viability and effectiveness of several key elements of the wing weight generation process. These include the parameterization of a finite element and linear aerodynamic model, the use of DOE/RSM techniques for computationally affordable function approximation, and recent advances in aeroelastic design methods to include trim optimization for the modeling of AAW technology. The use of such physics-based tools is necessary to effectively design for some advanced technologies such as AAW where the historically based equations are no longer valid. The study results indicate that AAW technology enables wing designs with better aerodynamic characteristics and reduced weight.

UNCERTAINTY MODELING FOR NEW TECHNOLOGIES; DECISION SUPPORT

Role in VSLCDE

For complex systems, the search for feasible and viable solutions often requires the application of multiple new technologies. The ability to accurately predict the tradeoffs between (and within) alternative technologies from a benefit, risk, and affordability viewpoint is of tremendous value to the designer/decision maker and a critical piece of the VSLCDE. In general, the impact of a technology is probabilistic in nature, even stochastic. The probabilistic nature arises from various contributing factors, including maturity of the concept, variability in the eventual performance, and the risk involved in integration of the technology into the larger system. Further, since the infusion of new technologies is targeted towards opening the feasible design space by affecting the constraints, penalties may be incurred in other disciplines as the “price” of the benefits. Finally, a thorough understanding of the “life-cycle” of a technology is required. This includes representation of the following: the milestones encountered during a generic technology development program, the sources of uncertainty during that development, and the potential methods for bounding and forecasting the uncertainty so that the impact on a system may be quantified. An example showing how the problem is addressed is discussed next.

Example

A large projected growth in commercial air traffic, increasingly stringent government regulations, increased throughput, the desire for affordability in all futures systems are all factors which point towards the increased role of innovative technologies in system design and development. An approach to modeling the merits of new technologies is needed. Such a method proposed is proposed under the VSLCDE framework to address this need. The method, described in detail in Ref. [21], evolved from the Technology Identification, Evaluation, and Selection (TIES) method described in Ref. [12, 22]. In Ref. [22], the focus was on a deterministic evaluation of the mix of technologies needed to meet some customer requirements with a brief discussion on the probabilistic nature of the problem. This later notion is expanded upon here. In particular, a methodical logic is developed to create the ability to forecast the impact of any emerging technology while accounting for technological uncertainty. This overall procedure is depicted in Figure 6.

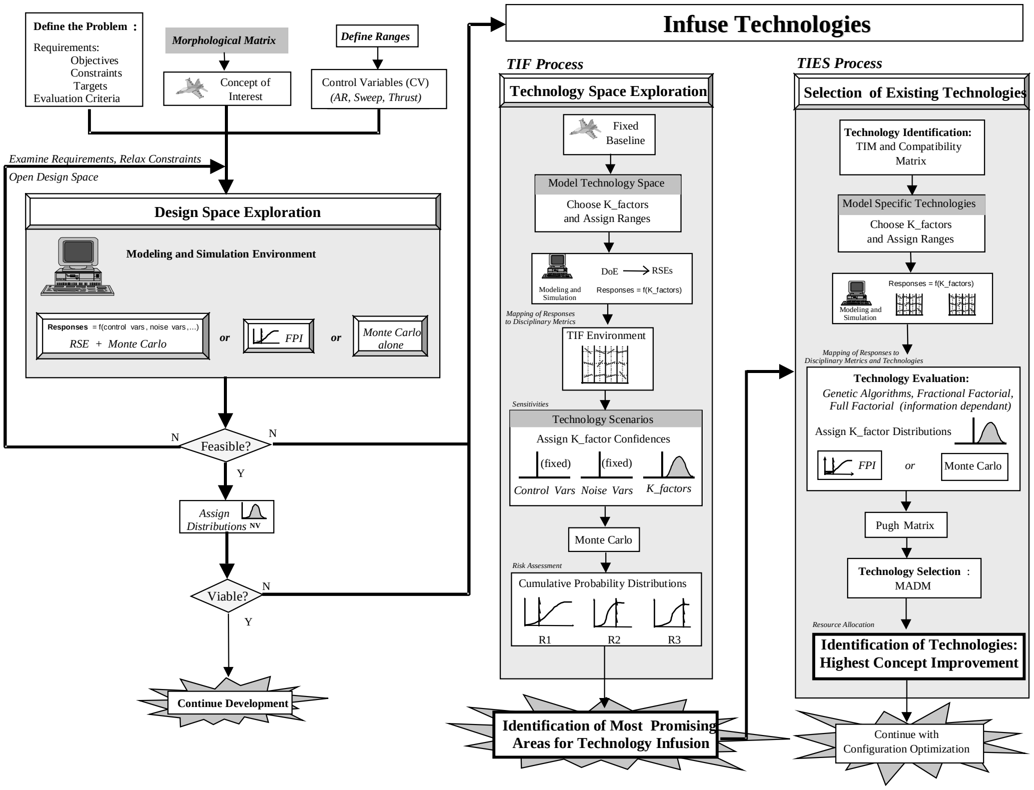


Figure 6: System Feasibility, TIF, and TIES for Decision Support (Ref. [23])

The portion of the figure on the left illustrates the process for defining the problem, determining the variables and responses of interest, and the development of a baseline to which the technology concepts are applied. Using the RSM and/or Fast Probability Integration (FPI), the design space encompassing the baseline is explored, and technical feasibility as well as economic viability is assessed. If it is determined that the aircraft requires some sort of technology infusion in order to be successful, the Technology Impact Forecast (TIF) process, discussed in detail later, is then initiated.

The innovative process by which a technology is developed can be qualitatively described through a monitoring of the major milestones achieved from concept formulation to widespread application. As defined by NASA for application in the aerospace community, the milestones have been characterized into a "metric known as the technology readiness level (TRL)" (Ref. [5]). A description of the NASA defined TRLs is listed in Table II. The TRLs represent a checklist to monitor the progress of a *successful* technology program. Consideration is not given to the influencing or constraining factors that may alter the progression such as schedule, budget, market demand, political or socioeconomic policy, physical limitations, etc. The TRLs simply describe the maturation and development process of a technology and provide a basis for which different technologies can be compared as they progress through the gates of maturation. For program monitoring, TRLs are appropriate but should be mapped to a quantitative scale for the purpose of decision making. To do so, one must understand how a generic technology develops and matures.

Table II: Typical Technology Readiness Levels

Level	Readiness Description
1	Basic principles observed and reported
2	Technology concept and/or application formulated (candidate selected)
3	Analytical and experimental critical function or characteristic proof of concept or completed design
4	Component and/or application formulated
5	Component (or breadboard) verification in a relevant environment
6	System/subsystem (configuration) model or prototype demonstrated/validated in relevant environment
7	System prototype demonstrated in flight
8	Actual system completed and flight qualified through test and demonstration
9	Actual system flight proven on operational vehicle

If one were to map the TRLs to a technology progress curve, the growth curve would be indicative of the component progression from TRL 1 to 5 *if the program is successful*. It should be noted the uncertainty that is reduced is the specific disciplinary impact for which the technology is being developed. As resources are invested and more knowledge is gained about the technology at the component level, the uncertainty reduces. Yet, when the component is integrated to the system in a relevant environment at a TRL of 6, the uncertainty of the system increases as shown in Figure 7. This uncertainty is caused by integration difficulties, degradation in other systems, manufacturing uncertainties, etc. For example, the use of Circulation Control (CC) is to increase the lift capability of the wing at low speeds and its current TRL is 4. This impact has been proven with various wind tunnel models [24, 25] to achieve very high lift augmentation. Yet, if the CC concept is then infused to the full system, issues around integration arise and include power required for operation, redundant systems for certification, available wing volume for ducting, etc. Additionally, prior to the introduction of the technology uncertainty already exists in the system due to ambiguous requirements, modeling and assessment assumptions, to name a few, as shown as the straight portion of the system uncertainty.

However, *if the technology development is not assumed successful*, the right hand side of Figure 7 is obtained. If one were to track the actual technology impact at the component and system level as the TRL increases, the mode value of the distribution *may deviate* quite a bit. The mode value is defined as the point of largest frequency (Ref. [26]). For a symmetric distribution, the mode is equivalent to the mean. Although uncertainty reduces, the deviation between the present day and desired capability is not evident with increasing TRL shown on the left. In fact, the desired impact may never be achieved unless some physical limitation is overcome, or a revolutionary technology is considered. The movement of the mode value and the shape of the distribution are a function of several factors. Those factors include the resources allocated to the development of the technology, the methods and tools used to analyze and design the technology, the information available, the desired impact level, integration to the system, and the technology itself. The next step is the identification of forecasting techniques to bound, quantify, and estimate the technology uncertainty.

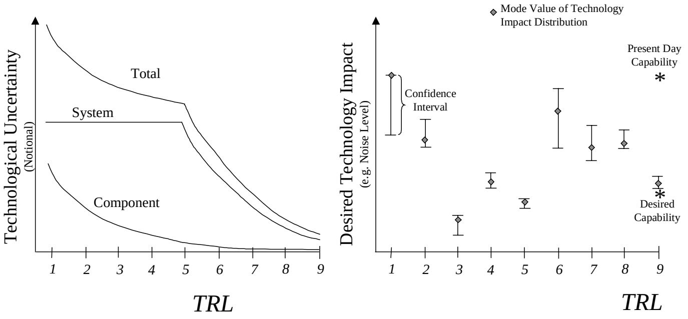


Figure 7: Technological Uncertainty (Ref. [21])

If a technology is in the infancy stage of development (low TRL), the shape of the development curve is not easy to predict due to lack of substantial data to establish a trend. Hence, the forecast must rely on expert, subjective opinions through the Delphi method with an assumed growth pattern. Subsequently, the forecast should focus on the evaluation of "the potential commercial benefits (and penalties) that might be achieved IF the (program) is successful" (Ref. [27]) and can be matured to the point of full-scale application. As more information and data becomes available, the forecast should be updated and re-evaluated.

Due to immaturity, the uncertainty, or confidence limits, may be bounded based on a logical reasoning of what should happen as a technology program progress as described previously. For example, one may assume that a successful technology program develops along a linear trend as shown in Figure 8. Point “A” represents a technology in the infancy stage of development. The desired capability of the performance improvement is Point “D” and is assumed the expert defined impact. This point is not yet fully realized due to knowledge impediments and may actually be higher or lower than the expert defined limit. Points “B” and “C” represent other levels of technology maturation. There are two sources that must be understood in order to bound the uncertainty. First, the inherent uncertainty associated with the technology development as described previously must be accounted. Second, uncertainty associated with forecasting the trend is involved. That is, the confidence limits of achieving a desired value “broaden as the time frame of the forecast increases, reflecting the growing level of uncertainty” (Ref. [28]) in knowledge. An analogy for this concept is the forecasting of the price of fuel. One could forecast what the price of fuel would be for the next day with a very high confidence. However, the confidence of what the price will be in fifty years is very low. Now, consider Point “A”, since the time frame of the forecast is large to the desired impact value and the distribution is very wide. Yet, for a higher TRL value, the confidence or probability of achieving the desired technology improvement increases since the forecast is for a shorter time frame and more information is available regarding the technology.

As shown in Figure 8, the uncertainty (depicted as distributions labeled a, b, c) in achieving the desired improvement should be skewed towards the desired level if the expert opinion is relatively accurate. Based on this rationale, the shape distributions associated with different TRLs may be established based on qualitative reasoning since insufficient data is available for the technologies considered.

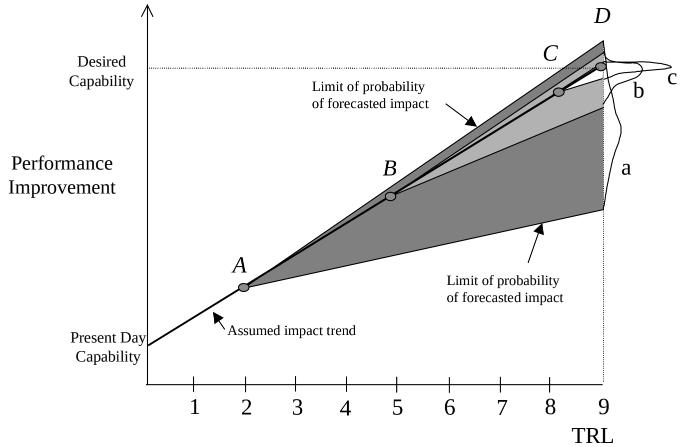


Figure 8: Uncertainty in Forecasting a Technology (Ref. [21])

The impact of a technology can be defined by a technical “k” factor vector whose elements consist of the benefits and penalties associated with the technology, as shown in Figure 9. Each element of the vector has an estimated impact value and an associated distribution based on the current TRL. Not all technologies will affect each element of the vector, but the vector must capture all technologies. An example technology impact matrix (TIM) is shown in Figure 9 for three technologies that influence four discipline metrics. In the deterministic example in Figure 9, T1 and T3 affect all “k” factors except for the second, while T2 does not affect the first or third. Each element of the vector is established via the Delphi method, literature reviews, or physics-based modeling (Ref. [22]). The vector *must* include benefits *and* penalties to accurately assess the impact of technologies on an aerospace system of interest. The identification of the appropriate shape distribution for a given TRL of the “k” vector elements is discussed in Ref. [21].

The technologies identified must now be applied to the vehicle concept and evaluated through the TIF process depicted in the right side of Figure 6. The evaluation will provide data and information to the decision-maker whereby selection of the proper mix of technologies may be performed. Yet, the search for that can be daunting, depending on the number of technologies (n) considered (2^n combinations, assuming that all combinations are physically compatible as defined by the compatibility matrix). In addition, the technologies must be assessed probabilistically, and so a cumulative distribution function (CDF) would need to be generated for each combination, which further complicates the evaluation. If the computational expense of the analysis is manageable, a full-factorial probabilistic investigation is acceptable. If not, (e.g., a finite element analysis), an alternate method is required. Genetic Algorithms are proposed in Ref. [22] as one possible remedy.

For the purposes of the current investigation, the computational expense is manageable due to the means by which the technology “k” vectors are modeled. Consider the TIM in Figure 9 and a metamodel representation of a system metric Ref. [29]. If one were to bind each “k” factor element of the technology vector, a metamodel in the form of a second-order RSE could be generated for each of the system level metrics defined in Ref. [22]. For example, “k” factor 1 is bounded between –10% and +4%, while “k” factor 4 is bounded between –4% and +3%. Hence, the system metrics could be created as a function of the “k” factors for a fixed geometry as shown through a Design of Experiments (Ref. [16]). An RSE of this form is thus defined for each metric and is valid for the “k” factor ranges specified. The evaluation of a technology on the metrics can be evaluated via a simple calculation of the RSE with the appropriate technology “k” vector values. The next step is to employ the RSEs in a Monte Carlo simulation. A shape function must be assigned to each variable, determined by a particular pre-selected scenario. These shape functions will determine the probability of achieving certain values of variables. Because the actual shape functions are subjectively selected and can heavily influence the results, it is up to the designer to use his/her database of knowledge and expertise to ensure the shape distributions are appropriate and reasonable. Variables that are not affected by the technology scenario are set at their most probable, or baseline, values.

The Monte Carlo simulation is run, and cumulative distribution functions (CDFs) for the responses are computed. Minimal computation power is required due to the simplicity of the secon-order polynomial evaluation. The signifcance of the RSM is seen when this is compared to running the same number of cases through the synthesis code. The CDFs give the probability of achieving a certain response given a certain confidence level.

If one assumes that the technologies are additive, then a combination of two or more technologies remains a simple Monte Carlo Simulation on the RSE of a given metric. Now, instead of the response, R, being a function of only one "k" vector, it is a function of the sum of the combination of vectors. This process is automatically performed with a commercial Monte Carlo software package. At this point, the process in Figure 6 is concluded, and these CDFs are then fed to the decision-making portion of the VSLCDE. This function is described next.

		Proposed Technologies		
	Technical "K" Factor Vector	T1	T2	T3
Disciplinary Metrics	k factor 1	+4%	~	-10%
	k factor 2	~	-3%	~
	k factor 3	-1%	~	-2%
	k factor 4	-2%	-2%	+3%

Figure 9: Example Technology Impact Matrix (Mapping of technologies to technology dials)

UNCERTAINTY MANAGEMENT AND DECISION-MAKING

Role in VSLCDE

Robust Design Simulation (RDS) is the decision-making part of VSLCDE where system level analysis achieved in the integration portion (accounting for uncertainty, economics, synthesis and sizing, technologies selected, and environmental constraints) is utilized. Application of RDS can be found in Refs. [30, 31]. A principle advantage of this construction is that it gives the designer the ability to concurrently consider the aforementioned aspects of design at the conceptual level. The premise behind robust design is that the best way to achieve customer satisfaction is to deliver a product that performs well not only in the environment for which it was designed, but in all environments. Design for robustness is achieved by finding settings for control parameters that will not only maximize mean performance in some sense, but also minimize the objective function variance while satisfying all constraints. This is accomplished in RDS by incorporating all elements essential to the success of the design into an overall framework, with the ultimate goal of affordability that is insensitive to uncertainty.

Further, a key issue in robust design is measuring the 'goodness' of a design, i.e. finding a criterion through which a particular design is determined to be the 'best'. Traditional choices in aerospace systems design, such as performance, cost, revenue, reliability, and safety, individually fail to fully capture the life cycle characteristics of the system. Furthermore, current multi-criteria optimization approaches rely on deterministic (i.e. perfect knowledge) information about the system and the environment to which it is exposed. In many cases, this information is not available at the conceptual or preliminary design phases. Hence, critical decisions made in these phases have to draw from only incomplete or uncertain knowledge. One modeling option is to treat this incomplete information probabilistically, accounting for the fact that certain values may be prominent, while the actual value during operation is unknown. Hence, to account for a multi-criteria as well as a probabilistic approach to systems design, a joint-probabilistic formulation is needed to accurately estimate the probability of satisfying the criteria concurrently.

Under the RDS, an initial statement of robust design optimality is as follows (from Ref. [11]). Note that since the uncertainty parameters are typically described in terms of probability distributions, the output from this mathematical model must also be a distribution. The formulation behind the overall objective, Probability of Success (POS), is described next.

maximize *POS = Joint Prob*$(Z_k(X_i, Y_j) < z_o)$
given *Z = measure of merit = fcn (X,Y)*
X_i *= vector of i deterministic variables*
Y_j *= vector of j uncertain variables*
z_o *= Target (particular value of Z), supplied by the customer*
satisfying *imposed constraints, design space ranges*

Example: A Joint Probabilistic Decision Making Technique

When criteria represent objective functions with corresponding goals, this joint probability can also be called *viability*. The proposed approach to probabilistic, multi-criteria aircraft design, called the Joint Probabilistic Decision-Making (JPDM) technique, will facilitate precisely this estimate. It is reported in more detail in Ref. [32].

Traditional objective function choices in aerospace systems design, such as performance, cost, revenue, reliability, and safety, individually fail to fully capture the life cycle characteristics of the system. Thus, a common approach has been to combine all criteria together into one equation termed the overall evaluation criterion, OEC. This equation is often very simple in its mathematical structure due to lack of any better model for the decision process. Recognizing this lack of proper decision process modeling, a different approach is proposed using the system attributes concurrently as *decision criteria* for the evaluation of designs. This evaluation is not based on a summation of criteria, but rather on the probability of satisfying all criteria at the same time, a notion similar to a Pareto-optimality. Pareto-optimality is the situation in which no one can be made better off without simultaneously making another worse off. The main difference with respect to Pareto-optimality lies in the objective function to be optimized, which is called probability of success (POS) in satisfying all criteria.

This multi-criteria approach to decision-making lends itself more suitably to aircraft design than a probabilistic single-criterion approach since customers typically like to see all decision criteria satisfied. For example, a probabilistic multi-criteria approach can yield the design solution, which maximizes the probability of low cost, high capacity, speed, and dependability, while a single objective design will only yield an optimum in one of these criteria, neglecting all others. An outline for determining the probability of success, the assumptions upon which its calculation is based, and its use for product selection and optimization is presented in Figure 10. This nine-step process, as well as the "Five Methods" mentioned in Step 7, is described in detail in Ref. [32].

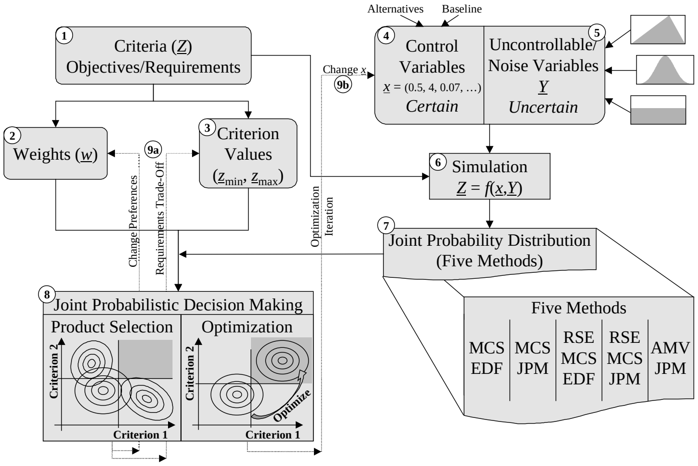


Figure 10: Joint Probability Decision-Making Technique (Ref. [32])

A Joint Probabilistic Decision-Making (JPDM) technique is developed to help the designer and decision-maker identify the best possible solution for a multi-objective design problem. It utilizes the information generated by modern probabilistic design procedures and combines this information into one evaluation criterion, the (joint) Probability of Success (*POS*). *POS* is the objective function used by traditional optimization methods for multi-objective optimization, or the selection criterion based on which the best design is identified among a closed set of alternatives. For a given set of values the *POS* is obtained through the use of one of two possible joint probability distributions for the decision-making criteria: the Empirical Distribution Function and Joint Probability Model. The JPDM technique also allows the decision-maker to gain additional insight about the decision-making problem by facilitating requirements trade-off studies. Given this insight, the decision-maker is able to identify which criterion is the hardest to satisfy, and by how much other criteria need to be relaxed in order to increase the chance of meeting the criterion goal. A proposed extension, which evaluates the sensitivity of *POS* with respect to the criteria or weighting factors, will further enhance the technique's capability. This extension is discussed in detail in Ref. [32].

The JPDM technique was successfully applied to a product selection problem, as reported in Ref. [32]. The techniques was able to identify the best out of three supersonic transport alternatives based on the following criteria: probability of exceeding 10% for the return of investment for the airline (*ROIA*) and 12% for the manufacturer (*ROIM*). The results indicate that the concept with the maximum number of passengers yields high values for *ROIA*, while the 'Baseline Configuration' yields high values for *ROIM*. In contrast, determining the best solution from just the marginal distributions for *ROIA* and *ROIM* is almost impossible. Only the use of *POS* reveals the 'Maximum Number of Passengers' concept as the better one, provided equal preference weighting for both criteria. If *ROIM* is more preferable than *ROIA* (by a 60/40 ratio), however, the 'Baseline Configuration' appears to be the better design solution. While this conclusion may seem intuitively obvious for the presented example with two criteria, the additional complexity introduced by an n-dimensional product selection or optimization problem could prove to be difficult to solve without the use of the joint *POS* as an evaluation criterion.

KNOWLEDGE INTEGRATION: COMPUTING INFRASTRUCTURE FOR THE VSLCDE

Role in VSLCDE

Knowledge integration in the VSLCDE setting is defined as the process of bringing together disparate information (in the sense of data type, fidelity, completeness) from the five elements in the context defined by human designers in order to create meaningful, traceable results. This is a difficult challenge, one that most enterprises still struggle with despite recent advances in computing technologies. To further complicate matters, this integration may occur over many geographically distributed sites, bringing issues of collaboration and internet-client methodologies to the forefront.

Key technologies have been devised that facilitate integration of the design-oriented, physics-based analyses, uncertainty models, technologies, and simulation elements of the VSLCDE. These technologies are based on accepted Internet practices where applicable. Agents are a key facilitator of VSLCDE and are defined as programmatic objects which facilitate the integration, whether direct or through approximating functions, of product and process based analysis models, Ref. [33]. Designers benefit from agents due to the automation of repetitive and monotonous tasks, such as of program execution and data archiving. Models are directly combined into agents and then linked to the architecture. The linking is accomplished via a 'wrapper' which provides a transparent gateway to computing services such as communications, name service, and platform support. Earlier discussions highlighting mechanisms for integration of first- and higher-order physics-based as metamodels are facilitated by agents. One or more of these techniques is used to implement each of the required analysis into the architecture.

Example: Internet Capable Design Frameworks

The implementation of advanced engineering environments in an internet-capable framework is critical to the usability of the VSLCDE. The resulting framework represents the next generation of design and analysis capability in which engineering decision-making can be done by geographically distributed team members. A new internet technology called the lean-server approach has been introduced as a mechanism for granting Web browser access to frameworks and domain analyses (Ref. [34]). This approach has the underpinnings required to support these next generation frameworks – collaboratories.

The authors are investigating a novel server alternative for the internet, called a lean-server, as a mechanism for providing the functionality needed by design frameworks operating on the internet. A schematic of a lean-server is shown in Figure 11. The lean-server operates simply by a) receiving requests from an internet client, b) passing the requests to the software in which it is imbedded through the application's programming interface, and c) returning a response to the requesting client. The lean-server can be imbedded directly inside a domain analysis as shown in the figure or directly within a design framework (which manages its own set of analysis tools). Note that the domain analyses as used here may also be part of a peer-based simulation architecture. This gives flexibility in the manner in which the lean-servers are deployed. The lean server has added benefits of minimizing internet overhead, maximizing transaction speed, and insuring compatibility with client-side applications.

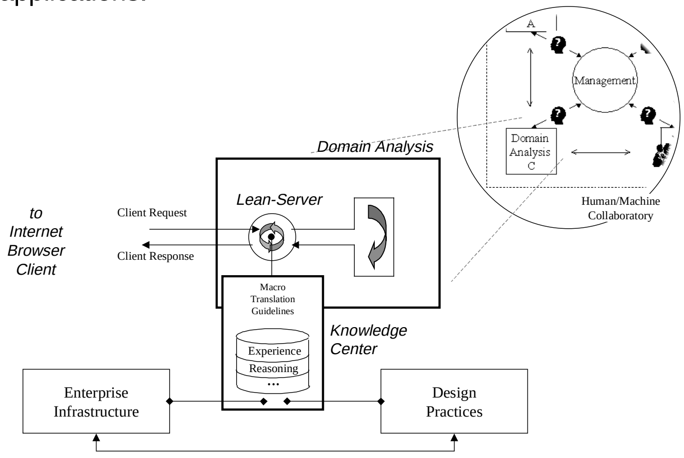


Figure 11: Lean-Server Approach (Ref. [34])

Unique to this approach is that the lean-server has access to a *knowledge center* that can capture models of corporate practice through real-time learning and other knowledge processing techniques. These capabilities facilitate the functions of a collaboratory as described earlier by permitting consideration of both enterprise infrastructure and design practices and their influence in design decision-making. This capability is under further investigation as a gateway to providing solutions for intelligence-based frameworks, such as those required for NASA's ISE Initiative.

The lean-server bridges peer-peer and client-server architectures by enabling internet requests to be serviced directly by simulation peers. The server is embodied directly with the simulation peer as represented in Figure 11 by a domain analysis. This enables the high-end inter-peer simulation activities to occur concurrently with Web requests. Simulation architectures such as the High Level Architecture consider timing, load-balancing of domain analyses, and fault-tolerance aspects not encountered in client-server architectures. These aspects are important if frameworks are to include simulations incorporating high-fidelity domain analyses and enterprise models.

An internet-enabled design framework called IMAGE (Intelligent Multi-Disciplinary Aircraft Generation Environment) has been created and is the prototype architecture for the VSLCDE. The prototype methods have also found their way into a Conceptual Aerospace Systems Design and Analysis Toolkit used by the Air Force Research Laboratory (Ref. [35]). The IMAGE framework demonstrates how a design framework can be equipped with internet services so that distributed users can access the framework using standard Web browsers.

CONCLUDING REMARKS/FUTURE DIRECTIONS

The purpose of the Virtual Stochastic Life Cycle Design Environment (VSLCDE) is to facilitate design decision-making over time (at any level of the organization) in the presence of uncertainty, allowing affordable solutions to be reached with adequate confidence. Currently, this environment serves as a testbed for a variety of research efforts. A summary of recent developments in elements of the VSLCDE has been presented in this paper. This has included advances in the use of metamodel techniques to assist in incorporating physics-based analysis into early design concept synthesis in an efficient way. A technique for the handling of new technologies during design was also summarized, with special emphasis on the modeling of uncertainty. In fact, dealing with uncertainty is a focus in nearly every element of the VSLCDE, from problem definition through decision-support and decision-making. Advances in methodologies for decision-support (through a joint probabilistic decision-making strategy) and the organization of the elements of the VSLCDE in a computing architecture that facilitates collaboration and data transparency were described as well.

Although research will continue in each of the five elements of the environment, integrated verification and validation of the VSLCDE concept is the key focal point for future work. It is hoped that such work will be performed in collaboration with government and industry organizations that have been instrumental in the development of the environment to date.

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