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ABSTRACT

A discussion of knowledge and Knowledge-Based design as related to the design of aircraft is presented. The paper discusses the perceived problem with existing design studies and introduces the concepts of design and knowledge for a Knowledge-Based design system. A review of several Knowledge-Based design activities is provided. A Virtual Reality, Knowledge-Based system is proposed and reviewed. The feasibility of Virtual Reality to improve the efficiency and effectiveness of aerodynamic and multidisciplinary design, evaluation, and analysis of aircraft through the coupling of virtual reality technology and a Knowledge-Based design system is also reviewed. The final section of the paper discusses future directions for design and the role of Knowledge-Based design.

INTRODUCTION

A review of the literature on design shows a wide diversity of methods, concepts, and ideas being investigated and developed¹⁻²². In general, these concepts fall into two groups, those that are Computationally-Based (CB) Design such as Multi-Disciplinary Optimization¹⁶ and those that are Knowledge-Based (KB) Design such as Decision-Based Design²². The primary assumption of CB Design is that a design process can be modeled in the computer to allow the computer to find the optimum design more efficiently than a human. CB Design systems are processes that are used to generate

designs. Another assumption behind the CB Design is based upon the use of explicit and critical knowledge only and does not recognize the role of tacit and intuitive knowledge and other human senses and capabilities in the design process.

At the other end of the design environment are KB Design systems in which it is recognized that all knowledge as well as passion is required to find the best design. KB Design systems consist of tools that allow a designer to utilize their skills, senses, and knowledge in pursuit of a desired outcome. KB Design should not be confused with Artificial Intelligence (AI) or Expert Systems (ES) because those systems assume that the human knowledge and decisions can be fully modeled into a process and computerized. It is important to note that this is clearly not the case because we do not know the extent of our knowledge.

A review of the aircraft design environment shows that the ability to perform efficient and effective aerodynamic and multidisciplinary design is quickly becoming a lost skill. A significant portion of this problem has resulted from the increased reliance by the aeronautics community upon computational tools for both aerodynamic analysis and design^{15,16}. This trend towards Computational Based (CB) design and decision making also dominates the multi-disciplinary design environment. As this trend continues, the knowledge and skills, which are the critical elements in the design practices, will slowly erode as the computational tools replace the need for human interaction. This trend will eventually result in a stagnant design technology landscape. While many still believe that computational design is the pathway to improved efficiency and effectiveness in the design environment others are starting to question the reliance upon computational tools. A significant portion of the design community believes that it is critical to maintain human involvement and learning in the design and analysis process¹⁷⁻²². This gives rise to the use of KB systems which model the aircraft design knowledge as a continuous landscape. The amount of information and data to be converted to knowledge to

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launch such a system is extremely large. Such a proposed system would require the evaluation, analysis, and interaction with significant amounts of additional information. This requirement can become an insurmountable task if traditional data display and manipulation media are used. However, it is expected that Knowledge Management Systems^{5,7}, Virtual Reality (VR) technology²³⁻³⁰, and other advanced information management and display technologies may offer the opportunity for KB design systems to reach their full potential.

The purpose of this paper is to have a discussion of knowledge and KB design as related to the design of aircraft in an effort to provide an alternative to CB design. The paper will first discuss the perceived problem and the concepts of design and knowledge. A discussion of KB design and a review of several examples will follow. The final section of the paper will discuss future directions for design and the role of KB design. A Virtual Reality, Knowledge Based (VR KB) system will be proposed and reviewed. The feasibility of Virtual Reality (VR) to improve the efficiency and effectiveness of aerodynamic and multidisciplinary design, evaluation, and analysis of aircraft through the coupling of virtual reality technology and a KB design system will also be addressed.

PROBLEM AND SOLUTION PATHWAY

Problem

The engineering design problems are many and diverse. They range from definitions to philosophy to our focus. Perhaps the number one issue is the failure of the engineering community to recognize that a designer is a unique and highly skilled individual and that only a designer can create. In our present environment, it appears as if everyone either wants to design or they want to control the design process, however, there is a severe shortage of designers. The distinction between a designer and a person doing design work is equivalent to the difference between a world-renowned violinist and a person playing a CD of their music. The first uses extreme intellect, knowledge, and passion to create and the latter executes a routine process that re-creates.

Another area of concern is the lack of focus and resulting fragmentation of the design efforts. A quick review of the literature revealed a large number of design system types¹⁻²², a few are shown in table 1.

However, there does not appear to be any organization, categorization, or classification of these systems. In addition, there are many different sub-methods and systems that are listed under each of the systems listed in table 1. This diversity in work inhibits the focusing of resources to develop the necessary skills, capabilities, and tools to support the design needs of the future.

TABLE 1.
Artificial Intelligence
Case Based Design
Computer Aided Design
Concurrent Design
Decision Based Design
Design of Experiments
Design Synthesis
Design to Cost
Expert Systems
Integrated Design
Knowledge Based Design
Multi-Disciplinary Analysis and Optimization
Multi-Disciplinary Design
Multi-Disciplinary Optimization
Pattern Recognition Design

Table 1. Design System Types

The present focus in design is faster, faster, faster and cheaper, cheaper, cheaper^{15,16}. This trend has resulted in cost concerns replacing creativity, innovation, and performance. The primary means to achieving the cost reduction goal has been through the use of computer modeling of design processes²³. While computers are a critical tool to the engineering design community, it is a critical mistake to view them as the heart and soul of design. In the quest to be viewed as on the forefront of technology, there is a mad rush to automate processes, and computerize the capabilities and skills of engineers^{1,2,9}. In developing this model of engineering capabilities, a select few have had to define the minimal set of critical data, information, and knowledge and treat the remaining knowledge and capabilities as a disposable commodity. A result of the computerization of the engineering discipline is the disregard for intuitive

data, information, and knowledge. This trend will result in the creative and innovative practices of the past being replaced with routine processes. Another byproduct of this trend is that there will be a severe lack of understanding of final design performance; this will result in costly redesign during the development and production activities.

The final issue is related to the design-development time line as shown in figure 1. The figure shows that the opportunities to impact performance or cost of a design are heavily weighted toward the conceptual design phase where the design activity is typically guided by first order effects and simple models^{10,16,17}. Only a fraction of the available knowledge for the particular design problem is associated with these methods and models. This inverse relationship between knowledge used and design impact must be corrected if significant improvements are to be achieved.

Solution Pathways

The proposed solution pathway leads through Conceptual Design and KB Design in three steps. The first step is to recognize that the Conceptual Design phase must be a highly creative, multidisciplinary activity in order to minimize cost and maximize design performance. Second, the Conceptual Design phase must be re-created into a KB Design activity that is without intellectual restraint. And the third step is the recognition that designers and not the design process are the critical element in design¹⁷. These ideas are graphically depicted in figure 2 in which Performance and Cost curves as well as Available Knowledge curves for the existing design processes and the proposed KB design practices are shown. By inserting more knowledge into the Conceptual Design phase, greater cost and performance benefits will be achieved. As a result, we achieve a better, faster, and cheaper design.

The remaining issue is whether KB or CB systems are more effective and efficient in integrating knowledge into a design. The argument in support of the KB system is graphically depicted in figure 3 in which the trend in cost against knowledge complexity is presented for both a KB and CB system. The figure shows that the cost for minimal knowledge is similar for both a KB and CB system, however, as knowledge complexity increases, the CB cost increases dramatically due to computational modeling, solution generation, and solution interrogation³¹. A much different trend is observed for a KB system.

The figure shows that a KB system requires minimal additional increases in cost for adding knowledge, once the system is established.

WHAT ARE DESIGN AND KNOWLEDGE?

Now that you are fully confused, violently disagree, or perhaps violently agree with the previous statements, a few points will be clarified by providing some definitions of design, knowledge and their associated terms.

Design

Each person is actively designing throughout his or her life. We design our day, our drive to work, our meals and our conversations. We design organizations, toasters, art, and airplanes. Designing is thinking, feeling, and knowing. However, to design an optimum "thing" requires a cognitive awareness of all knowledge relative to a desire. This is clearly not achievable by man or possible by computer. It is also clear that a designer is different from one who designs. In an attempt to clarify these points, the following terms must be defined:

A Design is a concept, model, or artifact with desired performance.

A Designer is a passionate and knowledgeable decision-maker that utilizes critical and intuitive skills.

Designing is a creative practice that stimulates and liberates and is learned through the acquisition of knowledge.

Knowledge

You do not know what you know, however, it is possible to use all that you know in the design process. To know that you do not know what you know is the first step in becoming a successful designer. This knowledge allows you to accept your intuition (i.e., gut feeling) as useful knowledge and as an integrator of knowledge.

It is important to use all of one's knowledge whether or not it relates directly to design. Therefore, thoughts derived as a child affect how one thinks and the decisions one makes as an adult. An example of a thought-provoking book relative to this subject is Dr. Seuss' "Oh, the THiNKS you can ThinK!"³².

Ted Geissel eloquently illustrates how anything is possible.

To define knowledge, as related to engineering, you must also define data and information. The following definitions are provided:

Data a group of facts or statistics that have not been assigned meaning.

Information data that has been assigned meaning.

Knowledge the sum of what has been perceived and learned that allows for the generation of information.

A graphical depiction of the interrelation between data, information, and knowledge is presented in figure 4. The figure shows that data is operated on by knowledge to produce information and a new set of knowledge. The new knowledge is combined with information to create knowledge. This knowledge set is then used in the interaction with new data and information sets.

Another important aspect of knowledge creation is the four modes of knowledge creation introduced by Nonaka⁵ in 1995, see figure 5. In this model, there are two basic types of knowledge, tacit and explicit. Nonaka states that knowledge is created by the conversion of tacit to both tacit and explicit and from explicit to both tacit and explicit. Relating these thoughts to the CB and KB design systems, we see that CB makes use of only two modes: tacit to explicit and explicit to explicit knowledge steps whereas KB uses all four modes.

The final knowledge concept is the notion of a "Knowledge Matrix"(see figure 6) which is borrowed from the work of Margolis^{7,33} in 1987 on a cognitive model he termed the "Belief Matrix". Margolis states that there is tension between critical and intuitive scrutiny to a question and the yes (+), no (-), and maybe (o) answers to the critical and intuitive question form nine affective states. In his model, a yes answer (+) to both the critical and intuitive questions is the knowledge affective state, upper left corner of matrix. For this discussion, the nine affective states of Margolis have been renamed to reflect levels of knowledge awareness. In the "Knowledge Matrix", there are four levels of knowledge awareness; Known Knowledge, Unknown Knowledge, Probable Knowledge, and Possible Knowledge. These states reflect the concept that "all" that is possible to be known can be known. The

important design aspect of this concept is that in typical design systems only the C+/I+ Known Knowledge state is utilized. However, in some design systems, all of the C+ states are used due to a blind reliance on computational results. The benefit of a KB system is that all nine states are used.

KNOWLEDGE-BASED DESIGN

KB Design has been discussed within the literature in the context of Artificial Intelligence (AI) and Expert Systems (ES) but not in the context of designer driven practices within a broad KB design space. The KB design system that is the topic of this paper is one that is practiced by a designer who relies upon intellectual optimization and thought experiments in developing a particular solution pathway. The designer respects simplicity, recognizes that nature and its laws are continuous, and understands that rebellion and debate are necessary tools. Another description that reflects this view is that expressed by Alexander H. Slocum¹³ in his position paper for the Decision-Based Design Workshop located at:

www.eng.buffalo.edu/Research/DBD/

"Designers have a bio-neural-net programmed for deterministic axiomatic thought while simultaneously achieving rapid-fire multi-techno happiness enhancement"

"Designers need tools that catalyze their thoughts....and harness an attribute that no neural net can dream of, a passionate lust to create a most awesome amazing orgasmic design."

Designer's Practice

The designer begins the design challenge by taking an infinite view of the problem. This first step is critical and may be viewed as designing the design. Designing the design provides context and content but does constrain or inhibit. This perspective is shown in the model of the design space shown in figure 7. The design space model shown has six regions depicted as successively smaller regions. This representation is consistent with the present design process. However, for a KB design system, this is only true for Possibility, Probability, Knowledge, and Known Knowledge spaces. For KB design, the Cb and Tb design spaces are not scaled and are not assumed to reside within the K² b design space

but are characterized as concept families. Another point to note is that the Constraint and Tool spaces are scaled by various factors such as politics, resources, and culture. In addition, the relative size of the Constraint and Tool spaces may reverse from that shown and they may extend outside of the K^2 into the K, Pr, and Po spaces. The goal in the practice of KB design is to utilize tools and constraints as influence factors in order to use as much of the design space as possible.

The next issue faced by the designer is the dilemma between using a "Design Process" or "Design Practice" as shown in figure 8. As one would expect, the designer prefers the Design Practice as depicted on the right side of figure 8. However, politics, resources, and culture attempt to drive the designer to a process as shown on the left. The major differences between the two are that the Process is an inside-out activity, which knowingly utilizes only a small section of the design space, whereas the Practice is an outside-in activity, which utilizes the full design space. The Process represents the scale factors (Xbsf's), constraints, and tools as hard models where the Practice recognizes and conceptualizes the existence of these desires and chooses the degree of acceptance.

The final challenge the designer faces is the work environment or team structure. As depicted in figure 9, there are three types of teams that are possible; Bureaucratic, Hierarchical, and Creative. The Bureaucratic team is formed by the organization and exists as an element of the organization. This team is recognized as being in competition with other elements of the organization and must operate within the organizational policies and culture. The Hierarchical team is formed by the participating elements of the organization to perform a task of mutual benefit. This team is supported as long as it is recognized as adding value to the individual elements of the organization. Those who have a shared passion and are committed to achieving success form the Creative team. The Creative team operates within the organization environment but not for the organization. The preferred team is the Creative team, however, it is not one that is typically supported by an organization. The characteristics of a Creative team are increased communications, productivity, and reduced complexity and cost compared to the other two teams.

The ability to create the preferred designers environment requires the recognition that knowledge

is the most valued commodity and that creativity and innovation are critical. If these three characteristics are present then a KB system can achieve success.

The next three sections of the paper will review the results of three activities from 1985, 1990, and 1995 that used KB design in a creative team environment.

Natural Flow Wing (NFW) Design

The Natural Flow Wing³⁴ (NFW) Design activity took place in 1985 with a team of four engineers representing the disciplines of aerodynamics, structures, survivability, and manufacturing maintainability. The design activity focused on the development of KB design rationale for including nonlinear effects into the conceptual design phase of the multidisciplinary design of highly efficient multi-point-design wings. The design approach was derived from experimental observations and an extensive parametric computational study. The proposed design rationale is based on criteria from the following disciplines; aerodynamics, structures, survivability, and manufacturing/maintainability. The combination of criteria for these disciplines indicates that the optimum wing would be a symmetric, planar geometry without breaks to the outer mold line.

The first step in the design is to develop an understanding of the various layers to the design space presented in figure 7. A description of each of these design space layers is presented in figure 10. The vision of the Possibility-based (Pob) design space is characterized by all 3-D shapes with smooth and continuous geometry. The recognition of the need for 3-D geometry is related to the volumetric and structural requirements of the design and the need for smooth and continuous geometry addressing aerodynamics and survivability considerations.

The second layer is the Probability-based (Prb) design space. Within this space, we add to the Pob design space description by calling for a benign pressure loading and an aerodynamic insensitivity to volume. These two additional descriptors characterize the expected aerodynamic performance of the design and provide a vision of a design with a very robust performance map.

A review of the descriptors for the Knowledge-based (Kb) design space shows that low drag, no movement of the aerodynamic center, and

increased volume are added to the Prb design space characteristics. These new characteristics add to the vision that the final design will be very robust and have excellent aerodynamic characteristics.

The next design space is the Known Knowledge-based (K^2 b) design space where design guidance is provided. For this design space, the intent is to take advantage of experimental and computational data observations of 3-D pressure loadings over similar planforms and then to use these contours as maps to guide the reshaping of the wing geometry to match the observed 3-D pressure loading.

The final two elements are the Constraint based (Cb) and Tool based (Tb) design spaces. For a traditional design, the Cb and Tb design spaces are assumed to reside within the K^2 b design space and are sized according to non-technical factors such as politics, culture and resources. However, for KB design, the Cb and Tb design spaces are not scaled and are not assumed to reside within the K^2 b design space but are characterized as concept families that are used to guide the design. For this design, the Cb design space description is that the volume will be sufficient to fly a candidate mission and the Tb design space will have an analytic geometry definition capability.

With the Pob through Tb design spaces thoughts and visions in hand, a design activity is initiated and managed by the designer. The resultant design is depicted in figure 11. Shown on the left of the figure are sketches of the NFW design and a traditional design. Note that the NFW design is flat and planar where the traditional design is characterized by having camber and twist. This geometric characteristic is critical in satisfying the survivability requirement. Another characteristic of the design is the increased volume for the NFW design over the traditional design. The resulting performance is shown on the right on the figure in the form of a drag polar. The NFW design had lower drag at all lift coefficients than the traditional design. These results indicate that the NFW design achieved all of the stated objectives and produced a new aerodynamic shape family that provides unique aerodynamic and survivability performance.

Advanced Aircraft Control Effector (AACE) Design

The Advanced Aircraft Control Effector (AACE) Design activity was conducted in 1990 with a team of 11 engineers representing aerodynamics, electromagnetics, controls, structures, propulsion, and

weights. AACE focused on the design of advanced aircraft control effectors that allow for the development of low drag, highly agile aircraft that are affordable and satisfy future observability requirements. In pursuit of this goal, it was recognized that several new concepts would be required that were passive devices or micro in size. Another concept introduced was the notion of designing the planform as a zero-order control effector and to actuate the planform through the use of micro motion boundary layer control devices.

As was done in the NFW design activity discussed previously, the first step in the AACE design was to develop an understanding of the design space. The list of characteristics for each of the 6 design space layers is shown in figure 12. A review of these descriptions shows that the design spaces are notionally described and each successive design space builds upon the description of the previous space. Another characteristics of KB design is the use of very aggressive performance objectives as shown in figure 12. An interesting point for this design is the absence of any significant Constraint or Tool based description. The Cb and Tb design space for the AACE activity must have infinite freedom to allow the creation of new technologies and concepts, that are required to meet such severe performance objectives.

Presented in figure 13 are the resultant technologies developed and performance benefits achieved in the AACE design. A graphic of the AACE design concept is also shown in the figure. The AACE activity produced a large number of new technologies of which five are patent pending. These technologies ranged from advanced planform concepts to micro boundary layer control devices. The success of these devices in achieving the stated goal is itemized in the table on the right side of figure 13. The AACE activity produced large aerodynamic, electromagnetic, control, and weight benefits as indicated. These results indicate that the AACE activity was successful and delivered new design technologies and a new design philosophy to the community.

High Speed Research (HSR) Arrow-Wing Design

The High-Speed Research (HSR) Arrow Wing Design activity was conducted in 1995 with a team of 6 engineers representing the disciplines of aerodynamics, structures, propulsion, controls, and weights. This design activity was the first attempt to

apply the military based NFW design philosophy to a commercial design problem. The focus of this effort was a numerically-optimized, Euler- (and Navier-Stokes) based arrow wing design within the HSR program. The focus of the design was to reduce the supersonic and transonic drag while increasing volume. It was expected that the NFW design approach would produce the characteristic flat wing and eliminate much of the waviness characteristic of the conventionally optimized designs.

As with the two previous examples, the first step in the design was to characterize the design space. It should be noted for this design, the HSR program had very strict constraints and requirements on volume, thickness, spar thickness and location, leading-edge radius, fuselage incidence, engine location and orientation, etc. However, the KB design activity did not hold these as rigid values as was done by other HSR design teams. This design study recognized the HSR constraints as desired outcomes ONLY. As a result, a review of the design space model for this activity show the same characteristics as those for the NFW design activity on figure 10, see figure 14.

Presented in figure 15 are the results of this design. Depicted at the top of the figure is a sketch of the wing main structural element and on the right are sketches of the airfoil sections for the conventionally optimized wing (CB) and NFW wing (KB). These sketches show how the NFW design has greater volume than the CB-optimized wing. Also note that the NFW included multidisciplinary effects by reshaping the structural box. A comparison of the performance of the two designs show that the NFW has three counts lower drag at the cruise point and has an increase of nearly 5% in useable volume. As with the two previous examples, these results clearly show that this KB design activity was successful in achieving its goal.

A review of the three examples shows the benefit of relaxing constraints and allowing creativity to have a role. The KB design process allows the designer to produce outstanding results with minimal resources. Each of the designs shown above was completed ahead of schedule and under budget. In addition, each of the design activities created new technologies that remain in use today.

FUTURE DIRECTIONS

The previous sections of the paper have addressed the general problem of design and have reviewed some aircraft design studies in the context of KB design. This section of the paper will provide an aerodynamicists view towards design and discuss some specific problems in aircraft design and propose a solution to these problems.

Over the past decade, there has been uncontrolled growth in the use of computers in the design of aircraft, consequently, there also appears to have been an equally dramatic uncontrolled reduction and shift in knowledge related to aircraft design. If this trend continues, the ability to use aircraft design tools would only require a limited understanding of aircraft design and aerodynamics and as a result we would approach Dr. Doug Dwoyer's 1987 prediction³⁵, *"If you ask me to envision what I see in the year 2020, there will be no wind tunnels. I would say we would be at the point where airplanes could be designed by rather low-paid technicians."*

At this time, the aircraft design environment has become intellectually stagnant and is focused only on computational efficiency. And within this design environment, the Aerodynamicist has become an observer unable to contribute to our design intellect and knowledge. It is clear from all points that we are losing large amounts of design potential by not including knowledge of nonlinear effects into the conceptual design activity. Our next generation of design methods must have the ability to capture and share knowledge. These new methods must support the creative and innovative activities of designers. And lastly we must not be constrained by existing performance boundaries.

To satisfy these needs, it is proposed that KB design tools and design practices be created that provide the framework for designers to reduce the design cycle time an order of magnitude and to achieve performance goals that exceed recognized boundaries by 50%. This new system could require Virtual Reality (VR) coupled with a KB system. A schematic of a proposed VR KB system is depicted in figure 16. The proposed system would utilize the VR technology as a means to increase the efficiency of the KB design system. The VR shell will create a designer-friendly work environment where knowledge and a design can be accessed in real time and integrated in real time to create a new design. A critical element of the KB system is an unrestricted

ability to create a smooth geometry of any concept or notion. Residing under the geometry shell are the synthesis tools that manage the existing knowledge as well as capture the new knowledge generated within the system. A critical element of this system is the efficient modeling of the information and knowledge domains, which would allow for effective transformation and morphing of these domains between problem sets.

The most important characteristic of a KB system is that it must be a learning system. This characteristic is depicted in figure 17 which shows the design cycle for a KB system. A design activity would start with a definition of the design space and the design goal. The generation or the importing of a description (geometry model) of the concept would follow. The designer would then interrogate the Knowledge Domain (KD) relative to the model and stated goal. If the KD is valid for this problem, the relative information is extracted and the results are synthesized into a possible solution and the process is repeated until the designer is satisfied. If the KD is not valid, there are two steps taken; the first is to characterize the KD relative to the problem and update the KD, the second option is to review the Information Domain (ID). A review of the ID takes the same form as the KD with the exception that if the ID is not valid, the resolution is to obtain new data to feed the ID and KD models shown in figure 18 and 19. It is important to note that without the learning capability of the proposed system knowledge would be lost and we would spend more time and resources re-creating than creating. Note the KB system utilizes both knowledge-based models and information based models as shown in figures 18 and 19. The transformation of data to information to knowledge is critical for the system to learn.

CONCLUDING REMARKS

Design is a greatly misunderstood and undervalued practice within the engineering community. This is especially true for KB systems despite the fact that each of us actively practice KB design in our everyday lives. When we arrive at work, we become "Dilbertized"³⁶ by our environment and fall into the daily process-management routine of re-creating knowledge. These random process acts must be restructured into creative and innovative practices using KB systems if we are to move technology forward.

Relative to aircraft design; it is important to recognize that the design philosophy, not the design process, defines the design space. The design philosophy, which is developed by the designer, must not be constrained by known rules, constraints, or by computational tools. It is also extremely important to recognize that the ability to perform conceptual nonlinear design is not contingent upon the ability to obtain a computational solution. The efficiency and accuracy of the conceptual design phase is directly related to the knowledge used, thus we must focus on including ever greater amounts of knowledge into the conceptual design phase.

To address the need for improved design capability, the following recommendations are offered:

- Establish a National Design Consortium to facilitate the development of design knowledge, design skills, and design systems.
- Accelerate the development of learning, knowledge-management systems for designers
- Accelerate the development of advanced display, information management, and virtual reality technologies.
- Recognize that design is a knowledge driven activity, not a computational process.

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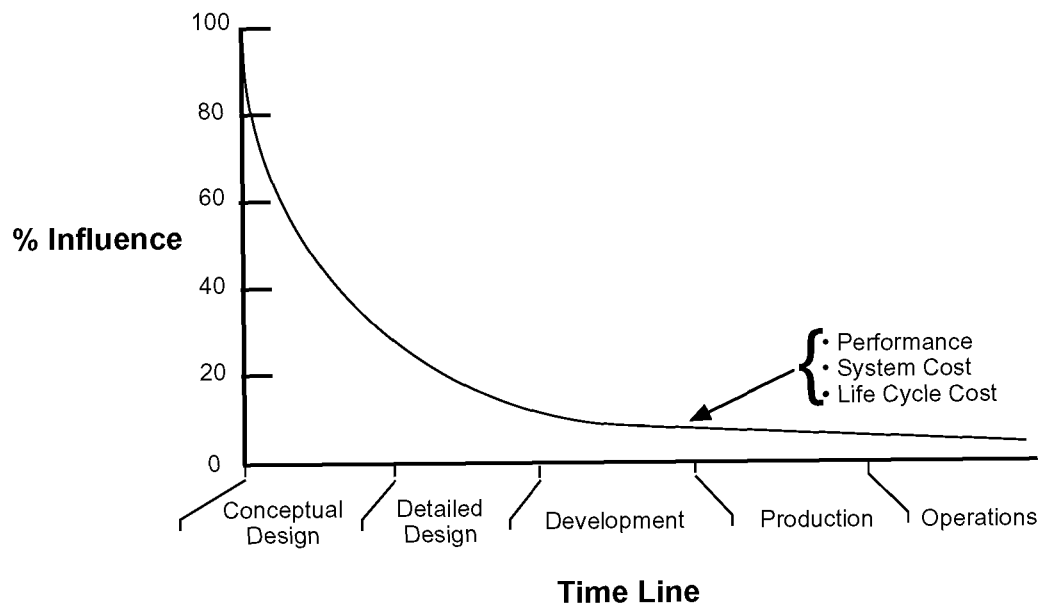


Figure 1. Graph showing the change in design influence on performance and cost with time.

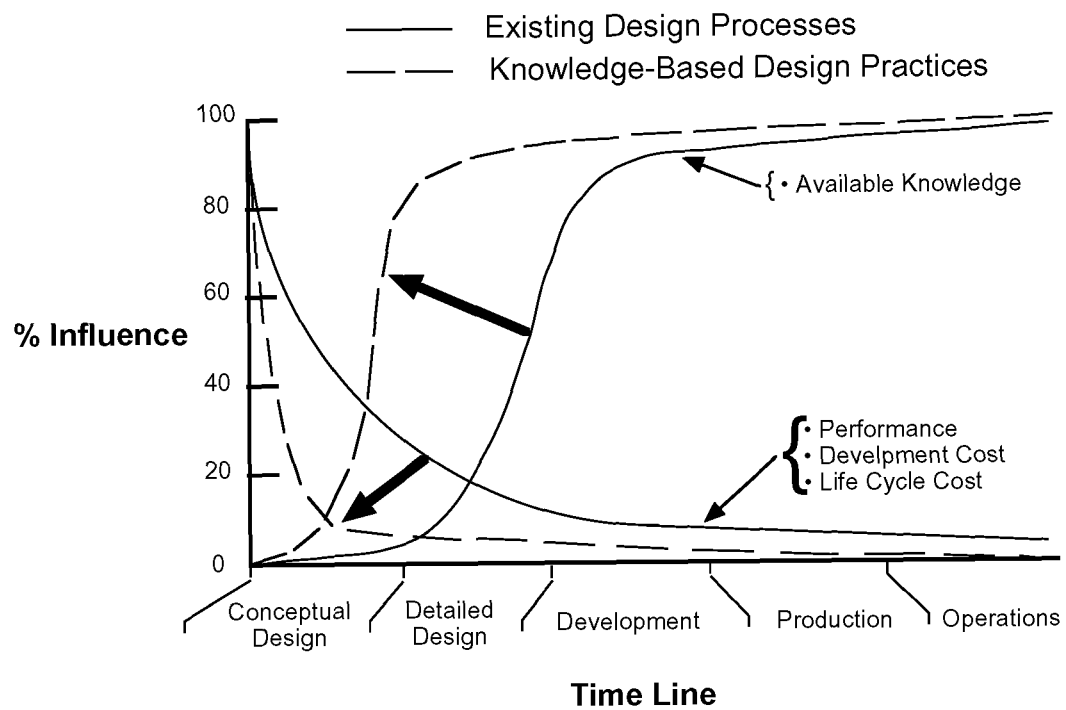


Figure 2. Graph showing the impact of knowledge on performance and cost in design.

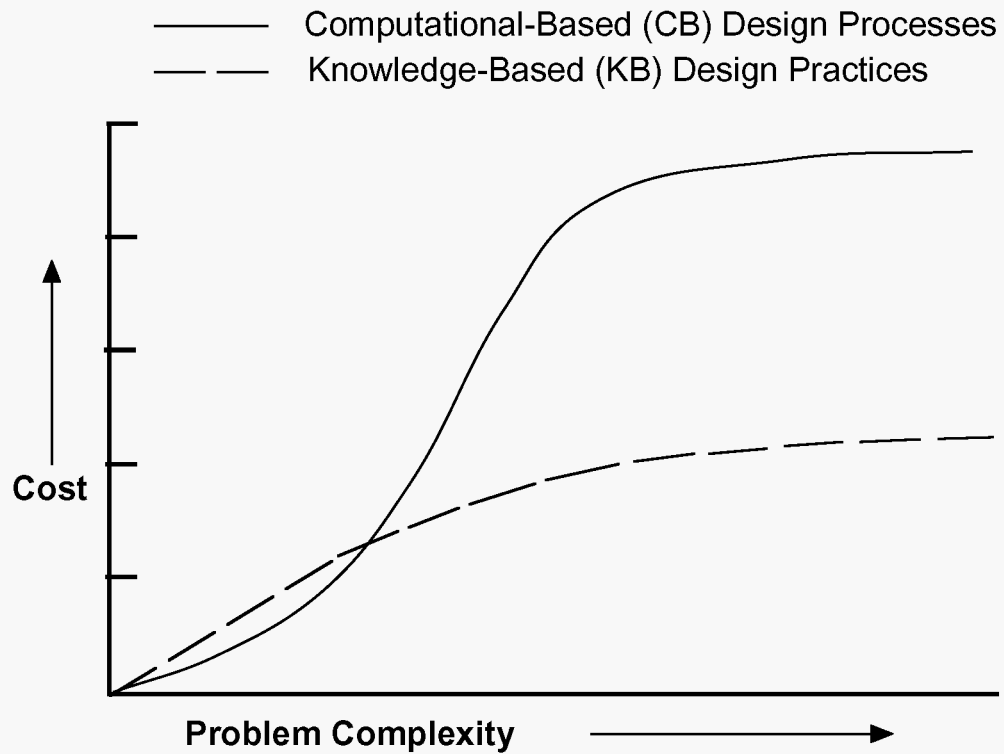


Figure 3. Graph comparing the cost of knowledge for CB and KB design systems.

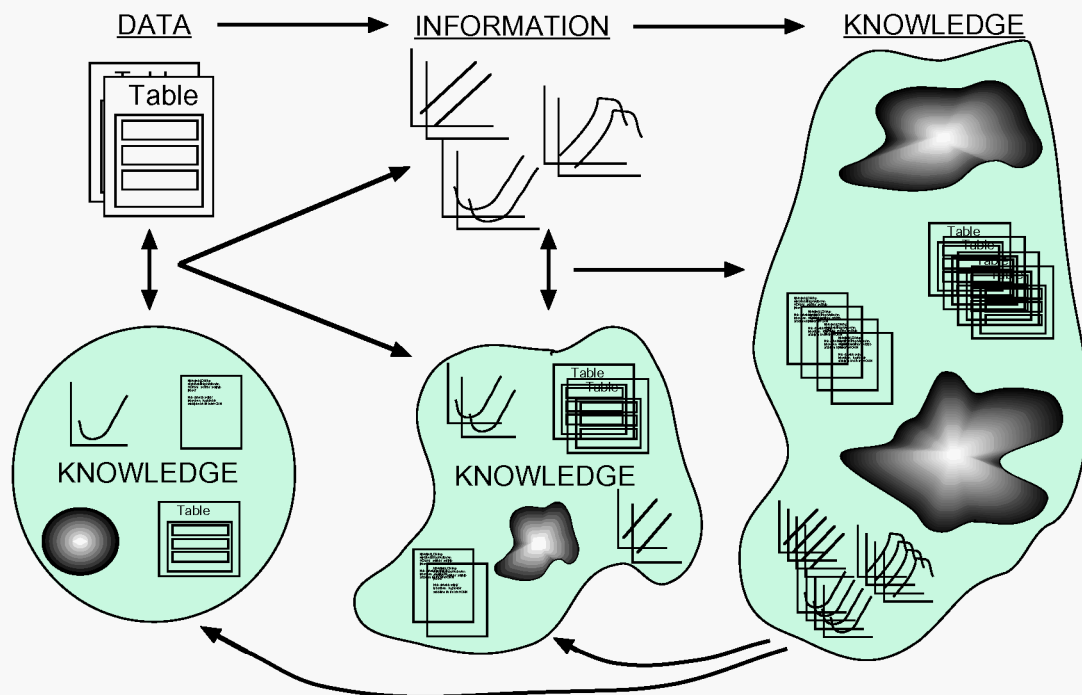


Figure 4. Sketch of the process of changing data to knowledge.

Tacit - implied but not expressed, subjective

Explicit - clearly developed meaning, objective

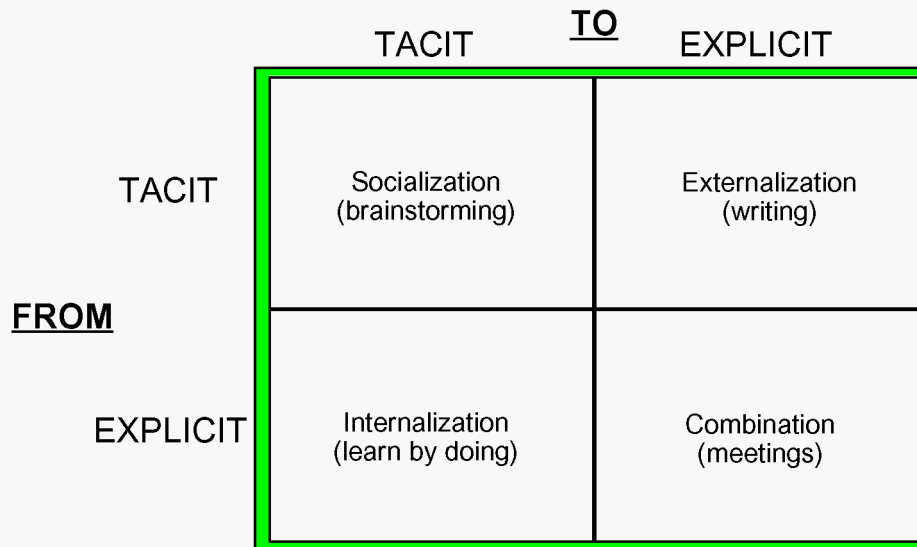


Figure 5. Four modes of knowledge creation by Nonaka⁵.

	YES	MAYBE	NO
Critical (C) Criterion = Do results look convincing/valid	C+	Co	C-
Intuitive (I) Criterion = Do results look/feel right	I+	Io	I-

C+/I+	Co/I+	C-/I+
Known Knowledge	Known Knowledge	Unknown Knowledge
C+/Io	Co/Io	C-/Io
Known Knowledge	Probable Knowledge	Probable Knowledge
C+/I-	Co/I-	C-/I-
Unknown Knowledge	Probable Knowledge	Possible Knowledge

Figure 6. Knowledge matrix.

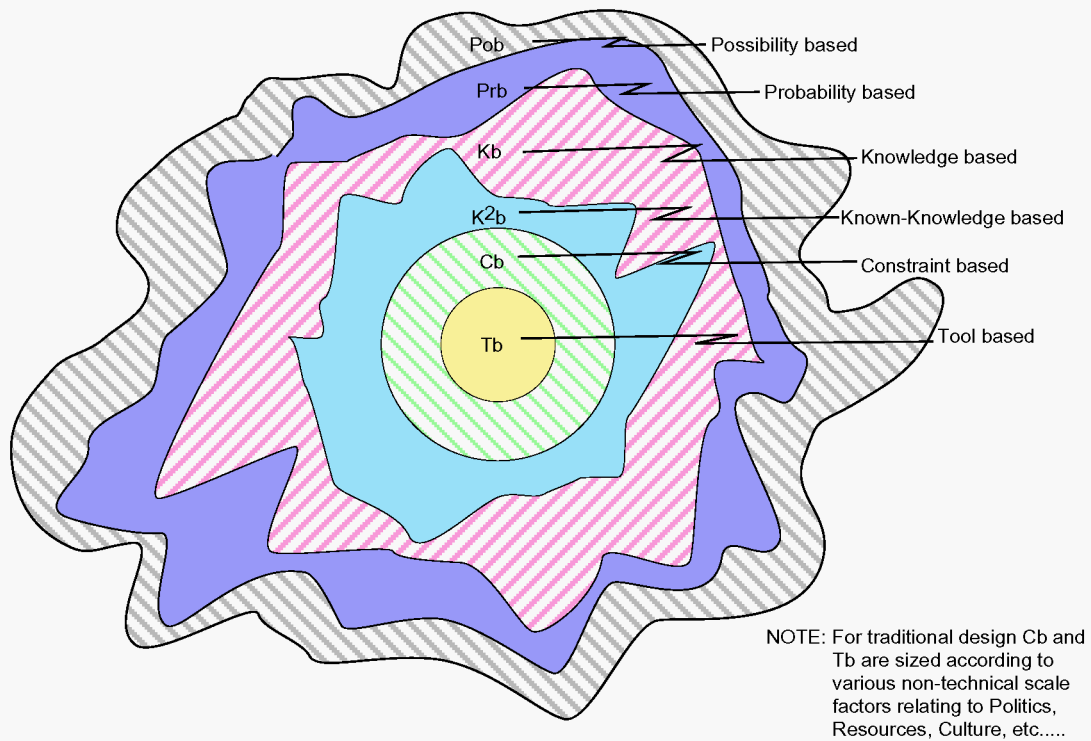


Figure 7. Sketch of design space model.

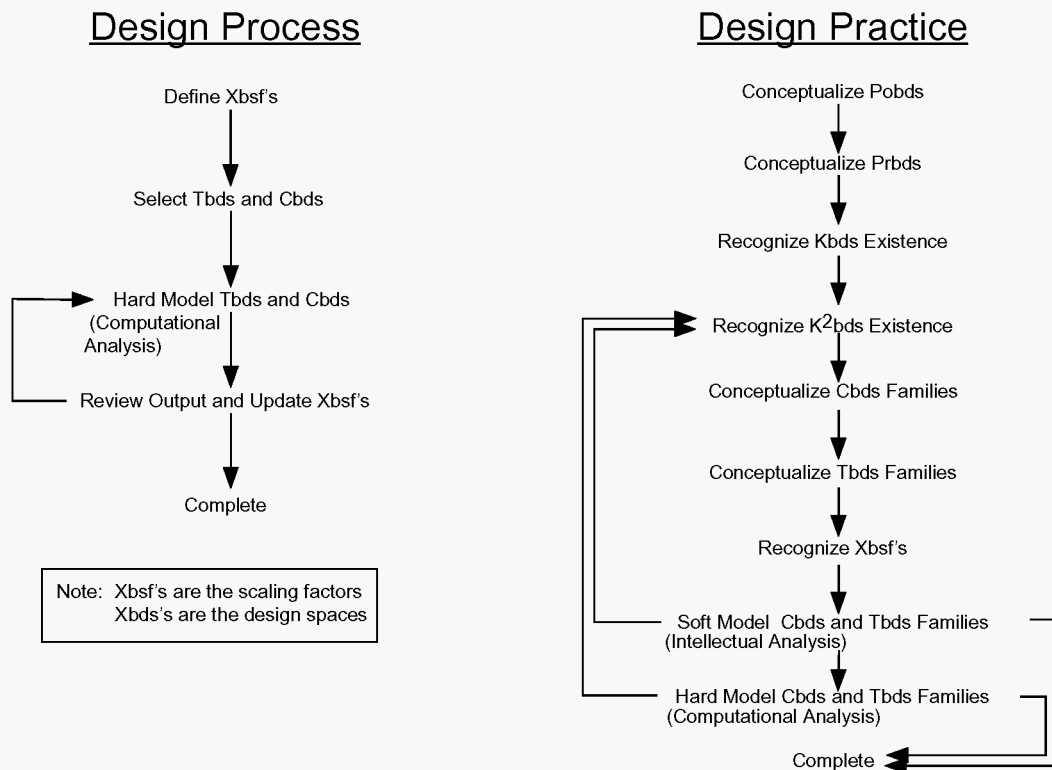


Figure 8. Sketch of design process and design practice models.

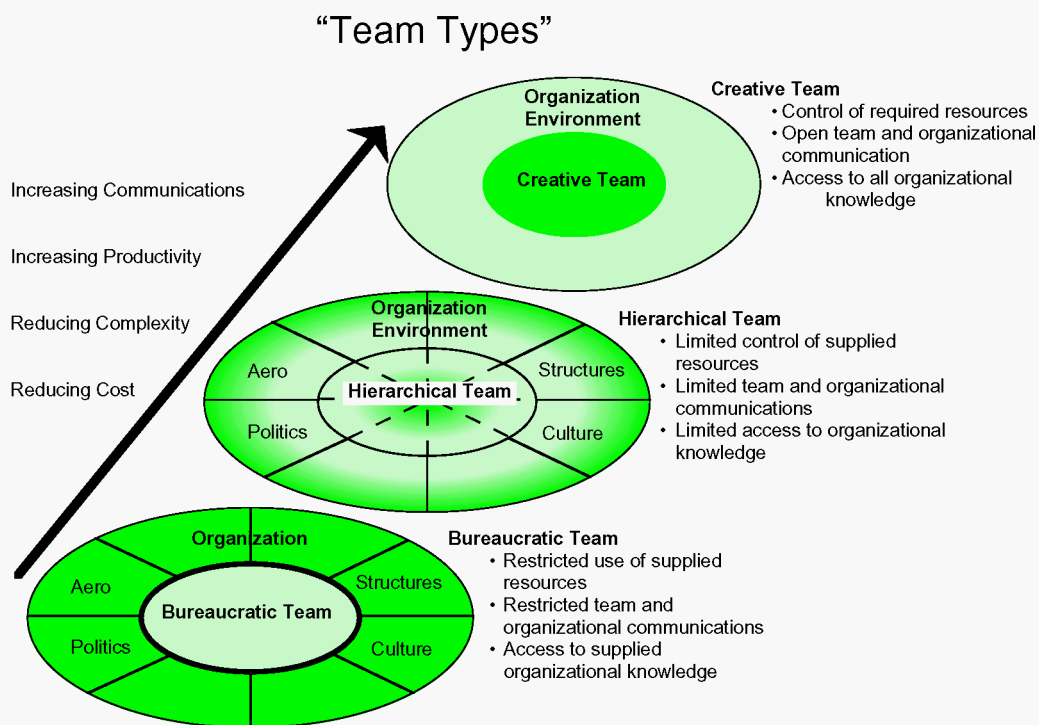


Figure 9. Sketch of team types.

Design Space	Description
Pob	All 3-D shapes with smooth and continuous geometry.
Prb	Pob + benign pressure loading, aerodynamic insensitivity to volume changes.
Kb	Prb + drag lower than Linear Theory minimums at all Mach numbers and Angle of Attack, no Aerodynamic Center travel, increased volume over existing designs.
K ² b	Kb + geometry matched to observed 3-D pressure loading pattern for swept wings
Cb	scale/volume required for mission
Tb	analytic geometry definition capability

Figure 10. Description of NFW design space.

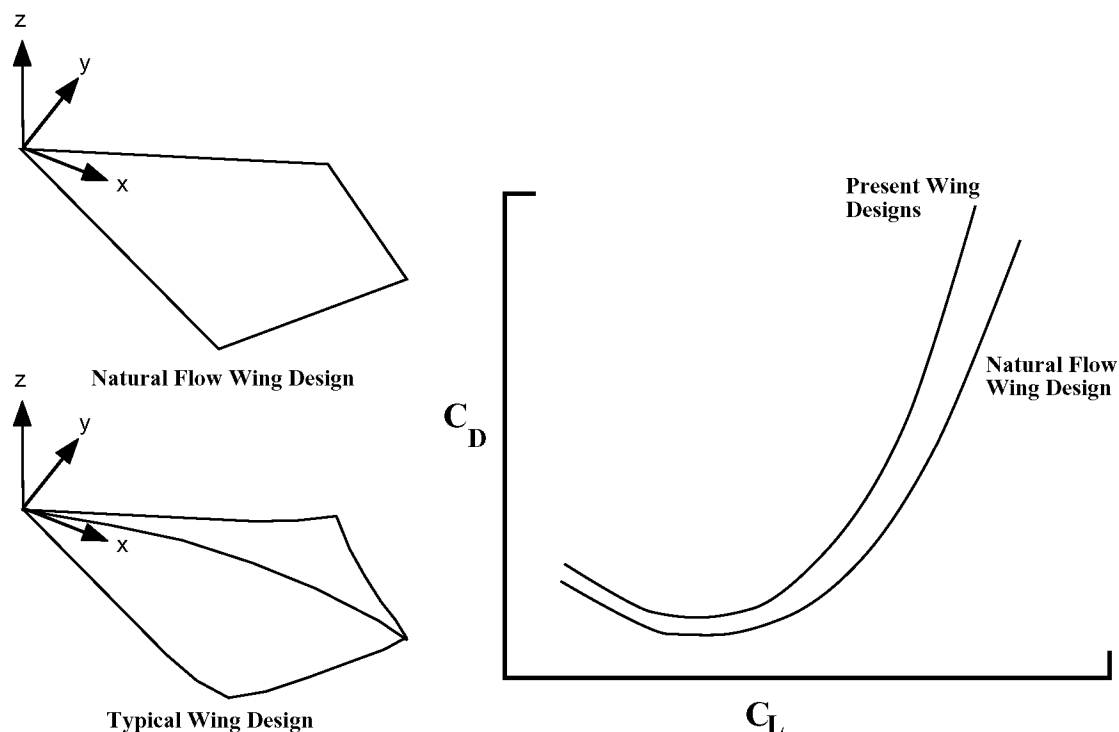


Figure 11. Details of the NFW design study.

Design Space	Description
Pob	All mechanical, fluidic, pneumatic, thermal, acoustic, etc. flow management and control effector concepts. All vehicle planform concepts comprising straight edges.
Prb	Pob + simple and lightweight. At least linear lift and pitching moment up to 50° angle-of-attack.
Kb	Prb + a minimum of 50% improvement in aerodynamic performance and a 50% reduction in volume requirements and weight.
K ² b	Kb + steady-state operation. Planar geometries with aligned edges.
Cb	must be NEW ideas.
Tb	none

Figure 12. Description of AACE design space.

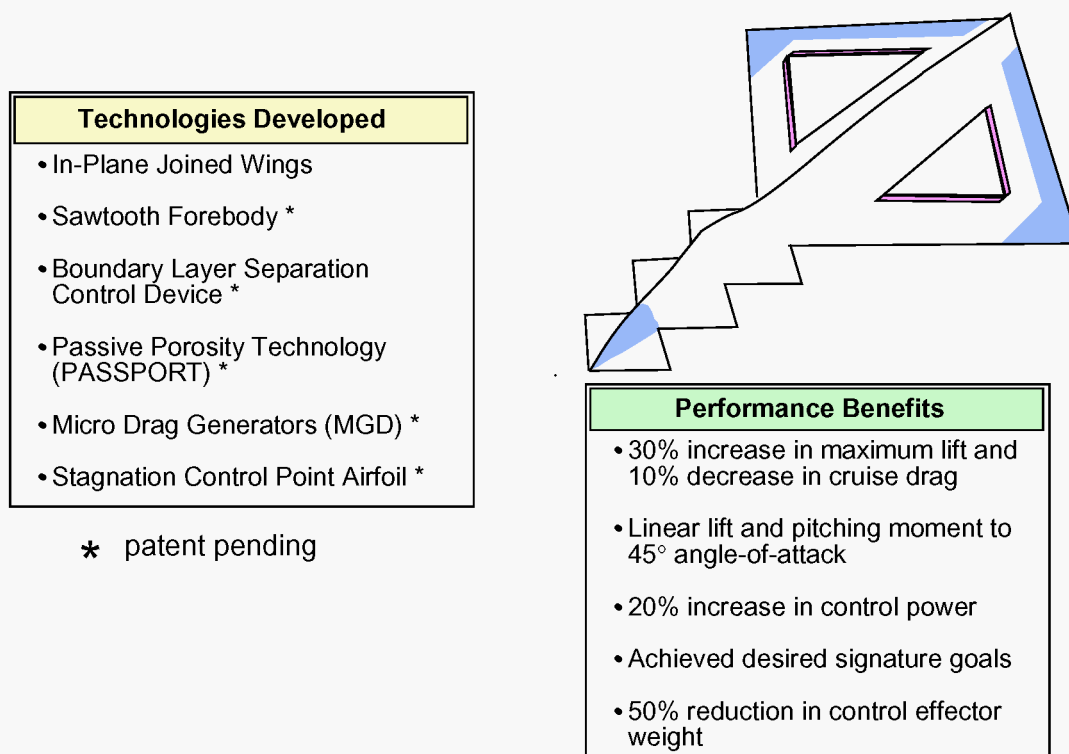
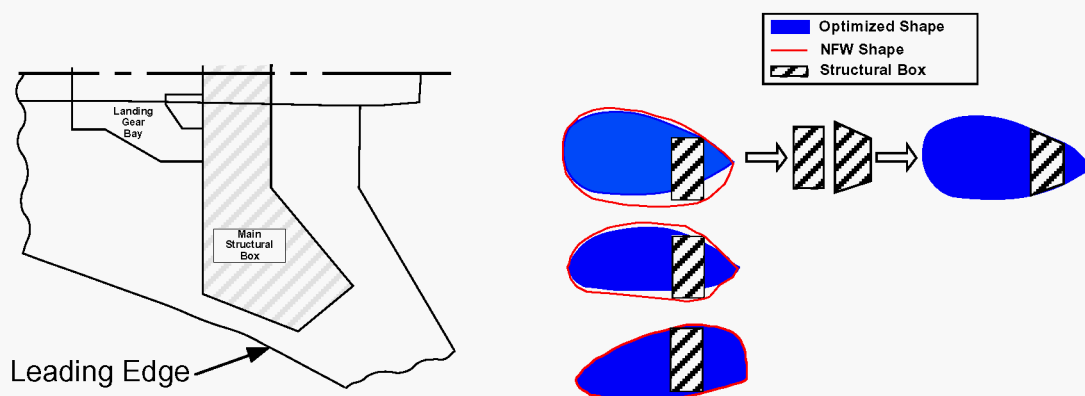


Figure 13. Details of the AACE wing design study.

Design Space	Description
Pob	All 3-D shapes with smooth and continuous geometry defined by the existing wing planform, vehicle structural volume, and engine locations.
Prb	Pob + planar edges, benign pressure loading, aerodynamic insensitivity to volume changes.
Kb	Prb + drag lower than Linear Theory minimums at all Mach numbers and Angle of Attack, no Aerodynamic Center travel, increased volume over existing designs.
K ² b	Kb + geometry matched to observed 3-D pressure loading pattern for swept wings
Cb	scale/volume required for mission
Tb	analytic geometry definition capability

Figure 14. Description of HSR design space.



Configuration	Δ Volume, %	ΔC_L	ΔC_D
Optimized	0.00	0.0	0.0000
NFW	4.82	0.0	-0.0003

Figure 15. Details of HSR design study.

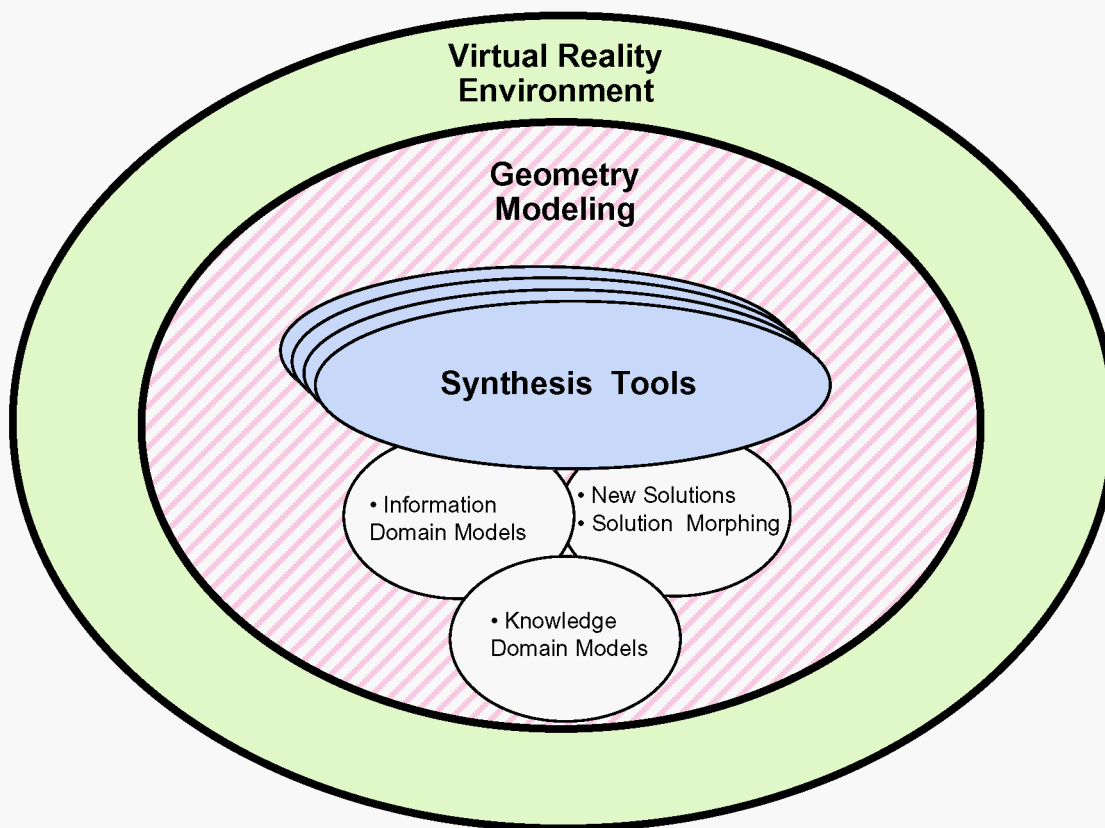


Figure 16. Sketch of virtual reality, knowledge-based design (VR KB design) model.

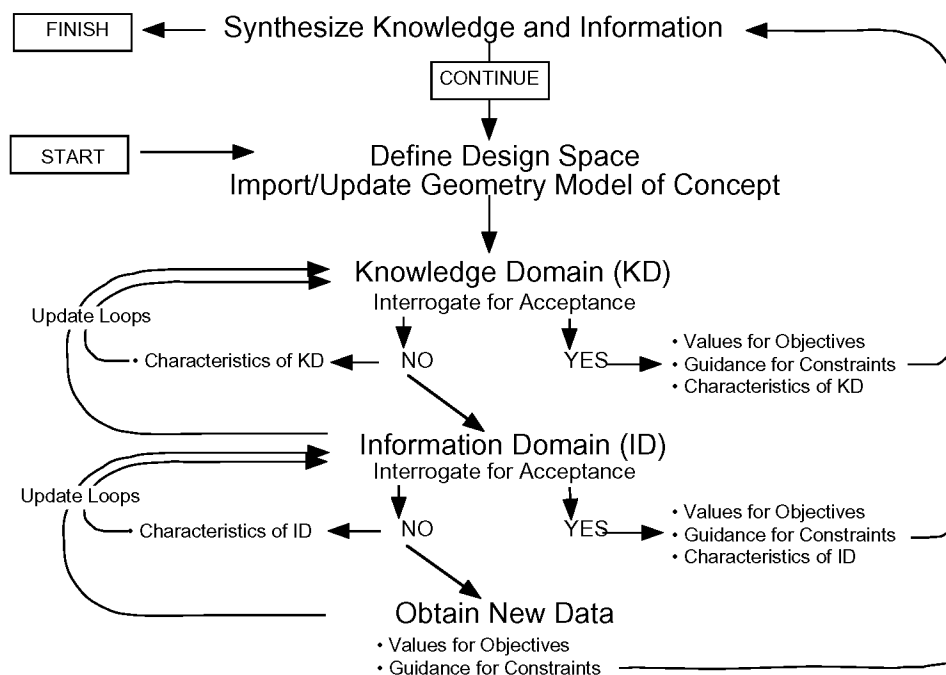


Figure 17. Sketch showing the steps of the virtual-reality, knowledge-based design system.

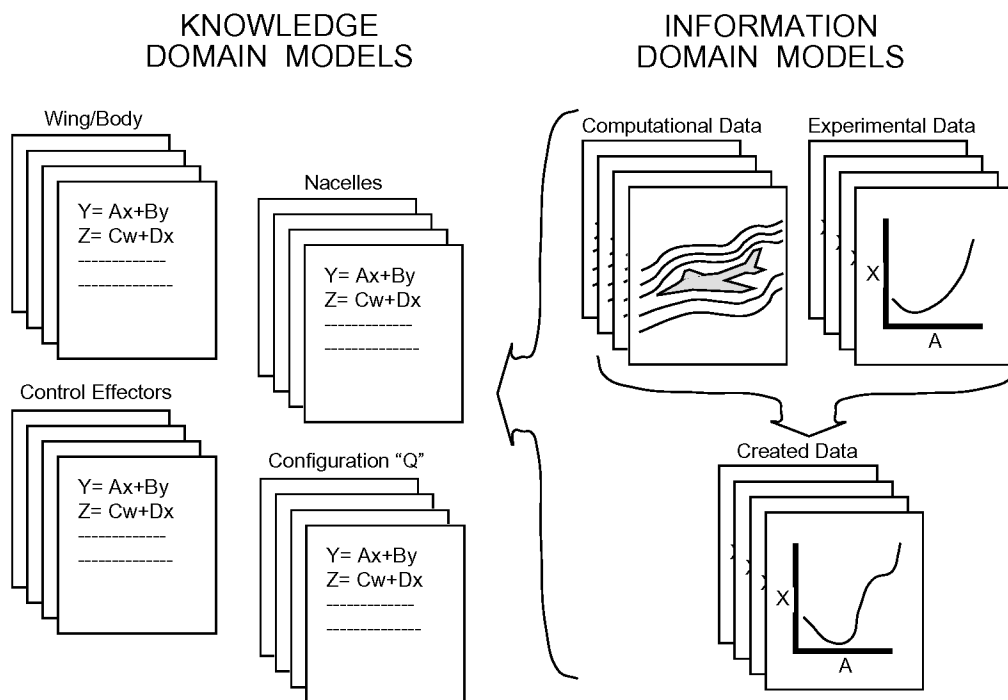


Figure 18. Sketch of knowledge and information domain models.

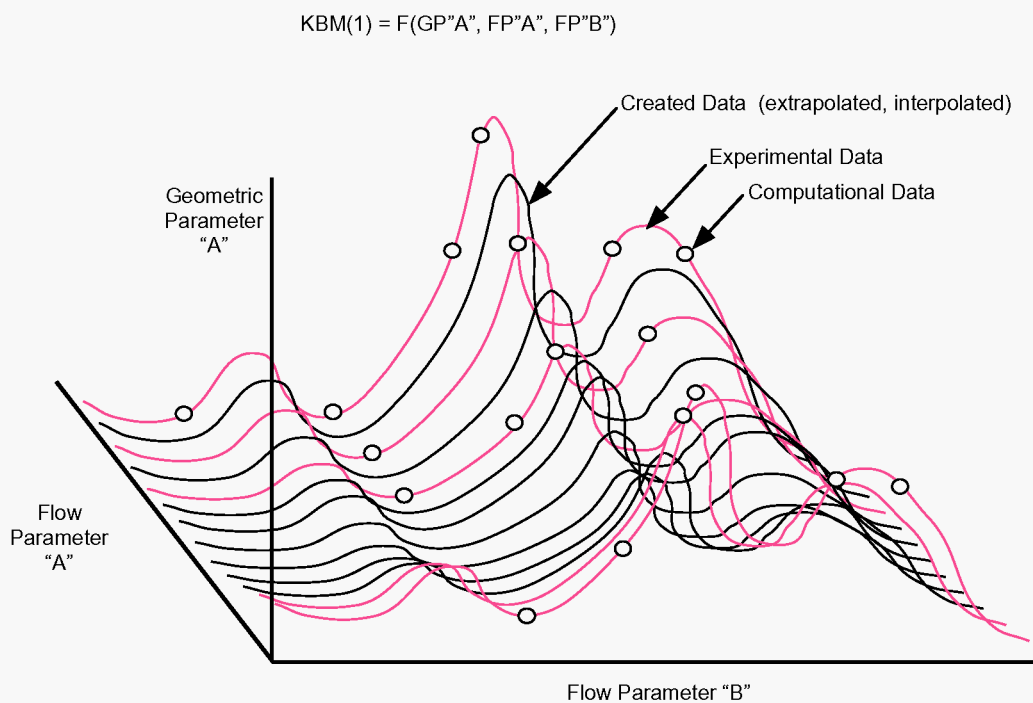


Figure 19. Representative sketch of knowledge domain model.