Evolution of generic flight vehicle design synthesis

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ABSTRACT

When defining a new product like an aircraft, space access vehicle or space mission, the Advanced Projects Group evaluates the available design space and compares it with the design space required to accomplish the specified mission. As with any product development process, the general life-cycle characteristics are established first during the conceptual design (CD) phase, clearly before a design proposal can be released to the follow-on design phases such as preliminary design (PD), detail design (DD), flight test (FT), and finally operation and disposal. As a rule of thumb, it can be assumed that around 80% of the flight vehicle configuration and mission tandem are determined during the CD phase alone, which is the key phase where the initial brainstorming has to take place. Clearly, it is the responsibility of the CD team to simulate the entire life-cycle of the project from 'cradle to grave' where the focus is on correctness rather accuracy in order to identify the design space and offer an overall proof of design convergence. Currently, the important primary aerospace vehicle and mission design decisions at CD level are still made using extremely simple analysis and heuristics. A reason for this scenario is the difficulty in synthesising the range of individual design disciplines for both, classical and novel aerospace vehicle conceptual designs, in more than an *ad hoc* fashion. Although the CD segment is seen as the most important step in the product development phase due to its pre-defining function, it is the least well understood part of the entire product evolution process due to its level of abstraction. This paper presents the roadmap towards the next generation of aerospace life-cycle synthesis systems, a software and management process capable to immediately calculate cost and time implications while simultaneously linking design, manufacturing, testing, and operation. A historical review of how design has been accomplished until today is presented. The design approaches are categorised and the characteristics of today's state-of-the-art design synthesis systems are discussed. A specification for the new class of intelligent generic design synthesis systems is presented capable of satisfying the demands imposed by the new breed of high-performance aircraft, space access vehicles, space missions, and others. Finally, the development status of the next generation aerospace vehicle design synthesis (AVDS-PrADO) simulation-based acquisition environment is presented.

NOMENCLATURE

AVD	aerospace vehicle design
AVDS	aerospace vehicle design synthesis
BWB	blended-wing body
C	certification
CAD	computer-aided design
CAM	computer-aided manufacturing
CD	conceptual design
CFD	computational fluid dynamics

Paper No. 3077. Manuscript received 20 February 2006, revised 18 February 2010, accepted 11 March 2010.

https://doi.org/10.1017/S0001924000004036 Published online by Cambridge University Press

D	disposal
DBS	data-based system
DD	detail design
DMS	data management system
DOC	direct operating cost
DoD	Department of Defense
FAA	Federal Aviation Administration
FAR	Federal Aviation Requirements
FBW	fly-by wire
FEM	finite element method
FT	flight test
FWC	flying-wing configuration
GE	General Electric
GUI	graphical user interface
HSCT	high-speed commercial transport
KB	knowledge-base
KBS	knowledge-based system
L/D	lift-drag ratio, aerodynamic efficiency
M	manufacturing, Mach number
MDA	multi-disciplinary analysis
MDO	multi-disciplinary optimisation
MVO	multi-variate optimisation
O	operation
OEW	operating empty weight
OFWC	oblique flying-wing configuration
OU	University of Oklahoma
OWC	oblique-wing configuration
PD	preliminary design
PrADO	preliminary aircraft design and optimisation
SAV	space access vehicle
SBA	simulation-based acquisition
SBA-SE	simulation-based acquisition synthesis environment
SCT	supersonic commercial transport
SSBJ	supersonic business jet
SSTO	single-stage to orbit
T	test
TAC	tail-aft configuration
TAD	technology availability date
TCA	technology concept aircraft
TCAS	technical competition analysis system
TFC	tail-first configuration
TSC	three-surface configuration
TSTO	two-stage to orbit

1.0 INTRODUCTION

We are in the midst of a technology revolution that is even larger and more dramatic in its sweep than the industrial revolution. Key to this revolution is design proficiency, the means by which new products are conceived, developed, and brought to market. One key ingredient for the development of highly competitive products like aircraft[1,2], space access vehicles[3,4], and space missions[5-7] in today's unforgiving marketplace is the availability of a product life-cycle simulation system capable to support non-linear creativity of the 'Renaissance Designer'. It is time to rethink our current approach chosen, a process routinely leading to aerospace project cost and schedule overruns but in particular failing to develop an affordable space transportation infrastructure. With the renewed emphasis on highly efficient aircraft and affordable space access, it is essential to provide the decision making bodies with a top-level simulation tool capable of visualising the interrelations between requirements, tasks, schedules, risks, investments and budget upfront during the conceptual design (CD) phase while offering trend and sensitivity information throughout the product life cycle. Overall, the concept of simulation-based acquisition (SBA) has shown potential to be a robust modelling and simulation environment across acquisition phases and projects.

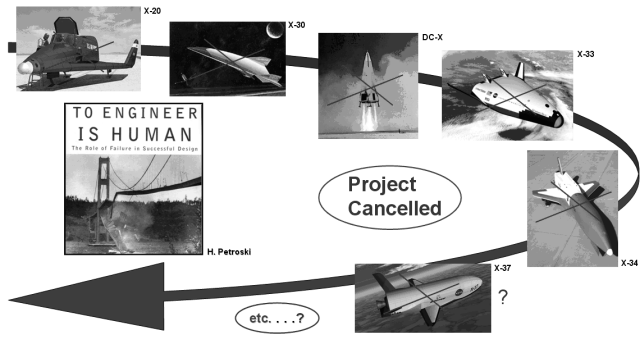


Figure 1. Design status of the emerging generation of reusable space access vehicles (SAV).

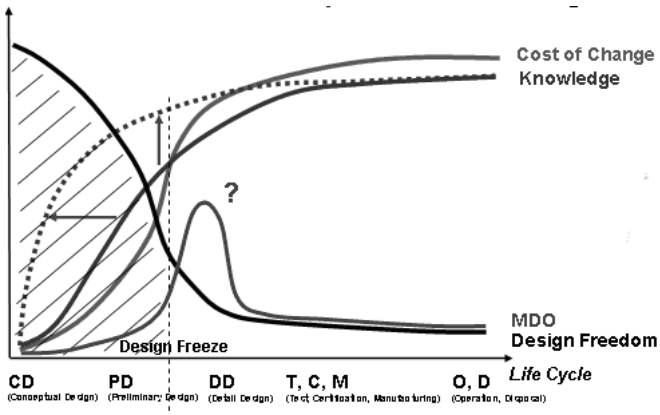


Figure 2. Design freedom, knowledge, cost of change, and MDO at CD, PD and DD levels.

1.1 'Managerial implication of computerised aircraft design synthesis' – revisited

The potential of computerised synthesis on product development is well recognised in the multi-disciplinary analysis (MDA) and multi-disciplinary optimisation (MDO) engineering domains. However, it appears that the implications of top level product synthesis on managerial decision-making are still underestimated and often not understood. In a classic paper written just over 30 years ago, William L. Straub[8] has evaluated managerial aspects of computerised design programmes. Now the AVD Lab is in the position to update this seminal study. Interestingly, our investigations[9-11] show that the advances seen with MDA and MDO techniques have not yet provided the managerial support decision tool foreseen by Straub. In particular, attempts to reliably quantify the design space, thus development risk associated with reusable SAVs have consistently failed, as the track-record of cancelled and failed SAV demonstrator projects indicates, see Fig. 1.

One reason for this obvious dilemma appears to be the difficulty to truly comprehend the life-cycle of the aerospace product. The flight vehicle design process is, in general, comprised of three sequential design phases: conceptual design (CD), preliminary design (PD), and detailed design (DD). The sequence starts with a set of requirements for the aerospace product. The first step towards a flight worthy vehicle is the definition of a configuration concept during the CD phase. This design phase is of utmost importance since around 80% of the configuration concept is determined here.

https://doi.org/10.1017/S0001924000004036 Published online by Cambridge University Press

Most importantly, the life-cycle cost of the flight vehicle has to be calculated reliably during the CD phase due to adverse cost implications otherwise, see Fig. 2. As the design evolves, the design freedom decays rapidly throughout the PD and DD phases while the knowledge about the product obviously continually increases. We see that the CD phase is the key phase where the initial brainstorming has to take place. Clearly, it is the responsibility of the CD team to simulate the entire life-cycle of the project from 'cradle to grave' where the focus is on correctness rather accuracy. Having a robust CD design process in place will enable the identification and visualisation of the parameter space that contains the solution to the mission performance sought accompanied by an overall proof of design convergence for the configuration concept selected.

The problem manifests in that the primary aerospace vehicle and mission design decisions at CD level are still made using extremely simple analysis and heuristics. A reason for this scenario is the difficulty to synthesise the range of individual design disciplines for both, classical and novel aerospace vehicle conceptual designs, in more than an *ad hoc* fashion. Although the CD segment is seen as the most important step in the product development phase due to its pre-defining function, it is the least well understood part of the entire product evolution process due to its level of abstraction. As a result, we see many design environments neglecting the CD phase throughout the life-cycle while trying to compensate for this deficiency with placing a stronger focus on high-fidelity tool residing in the PD and DD design phases. This results in losing the capability to understand and visualise the solution space; 'instead of overseeing the topography of the wood, the team is condemned to find a path through the trees'. Note, there is a difference between the evaluation only of a configuration concept and the determination of its characteristics, in contrast to sizing the configuration concept to a mission. As indicated with Fig. 2, MDO techniques have been successfully employed by coupling typically CFD and FEM tools during the PD and DD phase. However, the success rate has been less promising for integrating 20+ disciplines during the CD phase. Clearly, this situation does not yet offer the decision-making body with the anticipated multi-disciplinary 'digital crystal ball' enabling informed risk assessments and scenario simulations.

Overall, Straub's assessment from 1974 has not lost any of its sharpness and attraction today; it describes the potential a powerful synthesis environment offers to the decision-making body. The main problem, still, remains the difficulty to explain the importance to reliably screen the solution space for a design-direction during the CD phase and to arrive at a robust algorithm capable to converge a design proposal. Clearly, the initial CD phase is the key phase where project lead has to be able to cheaply oversee the risk potential of any project-related decisions. As a consequence, the present study spends some more time explaining the rôle of the key phase during the life-cycle, being the conceptual design (CD) phase. To avoid misunderstanding, the synthesis tool has to comprehend and properly balance all product evolution phases and associated components.

1.2 The simulation-based acquisition synthesis environment

A modern adaptation of design synthesis leads to the concept of simulation-based acquisition (SBA). The multi-disciplinary character of any SBA-environment, however, requires a well-integrated synthesis capability, capable of avoiding performance losses induced by multiple interfaces. Consequently, it is required to transition today's SBA-environment into a computerised SBA-synthesis environment (SBA-SE). Bearing in mind the technical complexity of any high-performance flight vehicle, only integrated SBA-SEs are capable to reliably trade the multi-disciplinary requirements dictated by either the aviation or space infrastructure. This permits the project lead to identify and quantify the associated design risks of alternative flight vehicle configuration concepts especially during the conceptual design (CD) phase.

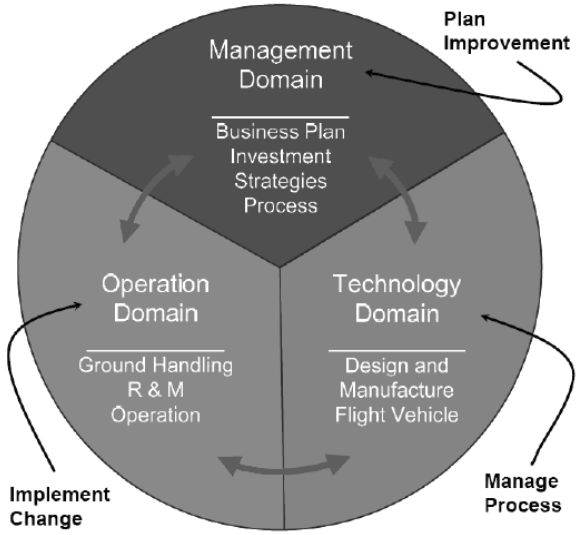


Figure 3. Generic process management life-cycle.

Experience developed with aerospace life-cycle design procedures by several aerospace organisations and collaborative engineering environments within NASA and DoD agencies indicate, that management will need to overcome significant cultural barriers to SBA-SE success. Apart from changes required in roles and responsibilities, programme requirements, policies, and procedures; which all require unified management support, only a computerised SBA-SE simulation tool will be capable to visualise the multi-disciplinary convergence design-space and mission-space topographies of an aerial or space transportation infrastructure in real time, a non-trivial task where the margin between success and failure may depend on numerical subtleties[11].

1.3 The generic process management life-cycle model

What are the three elements which resemble the generic process management model applicable to our product synthesis system AVDS-PrADO? As is illustrated in Fig. 3, the three inter-related top level domains are the management domain, technology domain, and operation domain. First, the management domain is required to plan improvements leading to a business plan, investment strategies and decision processes. In today's highly dynamic business environment, an aerospace project requires quick adaptation to changing environments and in particular the competition. Thus, it is required to monitor the status of the operational and technology domains by defining investment strategies and processes. The technology domain is primarily responsible to manage the design and manufacturing of all hardware (aircraft, SAV, space vehicle, etc.). Its focus is on utilising available design experience, design methodologies and design tools leading to the manufacture of low-cost and low-risk hardware. Overall, the technology domain is the core element of the aerospace transportation infrastructure since it is here where technical and economic feasibility of a project will be determined Finally, the operation domain is required to implement all activities related to ground handling, launch, and mission monitoring. Compared to other transportation systems such as road and water, the operational processes for air and space systems tend to be far more complex and expensive.

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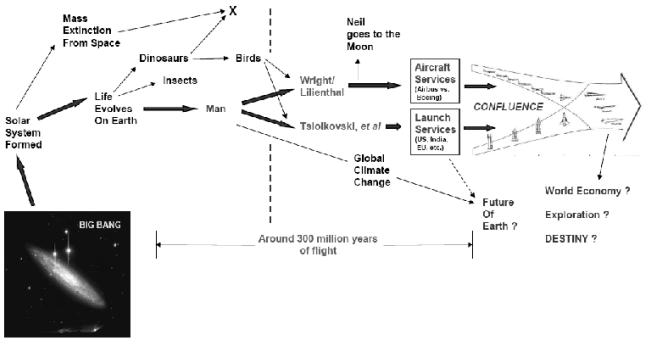


Figure 4. A cosmic view of the history of aerospace vehicle design evolution.

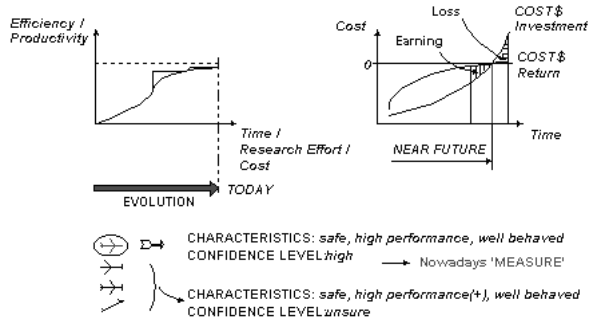


Figure 5. Problem description: Today's aircraft design problem.

1.4 The design synthesis specialist – a chess master mastering 'Three-dimensional chess'

With the availability of a computer-based synthesis environment capable of combining all three domains outlined in Fig. 3, the objective to centralise requirement formulation and managerial/technical decision making clearly enables the 'chess-master' to assess the design space via multiple examinations and visualizations of the trade volumes prior to locking requirements, time, budget and quality. Such comprehensive SBA-SE framework enables the project lead and synthesis specialist to monitor an aerospace-related project from 'cradle to grave'. All necessary top-down and bottom-up information is combined and centralised in the system. This enables the decision-making bodies 'to pull the strings in the cockpit' with a degree of transparency, speed, and accuracy not seen before. Thus, the current state-of-the-art seen with existing analysis and design systems is advanced towards a generic cause-effect synthesis process, enabling the project manager or engineer to walk through the processes and its management environment while obtaining unfiltered context information towards goal achievement.

A prototype system of a generic flight vehicle (aircraft and SAV) SBA-SE is under development at the Aerospace Vehicle Design Laboratory (AVD Lab), The University of Texas at Arlington. Having presented the grand research development perspective of AVDS-PrADO towards an effective air and space transportation infrastructure and system, we concentrate with the following on key ingredients and understanding required towards the functional synthesis system.

2.0 FLIGHT VEHICLE DESIGN PROFICIENCY

As outlined in the introductory section, key to the aerospace revolution for the second century of flight is design proficiency, the means by which new products are conceived, developed, and brought to market.

2.1 Confluence of aircraft services and launch services

When Professor J. Stollery presented The Sydney Goldstein Memorial Lecture with the title 'Aerodynamics, Past, Present and Future'[12], he offered his personal view of the period 1930 to 2030. He summarised his perspective on future aerodynamics work, in particular the research and development needed for the range of flying vehicles, likely future projects, and the intellectual challenges involved. Overall, this presentation vividly indicates the scope of technical, scientific, and intellectual challenges lying ahead. To complement such vision, Prem[13] forecasts an aerospace vehicle development scenario where we may see a confluence of aircraft and space launch services, see Fig. 4. Section I has indicated some of the shortcomings and the potential of the next generation aerospace product synthesis environments particularly during the conceptual definition phase. Clearly, current and future challenges, as identified by Stollery and Prem, have to be addressed first at the conceptual design (CD) level.

2.2 Today's flight vehicle design problem

Ben Rich, vice president of Lockheed and former director of the Skunk Works (1975 to 1991) writes in Skunk Works[14]. "In my 40 years at Lockheed I worked on 27 different airplanes. Today's young engineer will be lucky to build even one. The life cycle of a military airplane is far different from the development and manufacturing of anything else. Obsolescence is guaranteed because outside of a secret, high-priority project environment like the Skunk Works, it usually takes eight to ten years to get an airplane from the drawing board into production and operational. Every combat airplane that flew in Operation Desert Storm in 1991 was at least ten to 15 years old by the time it actually proved its worth on the battlefield, and we are now entering an era in which there may be twenty- to thirty-year lapse between generations of military aircraft. ... The development costs of fighters have increased by a factor of 100 since the 1950s, and unit procurement costs have risen 11% every year since 1963!"

This exactly mirrors the current military aircraft industry from the perspective of the aircraft designer. To complement this view, an analogy can be drawn to the commercial transport aircraft industry. Clearly, a detailed assessment and discussion of the dynamics of the past, present, and future civil and military aerospace industry is not the scope of the current investigation. The interested reader may be referred to Newhouse[1], Lynn[2], and Hayward[15] for further reading. However, it is instructive, to relate some of the above comments to today's aerospace flight vehicle design problem.

Scott[16] effectively illustrates Rich's statements by discussing the relation between an aircraft designer's career length and the number of new military designs worked on. He provides an overview which spans five decades (1950-2000), a 40-year career length is assumed in Table 1.

In light of Rich's and Scott's viewpoints, what are the adverse implications for the aerospace conceptual design (CD) engineering proficiency and excellence required when faced with the adverse developments available as highlighted with Table 1? Today, the aerospace industry continues to further experience company consolidations, budget cuts, programme cancellations and others, altogether resulting in further reduced hardware development opportunities for the practicing engineer. The author is convinced to see a connection between spiraling aerospace product cost and schedule overruns and the significantly lengthened project cycle times for fewer products. It is the opinion of the author that such situation generates highly specialised authorities in stand-alone disciplines, but dwindling

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Table 1
Design careers length versus new military designs by decade (1950-2000)

Time Span	Aircraft Projects
1950s - 1980s	XP-5Y, A-2D, XC-120, F-4D, F-3H, B-52, A-3D, X-3, S-2F, X-2, F-10F, F-2Y, F-100, B-57, F-102, R-3Y1, F-104, A-4D, B-66, F-11F, C-130, F-101, T-37, XFY, F-8U, F-6M, U-2, XY-3, F-105, X-13, C-133, F-107, B-58, F-106, F-5D, X-14, C-140, T-2, F 4, A-5, T-39, T-38, AQ-1, X-15, F-5A, X-1B
1960s - 1990s	A-6, SR-71, SC-4A, X-21, X-19, C-141, B-70, XC-142, F-111, A-7, OV-10, X-22, X-26B, X-5A, X-24
1970s - 2000s	F-14, S-8, YA-9, A-10, F-15, F-18, YF-17, B-1A, YC-15, YC-14, AV-8B, F/A-18
1980s - 2010s	F-117, F-20, X-29, T-46, T-45, B-2, V-22
1990s - 2020s	YF-22, YF-23, X-31, JSF, C-17
2000s - 2030s	UCAV, B-3??, ...

Source: Data adapted, in part, from Scott[16]

numbers of design integrators, synthesis specialists, and configurers which are required to overlook and lead a project through the design life-cycle, see Fig. 2. Having understood the difference in time, effort, and opportunity required to educate and train a proficient synthesis specialist compared to a proficient disciplinary specialist, the implications for today's aerospace project 'cost and schedule explosion' does not come as a surprise. If we assume that this trend will continue to be the scenario for the longer-term future, then we seriously have to evolve the synthesis mindset and toolbox accordingly into a 21st century life-cycle synthesis capability. Overall, the Class V generation not only integrates the individual design phases in a true multi-disciplinary system, but a library of historical parametric design case studies will enable the designer to reverse-engineer past and present design case studies, thereby readying him to apply such skill-set to present and future products.

It is a fact that the number of all-new military and commercial transport aircraft designs in the present decade has decreased spectacularly. The chance to participate in a number of different aircraft types and projects may seem small, a statement particularly valid for the commercial transport aircraft section. On the other hand, these design activities require more people for longer periods as Anderson outlines in the stimulating post face of his recent book[17]. Having in mind the military scenario as illustrated by Rich and Scott, the commercial transport aircraft companies in contrast concentrate, since the early days of the Boeing 707, primarily on aircraft derivative development, as implied by the modern family-concept strategy. Loftin[18] appreciates in Chapter Second-Generation Transports the contributing circumstances, along which the modern family-concept strategy evolved. 'All-new' development exceptions in the post B707-era of transport aircraft evolution have been aircraft like the Boeing 747 and the current Airbus Industrie A380 design. The above remark 'all-new' is merely supported by the fact, that exceptional and excessive technological and financial risks had been and are involved in these non-derivative developments, primarily due to the large aircraft scale involved, although these aircraft still resemble the initial B707 configuration concept.

The high technology aerospace industry primarily operates to make profit. In summary, this dynamic marketplace can be characterised as an environment, where virtually no diversity exists between commercial transport aircraft realised, where development cycle periods are constantly lengthening, where development costs explode, where aerospace companies consolidate, and where the availability of creative aerospace project engineers, who have to be a cut above mere specialists in their field, is reducing. An immediate consequence of the long development cycles of today's aircraft projects is the difficulty for the aircraft designer, to educate, maintain and augment his or her creative activity and authority by involving imagination, intuition and deliberate choice. Jack van Hengst remarks that " ... in this time our doing is our learning ..."[19]. The above notion appears to contradict the commercial aircraft derivative development trend, an environment pressurised by the need to introduce the appropriate product to market before the competition. Clearly, the ability to rapidly design and develop derivative aircraft of an evolved baseline design (e.g., regional transports) should not be mistaken with the design proficiency required for a new design.

Engineering problems have always been and will continue to be under-defined; there are many solutions, good, bad and indifferent. Bavitz from Grumman Aerospace has sketched a professional profile of the aircraft designer in an *Aerospace America* article[20]. He rightly characterises the individual, who has to balance industrial art and aircraft design technology towards a good solution. The aerospace industry is confronted with an ever increasing performance demand[21,22]. It remains doubtful, if some of the present engineering circumstances are truly compatible with today's high technology demand. Figure 5 illustrates the present aircraft design problem with consequent effects on the aerospace product.

The adopted commercial transport aircraft configuration resembles the XB-47, Dash-80, and B707 layout[23]. This aircraft layout has evolved throughout one century of aviation history, strengthening its overall characteristics especially from the early 1950s onwards. The tail-aft configuration (TAC) type has transformed towards a dependable vehicle, which represents today's standard for air passenger transportation. It has helped to define, thus complies with the current safety standards, shows performance characteristics which justify its operation and has matured towards a well behaved man-machine synthesis. The graph on the left in Fig. 5 qualitatively recapitulates how efficiency and productivity of the current aircraft arrangement strive asymptotically towards a plateau. The shallow slope of the graph visualises as a fact today's aircraft design problem. As a consequence, marginal efficiency and productivity improvements are enforced with ever-increasing research effort required, development time required, and the associated cost implications. To complement these facts, the graph on the right indicates the cost and profit issue qualitatively. The investment required to enable advancement is raising over-proportional towards infinity, whereby the return stabilises towards a finite figure. It remains the question when and how both curves intersect. It is left to the reader to decide, if the evolutionary advancement of the current commercial transport aircraft type operates in the region of relative profit or relative loss.

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Table 2
Foreseen excess design-potential of B707-type aircraft layout (1999 technology level assumed).

Indicator	Prof. D.I.A. Poll	Dr. R. Hilbig
L/D	Virtually no more to be gained in terms of aerodynamic efficiency; 20% improvement to fuel burn with application of laminar flow control	36% improvement to fuel burn with all measures
Propulsion	15 % within the limit of the gas turbine; 40 % improvement of propulsive efficiency	23% improvement to fuel burn with all measures
ructure, Construction, Weights	(-)	8% improvement to fuel burn with all measures

Source: Data adapted, in part, from Poll[28] and Hilbig[29].

The foregoing argumentation postulates, that the present TAC airframe-power unit configuration is close at the limit of its development potential. Such judgment obviously requires an assessment of the physical design boundaries and the associated aircraft design potential surplus. Jones[24], Richards[25] and Gabrielli and von Kármán[26] have attempted to define aerodynamic design boundaries for aircraft. More recently, Poll and Chudoba[27] started to re-examine the power ultimately necessary for mechanical flight and the power actually expended on flight of conventional (TAC) and advanced vehicles. The difficulty in assessing these boundaries becomes obvious when comparing estimates by Poll[28] and Hilbig[29] in Table 2. This comparison is of particular interest because one is tempted to assume consistency in the findings because both authors are well established aerodynamicists.

The above estimates of the aerodynamic efficiency (L/D) excess design-potential for the B707-type TAC transport aircraft configuration deviate significantly from each other. By questioning the airframe aerodynamic limit it is designed to, Poll considers today's commercial transport aircraft at the limit defined by Jones. He argues that in particular laminar flow control technology could modify this Jones's aerodynamic design limit. In contrast, Hilbig quotes a rather optimistic 36% excess design potential with reference to present technology standard. However, he does not specify how the B707-type aircraft should be shaped, whether the technology required to do so has the potential to demonstrate feasibility over the next 15 to 20 years. Although the latest generation of Airbus aircraft has demonstrated an impressive 30% performance advance to the initial A300 reference, it remains questionable if another 50% net performance gain over today's commercial transport can be realised by taking today's time and research effort expenditures and associated cost and profit implications into account. In this context, a recent update to Gabrielli and von Kármán's *What Price Speed*? has been published by Imperial College's Railway Research Group[30]. Without discussing this issue in more detail, it can be concluded that the question of what is attainable with respect to flight physics and aviation technology, is not yet answered conclusively.

The above outline has visualised today's struggle to satisfy the quest for reductions in direct operating costs (DOC). Further problems have to be expected in the near future in the form of operational constraints. Environmental issues will offset much of the potential performance profit to be expected with an ongoing B707-type TAC aircraft evolution. Of particular concern are restrictions on emissions, radiation and noise. It can be foreseen that these additional implications will aggravate today's time and research effort expenditures and associated cost and profit implications, further limiting the returns on investment.

Boyne[31] points out, that the speed, with which the Lockheed Skunk Works have incorporated outstanding examples of advancing aerospace technology in the past, is instrumental to their success. Table 3 compares aircraft design cycle times of selected military with civil programmes. Table 3 serves the purpose of illustrating the strengths of a highly capable aircraft development environment. As Rich14 remarks, any company whose fortune depends as well on developing new technologies should have a Skunk Works in operation. He comments why not so many Skunk Works-style units are scattered around various industries. "... But if Lockheed's Skunk Works has been a tremendously successful model, why haven't hundreds of other companies tried to emulate it? One reason, I think, is that most other companies don't really understand the concept or its scope and limitations, while many others are loath to grant the freedom and independence from management control that really are necessary ingredients for running a successful Skunk Works enterprise. Unfortunately, the trend nowadays is towards more supervision and bureaucracy, not less. ..." Overall, the Skunk Works formula to success has been expressed by Lockheed Martin as follows[32]: "... The key has been to identify the best individual talents in aviation, blend and equip them with every tool needed, then provide complete creative freedom so they may arrive at an optimum solution in short order ...".

An example for implementing Skunk Works style operation is an emulation by Boeing with Phantom Works[33]. Overall, it is of paramount importance for the quality and competitiveness of the aerospace product, to advance in-house product sizing processes on a systematic and enduring basis as obligatory within a Skunk Works environment. Most industrial conceptual design environments do not have the freedom to modernise their design and analysis capability to the state-of-the-art. However, the remaining aircraft design potential of the B707-type of aircraft can only be unlocked on a profitable scale, when the available aircraft specialist design experience is efficiently blended with cutting-edge computer resources available towards pushing the objective function 'benefit' towards short order and quality. It must be remarked, that the above understanding is rarely adopted by industry decision making authorities. As a consequence, conceptual design development tool inconsistencies and inadequacy may result in local design optima in comparison to global design optima, systematic design errors which are successively optimised with high-fidelity tools.

Clearly, any prospects of reducing aerospace product design cycle

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Table 3
Design cycle periods of selected civil and military aircraft programmes.

Aircraft	First Flight	Months from Go-Ahead to First Flight	Technological Advances
Do328	1991	40	High-Performance Regional Transport Aircraft
A300	1972	42	Twin engine wide body
A320	1987	36	FBW narrow body
Concorde	1969	59	Mach 2 commercial transport; FBW
XF-104	1954	13	Mach 2 aerodynamics; sophisticated engine inlets; weapons
U-2	1955	8	Ultrahigh altitude; lightweight structure
A-12	1962	32	Mach 3 speed; advanced propulsion; titanium structure
Have Blue	1977	18	Stealth
F-117A	1981	30	Stealth; weapons
YF-22	1990	46	Stealth; supersonic cruise; agility; weapons
B-2	1989	94	Stealth; flying wing configuration

Source: Data adapted, in part, from Boyne[31].

periods and strengthening competitiveness should justify the refinement of the conceptual design (CD) process. Furthermore, commercial transport aircraft manufacturers can benefit from Skunk Works style operation in several areas, when targeting reduced development time and research effort expenditures.

2.3 New flight vehicle design problem

At the present time, the projected rates of growth for passenger and cargo markets are such that the annual rate of consumption of aviation fuel will triple to quadruple by the year 2020[28,29,34]. In view of the growing international concern about the environment, it is probable that such high levels of atmospheric pollution will be politically unacceptable and, as was the case with noise, legislation will be introduced to force change. Innovative solutions are required if, as seems likely, improvements of more than a few percent are demanded. This is because the present airframe-power unit configuration is at the limit of its profitable development potential.

Section I has identified the significance of advancing the current generation of aerospace product conceptual design (CD) processes, an activity fundamental if there is on-going activity to probe hidden excess performance reserves of today's B707-type aircraft configuration on a profitable scale, see today's aircraft design problem. However, even more fundamental conceptual design method shortcomings materialise, when trying to appreciate aircraft configurations different in shape than the 'conventional' B707 type. The typical conceptual design office of commercial transport aircraft manufacturers clearly has not adequate analysis and design methods at hand, to consistently anticipate the performance potential and to evaluate the commercial feasibility of 'novel' aircraft configurations. This new aircraft design problem, however, provokes the question: Is it worthwhile at all to address development of a new generation of aircraft design processes and methods for advanced aircraft types, when the 'conventional' B707-type is successful in operation and has gained overall acceptance? It is the incentive of the following excerpt, to inspect the periodic commercial interest and curiosity towards advanced flight vehicle shapes, the fundamental vision and ingredients required to build trustworthy understanding.

Brown[35] writes in *Wings of the Weird & Wonderful*: "The unusual and unorthodox in aircraft design or operation has always intrigued me; the superlative in performance and handling has always excited me. Occasionally fortune smiles and combines all these characteristics in one rare bird to offer the thrill of a lifetime. ... I have never been able to regard aeroplanes as inanimate objects, ... One thing they can never be, and that is dull." The above quote acknowledges the evolutionary and revolutionary endeavor of winged aircraft development throughout one century of aircraft design. Kroo36 cautions the apparent stagnation of the evolutionary development of the B707-type aircraft configuration from the recent past until today by comparing the B707 and A340 commercial transports. He resumes that "When we think about what may appear in future aircraft designs, we might look at recent history. The look may be frightening. From first appearances, anyway, nothing has happened in the last 40 years!"

What are the reasons for this apparent stagnation in aircraft evolution? At first, it is argued that enormous economic risks are involved, consisting of investment risk and liability risk when progressing the revolutionary rather than the evolutionary track. Furthermore, any venturesome seems to be obsolete with the relative commercial success of the current B707 aircraft type. Sterk and Torenbeek[37] in contrast express rather optimistically that "It is unlikely that the design trends are set merely by conservatism, for example a desire to continue a proven concept in order to avoid the large financial risks of totally new development programmes. The sharp competition always sets incentives to new and innovative concepts since new designs must be considerably improved to be competitive to (derivative of) already established and proven types." The author is of the opinion that the evolutionary aircraft design history has revealed considerable conservatism and idleness, being originated by insufficient design knowledge acquisition and conservation as primary reason. One has to comprehend the loss of documentation belonging to several British aircraft projects and programmes[38,39], or the deliberate destruction of XB-35/YB-49 hardware and design documentation at Northrop[40], subsequently lost for B-2 development, just to mention some examples. This statement

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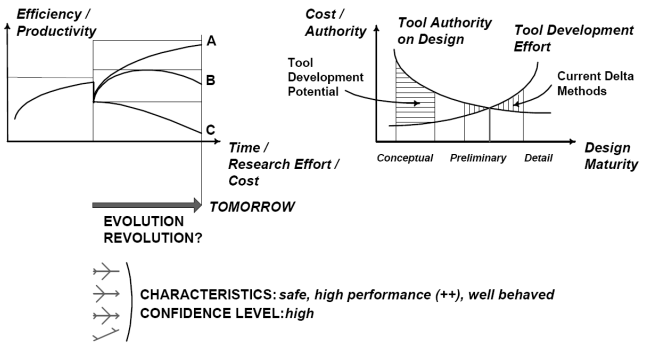


Figure 6. Problem description: new aircraft design problem.

challenges rebuttal, which itself can be counter-acted by asking the question: How many truly diverse aircraft design tool-boxes can be found, coupled with an operational design knowledge-based system (KBS) to take advantage of design information, experience and knowledge of past technology projects at the fingertips? As discussed above, technology awareness and true state-of-the-art capability is the particular strength of Skunk Works type environments. Bushnell[41] views the science of creativity and technology awareness as a process where you have to "self-examine and educate yourself about everything that has been done related to the problem."

It has to be acknowledged, that the current aircraft development practice and consequently products have been, so far, politically acceptable, a situation obsolete when catalyst legislation will act to force change. It is then, that sharp competition will set incentives to new and innovative aircraft concepts. An analogy may be drawn to the automobile industry, where today's strong industrial and political lobby is still promoting the powerful car with its impressive performance potential rather than the truly fuel efficient car compatible with environmental concerns. To prepare for this scenario, it is mandatory for the aero science triangle – industry and operator, academia and research institution – to rationalise the optimistic or skeptical 'opinions' in which advanced aircraft ideas are viewed, to enable comparison of a wider range of aircraft configurations on an impartial and rational basis. The technical challenge clearly lies in the design tool development activity with the goal to reduce development time, to increase design confidence, and consequently to increase design freedom. Systematic forming of aerospace product conceptual design (CD) competence is vital, to encourage decision-making bodies to rethink their responsibility and opportunities, whilst, at the same time stimulating creativity.

Figure 6 illustrates the new aircraft design problem with particular emphasis on visualising design tool authority and design tool development effort as a function of project maturity. The graph on the left qualitatively postulates the situation when studying 'novel' aircraft configurations. The foremost who challenges advanced aircraft ideas surely has to endure an intense learning period, accompanied with initially lower efficiency and productivity. It is this phase where true commitment and an informed approach are vital. It is the undisputed responsibility of the aircraft conceptual design (CD) team, to pre-select feasible aircraft arrangements with least development risk. Curve A represents the idealised aircraft efficiency and productivity curve. The attributes of the aircraft efficiency and productivity slope ultimately determine, if configurations under investigation represent the long awaited 'quantum leap' in aircraft design and operation. It is the research objective of the AVD Lab to contribute to this art by defining the slope in advance of any serious development commitment, thereby omitting aircraft types as represented by curves B and C.

The graph on the right (Fig. 6) reiterates the relation between tool authority on design and tool development effort required relative to design maturity. An attempt is made with the following to concisely describe the contribution of the individual product design phases during the design life-cycle, although it is to be expected to have blurred boundaries between the phases dependent on the characteristic of the development programme. It is an indisputable fact that conceptual design (CD) methods have predominant sizing authority throughout the entire development cycle. During the conceptual period, primary design decisions are made like selection, evaluation and pre-definition of the configuration type and election of global design parameters. Subsequent design levels, the preliminary (PD) and detail design (DD) phases, check in contrast the prescribed design space with higher-order design methods but limited authority to modify only global design parameters. Any modification proposed at preliminary and/or detailed design levels needs to be authorised at conceptual design level, if global design parameters are affected. Naturally, the authority of design tools on design decisions reduces when advancing the maturity of the product. However, the following phenomenon can be observed throughout the aero science triangle. It is a prevailing practice to invest predominantly into high-fidelity design and analysis methods (e.g. CFD and FEM). As a consequence, these methods absorb the major portion of tool development resources available, whereby their design influence onto the product reduces significantly towards the end of the design cycle. This imbalance is a contributing factor to today's aerospace vehicle and mission design problem, resulting in diminishing returns on investment.

To recapitulate, detailed (disciplinary) aircraft design investigations are today conveniently performed using all available resources like parallel supercomputers, high-level optimisation and sophisticated simulation. In contrast, the important primary aircraft design decisions (e.g. overall configuration selection) at conceptual (CD) and preliminary design (PD) level are still made using extremely simple analyses and heuristics. An exception is given with the response-surface approach where higher-fidelity analysis has been executed beforehand for well-defined design problems. However, the nature of CD is usually such that response-surface models are not available in the design trade timeframes allotted. Further, most existing computer-aided aerospace vehicle and mission design methodologies refer often to statistical data without necessarily questioning and balancing the physical rationale of the solution. A further limitation might be the restriction in capability to the 'classical' aircraft arrangement only. The reason for this scenario seems to be the difficulty of not knowing how to integrate multidisciplinary simulation of both normal and radical aircraft conceptual designs in more than an *ad hoc* fashion.

The author firmly believes that the multidisciplinary decision process at the conceptual design (CD) level needs to be further evolved and automated. This demands an improvement of the pertinent aircraft design disciplines involved (aerodynamics, stability and control, cost, etc.) with real-life design expertise and experience as vital ingredients. The development of a dedicated aerospace vehicle and mission design knowledge-based system (KBS)[42] is one key element in such undertaking. Clearly, this requires the formulation of the problem statement and the solution alternatives in the physical domain, resulting in a generic executable software solution. Summarising, a methodology concept of generic character needs to be systematically built with physical rather then statistical roots. This will enable effective exploration and comparison of normal and radical aerospace design concepts based on a consistent information database. But, do we really need such improved design tools and processes?

The recent period has been filled with exceptionally interesting developments and advances in aerospace science. Investigations into advanced future efficient flight vehicles world-wide substantiate the demand for enhanced project tools, to enable rational vehicle performance-cost tradeoffs. Table 4 shows a selection of winged aircraft programmes during the 2000 period with promising performance-cost potential or technology demonstration function towards that aim.

https://doi.org/10.1017/S0001924000004036 Published online by Cambridge University Press

Table 4
Future-efficient aircraft programmes (Status: 2000)

Civil Aviation	Military Aviation	Space Aviation
AeroVironment HELIOS (demonstrator)	X-31 (demonstrator)	X-33 (demonstrator)
Piaggio P180JET (project)	X-32 (demonstrator)	X-34 (demonstrator)
Airbus A300-600 ST Beluga (operation)	X-35 (demonstrator)	X-37 (project)
Airbus A340 TSC (project)	X-36 (demonstrator)	X-38 (demonstrator)
Airbus A3XX-100 (project)	X-39 (project)	X-41 (project)
Airbus A3XX TSC (project)	X-40 (demonstrator)	X-42 (project)
Boeing Blended Wing Body (demonstrator)	Lockheed F117A (operation)	X-43 (project)
Lockheed Supersonic Business Jet (project)	Northrop B-2 (operation)	Lockheed Martin Venture Star (project)
Boeing Oblique Flying Wing (demonstrator)	Boeing Blended Wing Body (demonstrator)	DaimlerChrysler Hopper (project)
Airbus ESCT, Boeing HSCT (project)	Lockheed YF-22 Raptor (demonstrator)	

Note: The above snap-shot presents examples of new technology projects and programs during 2000.

The author perceives the above illustrated quest for advanced aerospace products as an indication of how exciting the future will be! Capturing a market-share, however, requires understanding the significance of systematic technological advancement and utilisation as pre-requisite[11]. Ziegler[2] reflects the motivation by Airbus Industrie to develop fly-by-wire technology for the A320: "We have always been minded not to be conservative. We were not fascinated by technology, we were just being open-minded and seeing what could be build with the technology ... already available on the shelf." Sutter[2], father of the world's most profitable aircraft B747 responded at the time with "Airbus is not going to sell a lot of airplanes by touting technology". A company's vision, as expressed by Szodruch[43] from Airbus Industrie, conveniently concludes the exchange of views by saying, that the "... market cares about all this 'technical junk', and – in the end – competition will discriminate against technically and economically obsolete products!"

Bushnell[44] rightly categorises aeronautical development metrics since the early 1900's as "... higher, faster and larger is better... ". In contrast, the metrics of today and the foreseeable future are clearly different, and hence the nature of technological improvement demanded for transition: "These 'new' (civilian) metrics include affordability ... , productivity ... , safety and the environment ... " Acceptance for new technology and design freedom in military and space aviation has been traditionally high for a variety of reasons. The civil aviation evolution, in contrast, has presented itself as a less driving environment. Bushnell asked in 1998: "Is there an aerodynamic renaissance for the long haul transport?" The question clearly showed justification when reflecting the evolution of the aerodynamic figure of merit, Mach number times lift to drag ratio with time. The B707-era (1960s until today) is characterised by an increase of M $(L/D)_{max}$ of around 15%; the curve being almost flat[45]. As a response, Liebeck and others started to create and evaluate alternate configurations. Consequently, one of the advanced transonic aircraft configurations under development today in the USA is known as the blended-wing-body (BWB)[46,47], resembling a flying wing configuration for civil and particularly military application.

Another example of aeronautical revolution may be foreseen with the cancellation of the high-speed commercial transport (HSCT) programme in the US. The high-speed research team at NASA stated, that a new supersonic commercial transport aircraft " ... study will also look at alternative aircraft configurations, some of which will not be based on the four-engined layout of the present TCA (technology concept aircraft)"[48], and that the airframe element will " ... go back to basics ... " to re-examine all aspects of the design and technology which has been used to date. Davies[49] warns to avoid 'wishful thinking' but stimulates critical thinking and challenges rebuttal by judging the SCT design efforts to date: "The cost of developing any supersonic airliner is prohibitive. The prospects of their being able to operate economically is remote. The market for such an aircraft ... is very small." Seebass[50] in contrast resumes, that the book he has contributed to " ... focuses much of its attention on the underlying tools for the study of such (conventional SCT) aircraft, as well as on unconventional configurations ... " This translates into the prerequisite of having a means at hand, to either prove feasibility or to identify true show-stoppers of new aircraft projects.

At last, what is the technical rationale behind future aerospace vehicles and missions being especially design method demanding? Aircraft development programmes like the above mentioned blended-wing-body (BWB), supersonic commercial transport (SCT), supersonic business jet (SSBJ)[51], in particular single stage to orbit (SSTO) configuration concepts and mission strategies[52], are confronted with such narrow excess design margins, that the solution-space resolution delivered with the traditional single-point optimisation design methods has not yet been able to prove or disprove conclusively technical and commercial feasibility for the above mentioned examples at all. Such vehicles may only become reality, when it is possible to take advantage of truly integrated multidisciplinary aerospace vehicle design methodologies with the ultimate objective, being able to identify in short order vehicle performance potential. One of the key technologies, obligatory when addressing multidisciplinary tasks, is currently evolving, termed multi-disciplinary optimisation (MDO). However, much more needs to be done.

Concluding, with today's diversity of opinion prevailing when discussing advanced flight vehicle and mission arrangements, current conceptual design (CD) engineering practices demand systematic development. The author believes that only methodical background work enables construction of an acceptable confidence level into analysis methods for the initial design of conventional and advanced aerospace vehicles. With such preparation at hand, higher

https://doi.org/10.1017/S0001924000004036 Published online by Cambridge University Press

project risk levels can comfortably be accepted with focus on the performance/cost benefit. Ivan Shaw, Europa founder, puts it as "If you eliminate risks, you eliminate progress[53]".

2.4 Flight vehicle conceptual design (CD) synthesis

The aircraft and aerospace vehicle design process is conveniently broken down into the following three sequential phases: conceptual-, preliminary-, and detail design, followed by production, flight test and operation. For a detailed definition of those phases see e.g. Nicolai[54] and Torenbeek[55]. Moore[56] rightly recalls that most configuration synthesis occurs at the conceptual and preliminary design phases. Clearly, the boundary between the two phases is not distinct, "... but conceptual design extends from the development of requirements to the determination of a vehicle concept and a size estimate, while preliminary design carries the design to the point where there is a geometric definition of the vehicle which will support the design of actual hardware." Clearly, the design space is defined at conceptual design level, whereby a first design solution is proposed at preliminary design level. As a rule of thumb, it can be assumed that around 80% of the aircraft configuration is determined at the conceptual design phase alone. The present research investigation is therefore primarily concerned with the conceptual design (CD) phase. As identified in Section I, this phase can be seen as the most important but least well understood phase of the product evolution process.

2.4.1 Characteristics of the conceptual design (CD) phase

During the conceptual design phase, principal design-decisions are made leading to vehicle configuration choice, -shape, and -size. This involves deciding which parameters need to be used to describe the design. Overall, such decisions will, to a large extent, determine the final cost of the vehicle and mission. Hollowell and Bitten[57] illustrate, that "... conceptual design tends to be very fast paced, with the total time from start to transition into preliminary design typically measured in months." However, the overall design-criticality of the conceptual design phase is not apparent when reviewing the typical size of conceptual design teams.

The CD process is an intense learning phase for the project team due to its iterative process structure, where feedback loops and successive refinements are involved. The following comments by Hollowell and Bitten[57] deserve special attention in this context. "The final quality of the design is directly related to how much the design team learned during the conceptual design process. We have observed that how much the team will learn is a strong function of how much of the design space is explored. This, in turn, places a premium on being able to iterate through the design cycle rapidly. During the process the chief designer/engineer will have many questions that must be answered by the various specialists very quickly in order to keep the process on schedule. If a specialist does not provide the answer when it is needed, then the chief designer/engineer will quite often make the best decision he can based on past experience, without input from the specialist. When this happens, the specialist has lost his opportunity to positively influence the design. This is an extremely important observation relative to the application of optimisation techniques to the conceptual design process. TIME IS OF THE ESSENCE!"

The above mentioned emphasis on quick design-responses during the CD phase results in the use of simplified analysis techniques. Clearly, it is a distinct characteristic of the CD phase that correct trends are more important than absolute accuracy. To further complicate the issue, the aircraft designer is often more interested in the interactions between the disciplines that the methods apply to, than in the individual methods themselves. However, the dilemma unfolds in that simplistic models usually do not accurately predict the impact (trends and sensitivities) of new technologies on the design, to help provide the basis for the allocation of engineering development resources.

2.4.2 Classification and characterisation of vehicle synthesis efforts

Literature shows numerous classification schemes, to distinguish the multitude of vehicle analysis methods and vehicle synthesis environments. Classification schemes adopted have been according to:

Development period (pre-computer, CAD-era, etc;)
Application type (aircraft, aerospace vehicles, fighter, etc;)
Development phase (conceptual design, preliminary design, detail design, manufacture, single- and multi-level analysis/synthesis, etc;)
Modelling complexity (empirical, analytical, numeric, parametric, response surface, optimiser types, etc.)

Using the development period alone as a classification scheme in not thought to be useful, although the individual design approaches may have originally evolved throughout a distinct era. Several of the 'dated' methodologies are in use today and are even further-developed for a variety of reasons. Classification according to the targeted vehicle application type clearly works for some of the methodologies considered. However, the development intention towards the generic methodology type prohibits such grouping. Classification according to development phase involves considerable uncertainty due to non-regulated definitions and understanding of the separate development phases. The classification scheme selected in the present context distinguishes the multitude of vehicle analysis and synthesis approaches according to their modeling complexity, expressing their limitations and potential.

The following categorises five different classes of vehicle design sophistications. It should be noted that the range of vehicle synthesis approaches, from Class I to Class IV, is in use today. Class V synthesis systems are under development, and are not yet considered operational.

Class I synthesis approach (early dawn)
From the earliest days until around 1905, aircraft design was characterised by the experimentalist, operating via intuition, limited or no experience, and sometimes via the trial and error approach[58]. With some exceptions, the most prominent early systematic researchers are Otto Lilienthal[59] and the Wright brothers[60], there was obviously no common systematic approach to aircraft design, an era where intuition and common sense had to prevail.

It was this early period, where the margin between success and failure was virtually non-existent. It should be recalled that the Class I approach to aircraft design is still practiced today by the majority of aero model builders. The experience gained may result in a sound physical understanding of the main design variables. Clearly, such background should not be underestimated, since probably every aircraft designer may have gained experience with the Class I aircraft design approach during his/her design career.

Class II synthesis approach (manual design sequence)
The period from 1905 until around 1955 is characterised by methods based on a mixture of fundamental principles and empirical data. Lovell[61] recalls that during the early period, "... due to the relative simplicity of design, development and manufacture, the specification and evaluation of costs was not a significant feature of the design process," an issue which soon had to change. The evolving manual but practical design sequences, as exemplified by the standard aircraft design handbooks, were based on limited analytical derivations.

Many of today's embedded analysis techniques were initially devised within this period, with the objective to bridge the gap between physical observation and practical implementation. Aircraft design was typically done by means of parametric studies, involving the interpretation of a series of plots to locate the appropriate configuration. The methods by von Mises[62], the rapid sizing method by Loftin[63], and the graphic method by Cherry and Croshere[64] belong in this category. Countless hours of research were dedicated to developing parametric data bases that could be applied to new

https://doi.org/10.1017/S0001924000004036 Published online by Cambridge University Press

aircraft designs. Some sort of 'mechanical' automation of analysis sequences had been devised with special purpose slide rules, nomographs and overlay methods, allowing for an initial rapid evaluation and parametric analysis of new aircraft concepts, see Driggs[65].

Overall, design synthesis itself was entirely manual with the result that only a small number of design options could be calculated by a finite number of people. "The usual procedure has been to rely on experience and quick 'back of the envelope' studies to get into the 'ball park' and then conduct a series of two- or three-dimensional parametric studies to establish a refined conceptual design", Jensen *et al*[66]. Clearly, the outstanding benefit of Class II design methods is the degree of physical design transparency they offer. The ability to gain explicit insights into the design-effects of each separate discipline involved enables the designer to develop a feel for the sensitivity of the individual design parameters on the overall configuration, including an appreciation of how their assumed level of technology actually influences the results. Clearly, the succeeding Class III to Class VI design methodologies are developed based on Class II methods. Today, Class II methods are in use to a certain degree within the general aviation industry and the aircraft home-builder scene.

Class III synthesis approach (computer automation)

The advent of multiprocessing computers around 1955 enabled the automation of isolated Class II analysis methods, enabling less reliance on judgment and more reliance on detailed design tradeoffs. "Initial computer applications were confined to aspects of structural analysis and wing design. There was some resistance to the use of computers in initial project design because of the complex decision-making process involved. However, they enabled more detailed analyses to be made and hence allowed a greater range of carpet plots with additional overlays to be prepared to show the effects of configuration variables on performance."[61] Such accelerated analysis reduced design cycles significantly, thus allowed a more detailed exploration of the design space in the time given. However, design synthesis was still performed manually with discipline-specific (stand-alone) software programmes, separately developed by specialists in different departments in the aircraft industry.

Further automation and enhancement of the design-estimation quality was made possible with the advancement of computers and numerical mathematics, which enabled solving of more demanding problems. The application of numerical optimisation techniques was first attempted in structural design[67]. The capability to simulate the actual physics of the problem by solving the governing mathematical equations resulted in one-dimensional (single-point) optimisation capability.

Class IV synthesis approach (multidisciplinary integration)

"There followed a number of attempts at applying numerical optimisation techniques to the initial layout of aircraft. These had little success because of the gross simplifications made in the aircraft design synthesis in order to obtain a solution within a reasonable time using the limited computing power available in the early 1960s. ... The main reasons for this position were the continuing difficulties of interpreting and visualising the resulting configurations, and the lack of confidence in the mathematical algorithms used for obtaining optima. ... To try to circumvent this problem a Latin square technique was used." [61] The 'Latin square technique' resembles a least-squares fitting procedure and is described by Healey *et al*[68].

However, the introduction of computer graphics capabilities in the 1960s[69] initiated the trend, to assist the designer by integrating the stand-alone analytical programmes into a complete computerised design system, consisting of libraries of analysis programmes. Using computer graphics lessened the difficulties of communication between man and computer. At first, this allowed participants to share common aircraft databases with the advantage of reduced data transcription errors. The demand to interchange design information between different departments was addressed with the introduction of a first generation of multi-variate optimisation (MVO) techniques during the 1970s.

Substantial increase in computing power with reduced computing cost converted the computer from an exotic research facility to the every-day tool for the designer. Acceptance of computer-aided design and manufacture (CAD/CAM) systems "... removed much of the prejudice against automated design methods"[61]. Development of more robust optimisation algorithms resulted in more complex design synthesis systems for conceptual design application. The problems of integrating MVO and the resulting increase in design complexity were discussed in the mid 1970s. MVO enabled economical multidimensional design optimisation that resulted in substantial improvements in design cycle time and quality of the design.

The activity of centralising design authority from the functional, disciplinary groups to configuration management, enabled increased problem visibility of the design process across the disciplinary lines up to managerial levels. This approach eliminated the traditional decentralisation and its associated problems. Advanced generations of computer systems have enabled the first steps towards true multi-dimensional (multi-point) optimisation capability, still with little physical insight into the multidisciplinary coupling effects. Today's latest generations of such integrated systems offer a potentially valuable guide in selecting the overall vehicle configuration for more detailed consideration, see Van der Velden[70]. Clearly, such ability is in its infancy today with limited or no capability to reliably assess advanced vehicle layouts. Although these systems are expensive and complex, they are essential in a commercially competitive manufacturing environment"[71].

It is not entirely coincidental, that nearly all Class IV synthesis systems are capable of dealing with the typical XB-47/B707 type aircraft arrangement only. The success of the tail-aft configuration (TAC) stems in part from its non-integrated arrangement, because size and position of the wing, fuselage, empennage and engines are independently variable within wide limits before such arrangement becomes inappropriate[72]. It can be concluded that Class IV type systems "... operate by sizing the main components independently, and 'assembling' them into very simple geometric relationships. The next challenge for configuration design synthesis is to tackle designs with a high degree of structural (and other) integration, with realistic and complicated relationships between airframe and non-airframe components" as expressed by Moore[56]. Clearly, most Class IV systems have not the competence to become Class V methods. Only a minority of systems can be considered state-of-the-art Class IV design environments with development potential towards Class V synthesis methods.

In summary, today's computational systems for conceptual design (CD) evaluation are software limited rather than computer limited. Table 5 assembles an overview of former and contemporary Class IV design synthesis systems, given with their acronyms, originator, and field of application[9].

3.0 SPECIFICATION FOR CLASS V AEROSPACE LIFE-CYCLE SYNTHESIS SYSTEMS

At this point it is apt to quote D. Küchemann's 1978 thoughts towards a design framework system. "Most valuable for practical design purposes are those methods which bring out clearly the physical concepts and provide conceptual frameworks which can guide the designer towards the realisation of those characteristics which he wants his aircraft to have. Above all, conceptual frameworks which are firmly based on physics allow the designer to practice the art of the soluble and prevent him from being deluded into chasing phantoms which cannot be realised in practice."[73]

https://doi.org/10.1017/S0001924000004036 Published online by Cambridge University Press

Table 5
Aerospace vehicle Class IV synthesis systems

AAA	Advanced Airplane Analysis	DARcorporation	Aircraft
ACDC	Aircraft Configuration Design Code	Boeing Defense and Space Group	Helicopter
ACDS	Parametric Preliminary Design System for Aircraft and Spacecraft Configuration	Northwestern Polytechnical University	Aircraft and AeroSpa
ACES	Aircraft Configuration Expert System	Aeritalia	Aircraft
ACSYNT	AirCraft SYNThesis	NASA	Aircraft
ADAM	(-)	McDonnell Douglas	Aircraft
ADAS	Aircraft Design and Analysis System	Delft University of Technology	Aircraft
ADROIT	Aircraft Design by Regulation Of Independent Tasks	Cranfield University	Aircraft
ADST	Adaptable Design Synthesis Tool	General Dynamics/Fort Worth Division	Aircraft
AIDA	Artificial Intelligence Supported Design of Aircraft	Delft University of Technology	Aircraft
AircraftDesign	(-)	University of Osaka Prefecture	Aircraft
APFEL	(-)	IABG	Aircraft
Aprog	Auslegungs Programm	Dornier Luftfahrt	Aircraft
ASAP	Aircraft Synthesis and Analysis Program	Vought Aeronautics Company	Fighter Aircraft
ASCENT	(-)	Lockheed Martin Skunk Works	AeroSpace Vehicle
ASSET	Advanced Systems Synthesis and Evaluation Technique	Lockheed California Company	Aircraft
AVDS	Aerospace Vehicle Design Synthesis	AVD Laboratory	Aircraft, Space Acce
AVID	Aerospace Vehicle Interactive Design	N.C. State University, NASA LaRC	Aircraft and AeroSpa
AVSYN	?	Ryan Teledyne	?
BEAM	(-)	Boeing	?
CAAD	Computer-Aided Aircraft Design	SkyTech	High-Altitude Compo
CAAD	Computer-Aided Aircraft Design	Lockheed-Georgia Company	Aircraft
CACTUS	(-)	Israel Aircraft Industries	Aircraft
CADE	Computer Aided Design and Evaluation	McDonnel Douglas Corporation	Fighter Aircraft (F-15
CAP	Configuration Analysis Program	North American Rockwell (B-1 Division)	Aircraft
CAPDA	Computer Aided Preliminary Design of Aircraft	Technical University Berlin	Transonic Transport
CAPS	Computer Aided Project Studies	BAC Military Aircraft Devision	Military Aircraft
CASP	Combat Aircraft Synthesis Program	Northrop Corporation	Combat Aircraft
CASTOR	Commuter Aircraft Synthesis and Trajectory Optimization Routine	Loughborough University	Transonic Transport
CDS	Configuration Development System	Rockwell International	Aircraft and AeroSpa
CDS	Conceptual Design Shop	NASA Langley Research Center	Aircraft
CISE	(-)	Grumman Aerospace Corporation	AeroSpace Vehicle
COMBAT	(-)	Cranfield University	Combat Aircraft
CONSIZ	CONfiguration SIZing	NASA Langley Research Center	AeroSpace Vehicle
CPDS	Computerized Preliminary Design System	The Boeing Company	Transonic Transport
DA-12	Integrated Conceptual & Preliminary Design and Analysis Environment	The Boeing Company	Transonic Transport
DesignSheet	(-)	Rockwell international	Aircraft and AeroSpa
DRAPO	Definition et Realisation d'Avions Par Ordinateur	Avions Marcel Dassault/Breguet Aviation	Aircraft
DSP	Decision Support Problem	University of Houston	Aircraft
EASIE	Environment for Application Software Integration and Execution	NASA Langley Research Center	Aircraft and AeroSpa
ESCAPE	(-)	BAC (Commercial Aircraft Devision)	Aircraft
ESP	Engineer's Scratch Pad	Lockheed Advanced Development Co.	Aircraft
FASTPASS	Flexible Analysis for Synthesis, Trajectory, and Performance for Advanced Space Systems	Lockheed Martin Astronautics	AeroSpace Vehicle
FLOPS	FLight OPtimization System	NASA Langley Research Center	?
FPDB & AS	Future Projects Data Banks & Application Systems	Airbus Industrie	Transonic Transport
FPDS	Future Projects Design System	Hawker Siddeley Aviation Ltd	Aircraft
FVE	Flugzeug VorEntwurf	Stemme GmbH & Co. KG	GA Aircraft
GASP	General Aviation Synthesis Program	NASA Ames Research Center	GA Aircraft
GPAD	Graphics Program For Aircraft Design	Lockheed-Georgia Company	Aircraft
HADO	Hypersonic Aircraft Design Optimization	Astrox Corporation	Hypersonic Aircraft, I
HASA	Hypersonic Aerospace Sizing Analysis	NASA Lewis Research Center	AeroSpace Vehicle
HAVDAC	Hypersonic Astrox Vehicle Design and Analysis Code	Astrox Corporation	Hypersonic Aircraft, I
HCDV	Hypersonic Conceptual Vehicle Design	NASA Ames Research Center	Hypersonic Aircraft, I
HESCOMP	HElicopter Sizing and Performance COMputer Program	Boeing Vertol Company	Helicopter
HiSAIR/Pathfinder	High Speed Airframe Integration Research	Lockheed Engineering and Sciences Co.	Supersonic Commer
Holist	?	?	Hypersonic Vehicles
ICAD	Interactive Computerized Aircraft Design	USAF-ASD	?
ICADS	Interactive Computerized Aircraft Design System	Delft University of Technology	Aircraft
IDAS	Integrated Design and Analysis System	Rockwell International Corporation	Fighter Aircraft
IDEAS	Integrated DEsign Analysis System	Grumman Aerospace Corporation	Aircraft
IKADE	Intelligent Knowledge Assisted Design Environment	Cranfield University	Aircraft
IMAGE	Intelligent Multi-Disciplinary Aircraft Generation Environment	Georgia Tech	Supersonic Commer
IPAD	Integrated Programs for Aerospace-Vehicle Design	NASA Langley Research Center	AeroSpace Vehicle
MacAirplane	(-)	Notre Dame University	Aircraft
MIDAS	Multi-Disciplinary Integrated Design Analysis & Sizing	DaimlerChrysler Military	Aircraft
MIDAS	Multi-Disciplinary Integration of Deutsche Airbus Specialists	DaimlerChrysler Aerospace Airbus	Supersonic Commer
MVA	Multi-Variate Analysis	RAE (BAC)	Aircraft
MVO	MultiVariate Optimisation	RAE Farnborough	Aircraft
ODIN	Optimal Design INtegration System	NASA Langley Research Center	AeroSpace Vehicle
OPDOT	Optimal Preliminary Design Of Transports	NASA Langley Research Center	Transonic Transport
Paper Airplane	(-)	MIT	Aircraft
PASS	Program for Aircraft Synthesis Studies	Stanford University	Aircraft
PIANO	Project Interactive ANalysis and Optimisation	Lissys Limited	Transonic Transport
POP	Parametrisches Optimierungs-Programm	Daimler-Benz Aerospace Airbus	Transonic Transport
PrADO	Preliminary Aircraft Design and Optimisation	Technical University Braunschweig	Aircraft and AeroSpa
PreSST	Preliminary SuperSonic Transport Synthesis and Optimisation	DRA UK	Supersonic Commer
PROFET	(-)	IABG	Missile
RCD	Rapid Conceptual Design	Lockheed Martin Skunk Works	AeroSpace Vehicle
RDS	(-)	Conceptual Research Corporation	Aircraft
Rubber Airplane	(-)	MIT	Aircraft
SENSxx	(-)	DaimlerChrysler Aerospace Airbus	Transonic Transport
SSP1	System Synthesis Program	University of Maryland	Helicopter
SSSP	Space Shuttle Synthesis Program	General Dynamics Corporation	AeroSpace Vehicle
SYNAC	SYNthesis of AirCraft	General Dynamics	Aircraft
TASOP	Transport Aircraft Synthesis and Optimisation Program	BAe (Commercial Aircraft) LTD	Transonic Transport

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3.1 Development objective: Class V synthesis approach (generic design capability)

Taking the lessons into account as described through Sections I and II, our development aim is the next-generation life-cycle synthesis system AVDS-PrADO. This sophisticated life-cycle synthesis system integrates the three domains, the management domain, operation domain, and technology domain into a coherent environment. Configuration independent (generic), more rigorous disciplinary analysis methods are linked to a sophisticated design synthesis framework. At the heart of the process lies design space screening, design space visualisation, and proof of convergence for the business case. This enables consideration of a wider range of product alternatives explored with true robust multi-disciplinary optimisation capability. "Once robust design methods are developed within the technical discipline, multidisciplinary design problems can be attacked" as expressed by Burgess[74]. Academia, industry and research institutions have taken only a first step in the direction of this higher level of sophistication when compared to Class IV design methods. Burgess continues that "... these capabilities will come together to enable designers to fully explore the synergistic relationships that exist in aircraft ..."

Class V systems will enable robust business case assessments leading to reliable risk quantification. With this objective, we are one step closer towards true inverse design capability. The inverse design problem quests: Which design characteristics produce the desired results? The generic design capability facilitates the initial configuration selection and definition phase. Consequently, consistent vehicle configuration and mission comparisons are made possible for a class of vehicles, where the ultimate performance may hinge on numerical subtleties. Such design resolution and capability is not seen with today's Class IV design methodologies. In contrast to Class IV design methods, the gross design variables are not frozen before the potential benefits of multidisciplinary interaction effects are explored.

3.2 Specification for generic Class V product synthesis

All AVD Lab method development activities aim towards the continued evolution of AVDS-PrADO, a state-of-the-art product life-cycle synthesis system complying with the top-level managerial expectations surveyed in Ref. 75 and summarised below:

- Availability of a 'cockpit to steer the ship';
- Accelerate design response time;
- Increase design freedom, accuracy, and reliability of results;
- Ensure a systematic and transparent design process;
- Provide a flexible process and tools capable to evaluate present and future market opportunities;
- Ensure generic product synthesis functionality.

The activity to formulate a thought through specification aims to systematically advance the existing AVD Lab tool-box not only to advance knowledge, methods, and software, but to link people organisation-wide. Clearly, the correct choice of philosophy for the targeted AVDS-PrADO synthesis methodology is key to its success in today's and especially tomorrow's competitive product development environments. The specification[75] has been organised as follows: 1. Availability, 2. Estimation modules, 3. Focus-to-market models, 4. Design applications, 5. Design process, 6. Calculation routines, 7. Knowledge management, 8. Optimiser library, 9. Input/output, 10. Generic geometry modelling, 11. Programme control, 12. Software development, 13. Software familiarity, 14. Integration into organisation. A detailed discussion of the above groups is beyond the scope of the present document.

Figure 7 pictures the overall effect of having a AVDS-PrADO integrated into a product development organisation. The top figure

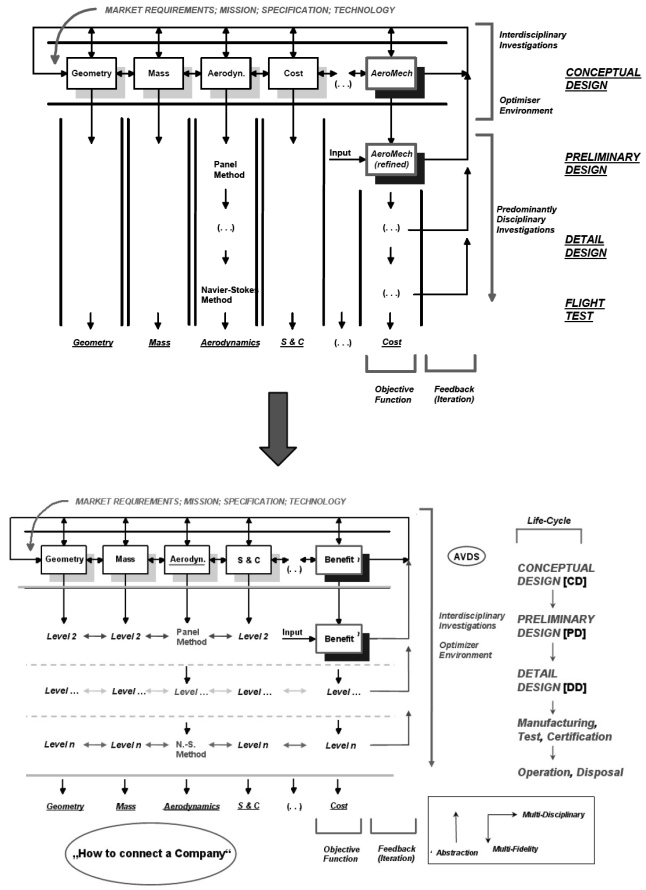


Figure 7. Traditional product development organization (top) compared to the same organisation streamlined with the help of a product development synthesis system (bottom).

shows a traditional product development organisation in comparison with a streamlined organisation employing a synthesis system at the bottom. As the figures indicate, the conceptual design team operates at the highest level of abstraction. During the conceptual design level, the disciplinary analysis routines are linked 'horizontal', requiring consistent (single fidelity) calculation routines. In contrast, evaluations at preliminary and detail design level are predominantly disciplinary only in the traditional organisation. As shown with the bottom figure, a synthesis environment ensures multi-disciplinary investigations throughout the design cycle leading to rapid feedback iterations. To ensure an efficient overall design process, those rapid feedback communications have to link the specialist departments with the conceptual design team to ensure that design solutions proposed by the specialist departments are harmonised in the multi-disciplinary context. Clearly, detail design work is characterised by 'vertical' disciplinary investigations using variable-fidelity methods.

Having visualised the product evolution process with Fig. 7, Fig. 8 is comparing the 'life-cycle depths' of the three primary engineering phases CD, PD, DD with each other. First, the schematic clearly indicates that the CD phase is required to simulate the largest life-cycle spectrum. Second, the arrows symbolise the essential iteration feed-back to the 'life-cycle simulation engine'. With a well integrated synthesis system, the CD phase still should play a role when the development has advanced towards the PD or DD phase.

The generic configuration concept requirement is shown with Fig. 9 for the space access vehicle (SAV) and aircraft version. For example, when evaluating a given aircraft mission requirement, the product synthesis system is first evaluated for the tail-aft configuration (TAC) and the overall benefit of this geometry is quantified. In successive steps, the process is

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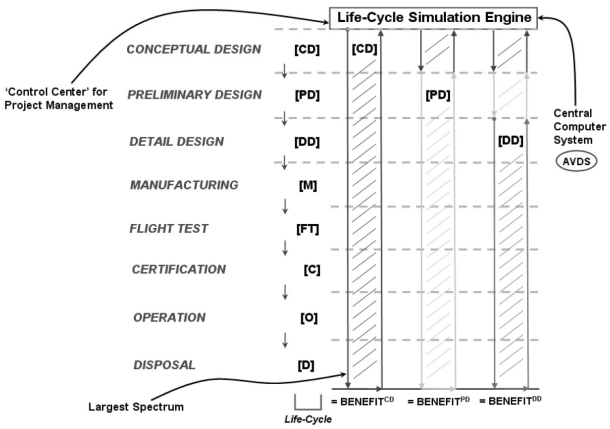


Figure 8. Comparison of CD, PD, DD product life-cycle spectra.

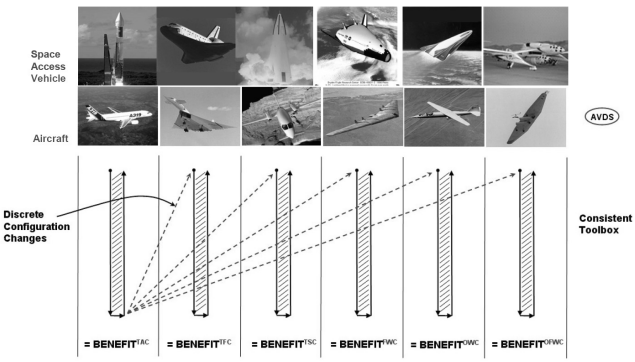


Figure 9. Generic character of the life-cycle synthesis system showing discrete configuration concept changes as realised for the Class V system.

repeated for a different configuration concept like the flying wing configuration (FWC). Having a consistent generic toolbox available, this enables, for the first time, to rationally compare the 'conventional' configuration with 'unconventional' configuration concepts.

The *n*-dimensional design volume of the generic product development framework is visualised with Fig. 10. The 'n-dimensional chess board' clearly emphasises the challenge and potential of having a generic methodology framework available. We would not be allowed to call our framework system a 'synthesis system' without having a logic in place capable of screening the required/available design space while proofing design convergence for every configuration concept permutation calculated. First, we need to distinguish the term synthesis from analysis, design, and MDO. The AVD Lab has adopted the following working definitions:

Analysis: "Analysis is the process of considering something in order to understand it or explain what it consists of." (Note: The ability to design follows the ability to analyse.)

Design: "Design is the thought process comprising the creation of an entity." (Note: It is usually a multi-disciplinary iterative cycling through a sequence involving exploration, evaluation, and decision making.)

Multi-disciplinary optimisation (MDO): "A methodology for concurrently incorporating analysis models into a design synthesis process by coherently exploiting the synergism of mutually interacting phenomena."

Synthesis: "The translation of top-level requirements into possible life-cycle design solutions satisfying those inputs."

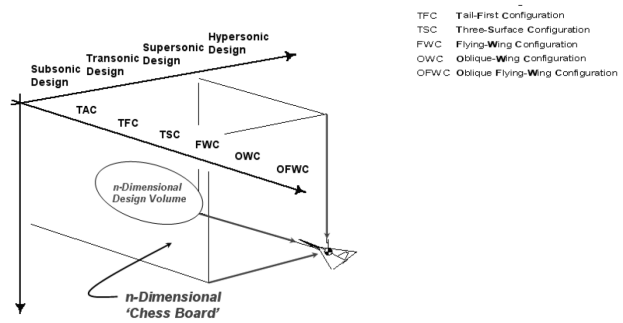


Figure 10. A generic design methodology offers the design engineer an *n*-dimensional design volume. The methodology consists of configuration-independent design processes and analysis tools capable of consistently assessing classical and novel design alternatives.

Biology	Computer	Life-Cycle Synthesis Simulator
Horse	Processor	Synthesis System
Brain/Muscles	Bus/Memory/Controller	Design Process/Strategy/Logic
Cells	Finite State Machines,	Framework, Data Management System
Organelles	Shift Registers, Adders, etc.	Optimizer, Decision Support Tools
Proteins	NAND Gates	Analysis Methods (analytical, empirical, numerical)
Genes	Transistors, Wires	Formulas
Molecules	Molecules	Design Variables

Figure 11. Comparison of the sub-level entity hierarchies assembling a horse, computer, and finally life-cycle synthesis system.

Clearly, the synthesis system is considered a top-level entity. Today, 'design' is performed at various sub-level entities. The hierarchy presented in Fig. 11 compares the life-cycle synthesis simulator with entities assembling a horse and a computer. Most Class IV design systems incorporate the build-up range from design variables to framework, data management system. The difficulty in developing a synthesis system is not only the integration of otherwise dispersed analysis tools into a single framework, but to add a design process, strategy, and logic capable of design space screening, visualisation of the parameter space topography, and to offer a proof of design convergence.

Our failure to arrive at a successful space access vehicle (SAV) until today demonstrates our inability to reliably quantify the existence of the feasible design space. Figure 12 qualitatively compares the design spaces of surface transportation with air and space transportation. In general, the available design space for two-dimensional surface-transportation, as exemplified with the car, tends to be largest due to its functional simplicity. Compared with the aircraft class, which operates at a higher complexity level (three dimensions), the feasible design space tends to be far more constrained, thus reduced in space. This fact is quickly understood when surveying the number of test flight crews lost per year testing rather 'conventional aircraft'. In contrast, the design space for reusable SAVs shrinks significantly compared to all other man-made transportation vehicles. As discussed elsewhere[72], the design sensitivities to arrive at a positive payload to orbit are driven by the corresponding relationships among subsystems, in particular numeric subtleties amongst design parameters. In case the design space is as small as indicated for the single-stage-to-orbit (SSTO) SAVs, the immediate danger is that the configuration concept design selected is not within the feasible design space but without the design team knowing (as indicated with HOTOL)[52].

Finally, the following figures relates to D. Küchemann's quote at the beginning of Section III. Any design solution has to be selected in context of its solution space topography. Failure to visualise such reminds of a 'blind date'. Figure 13 presents the range performance convergence design space for the array of subsonic to hypersonic

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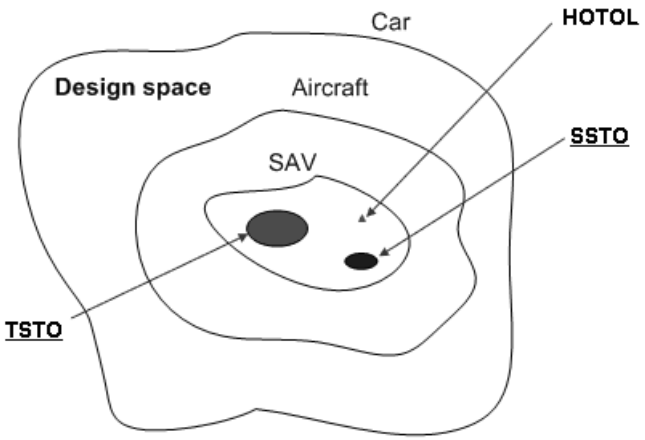


Figure 12. Qualitative design space comparisons.

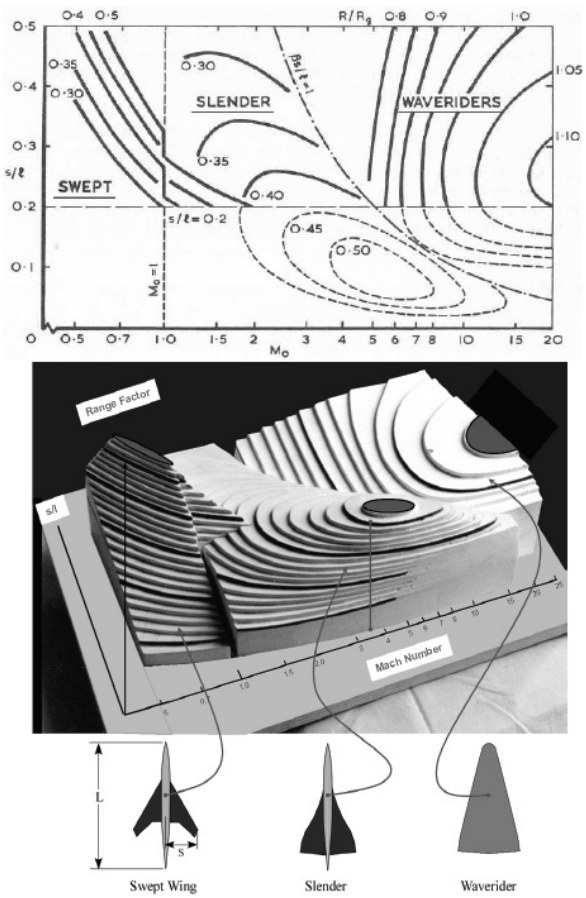


Figure 13. Comparison of range performance for transonic, supersonic and hypersonic configuration concepts by D. Küchemann from the 1970s![73,52,76].

flight vehicles as visualised for the total flight vehicle by Küchemann in the 1970s[52,73,76]. Figure 14 presents a design space visualisation based on the first CD assessment step modeled in AVDS-PrADO which is history-based[42,52,76].

Optimisation history needs to be rigorously made transparent to the engineer, visualising the design-influence of the variety of disciplines and their assumed level of technology on the aircraft. This capability is of paramount importance, to ensure transparency of the

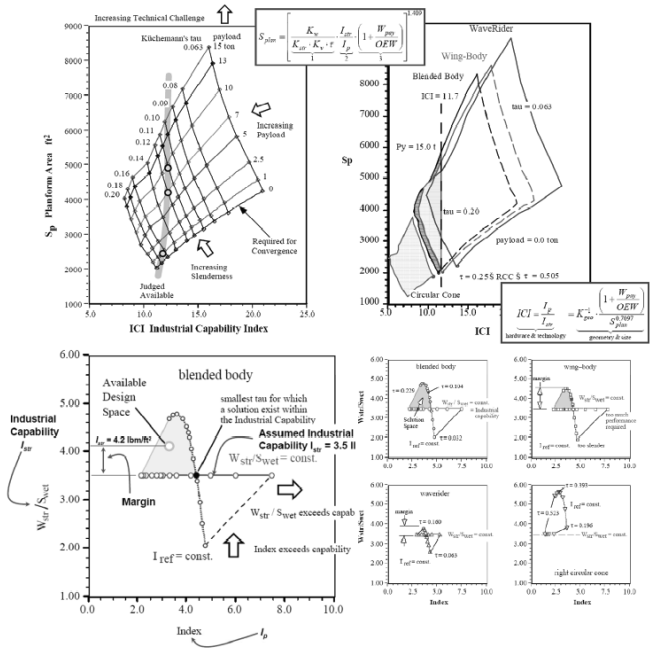


Figure 14. Comparison of the capability index convergence design space for prospective space access vehicles like the right circular cone, blended-body, wing-body, and wave rider[52,76,42].

underlying physics and finally to enable so-called 'sanity-' or 'reasonableness checks'.

Inclusion of a technical competition analysis system (TCAS) and a dedicated aerospace knowledge-based system (KBS)[42] truly accelerates the learning process of the conceptual design team. The learning capability of the KBS provides a dynamic and intelligent design architecture with growth potential, to support decision making while having design information available 'at the fingertips'. Finally, coupling of the life-cycle synthesis environment with a dedicated engineering flight simulator enables inclusion of certification related constraints and -requirements at the earliest stage possible.

4.0 AVDS-PRADO CAPABILITY OVERVIEW

4.1 Capability summary of the core system PrADO

The AVD Laboratory is operating and continually advancing in cooperation with the University of Braunschweig, Germany, a unique state-of-the-art generic aircraft life-cycle synthesis process and software AVDS-PrADO, capable of screening the design space in a truly multi-disciplinary context leading to converged aerospace mission design solutions. The operational status and maturity level of AVDS-PrADO offers a unique test vehicle with which it is possible to explore: (a) proposed top-level design processes, (b) standardised software/method integration strategies, (c) common data-management approaches, (d) design space visualisation and design convergence issues, (e) families of MDO policies, (f) code parallelisation investigations, (g) bench testing of disciplinary analysis modules for validation and calibration purposes, and as well (h) independent design assessments of customer development projects.

AVDS-PrADO is an ideal prototype platform for preparing the customer's enterprise for the next generation of company-wide simulation-based acquisition (SBA) systems, a development to be expected in the near-term future. We are in the process to further

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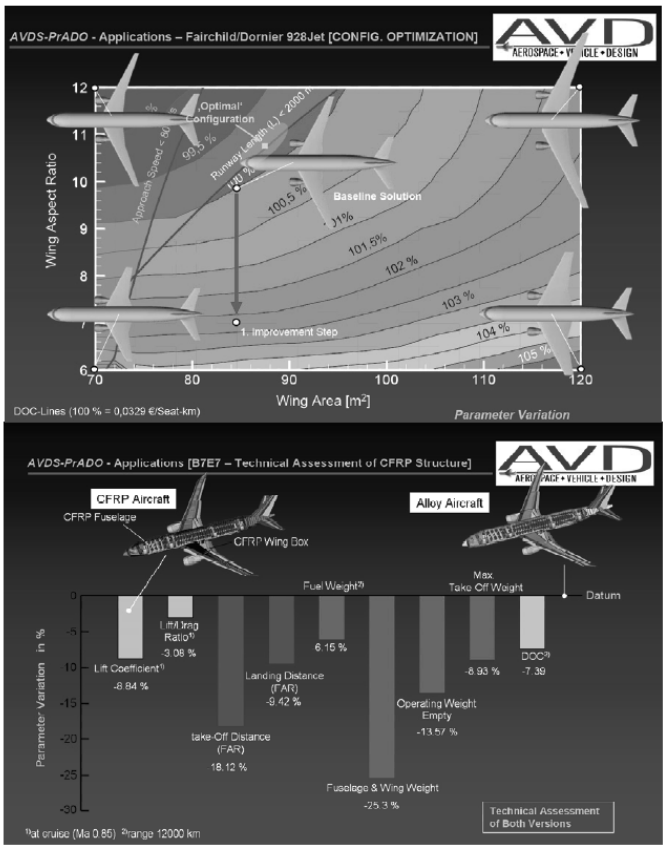


Figure 15. PrADO application: (a) Fairchild/Dornier 928Jet solution space visualisation, (b) Boeing 7E7 technical assessment of alloy *vs* CFRP airframe.

evolve the AVDS-PrADO synthesis framework into a generic process management life-cycle model to provide decision making bodies with a top-level simulation tool capable of visualising the interrelations between requirements, tasks, schedules, risks, investments, and budget upfront during the conceptual and preliminary design phases. Such comprehensive framework enables the project lead and synthesis specialist to monitor an aircraft project from 'cradle to grave', see Fig. 15. This permits the decision-making bodies 'to pull the strings in the cockpit' with a degree of transparency, speed, and accuracy not seen before, while obtaining unfiltered context information towards goal achievement.

4.2 Methodology summary of PrADO

The architecture of the current version of PrADO is organised into four programme levels and the data management system (DMS), see Fig. 16.

The following concisely describes the generic programme logic of PrADO.

1. Data input and representation of results (visualisation)
This programme part is responsible for all pre- and post-processing activities, for the preparation and presentation of input data available and output data generated. The major programme sections and sub-routines are joined at this programme level, which generate the user-defined aircraft project data-base (DB) itself being administered by the data management system (DMS). Specific sub-programmes are responsible for the visualisation of the output information generated in form of technical diagrams, 3D aircraft geometry, optimisation history, etc. Overall, the pre- and post-processing activities are supported with a

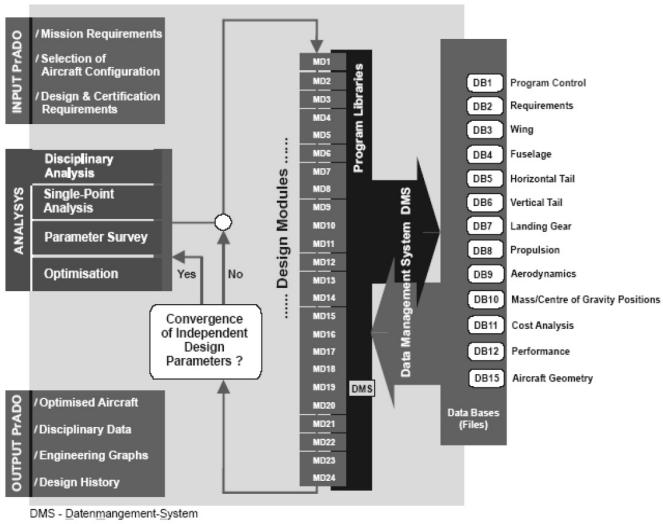


Figure 16. PrADO software architecture – an overview.

JAVA-based graphical user interface (GUI), which can be easily modified since it is based on a script language. The commercial visualisation software AMTEC Tecplot is used to augment post-processing activities.

2. Single-point analysis/parameter survey/optimisation (design tasks)
This programme section contains mathematical procedures to effectively optimise those independent design variables of the flight vehicle under investigation (geometry parameters of the hardware, engine parameters, etc.), which are held constant during the iterative design process (Step 3). It is the aim of these sub-programmes to maximise/minimise an objective function (e.g., DOC, mass) for the actual flight vehicle variation under investigation, whilst assuring that the design constraints (e.g., balanced field length) are satisfied.

3. Iterative design process (convergence-check; programme execution)
This programme section provides the means to design the aerospace vehicle configuration concept under investigation in a true multidisciplinary context. The overall design sequence is split into well structured subtasks (e.g., estimation of flight vehicle geometry, aerodynamic characteristics, performance analysis), where each separate design module is assigned to one disciplinary sub-task. The design modules are executed sequentially and iteratively and they exchange design data only via the DMS. The design modules calculate the actual values of the dependent design variables (e.g. fuel mass, idle thrust, OEW) whilst taking user requirements and calculation results from preceding design modules into account. If the dependent design variables converge after a specified number of iteration loops, the design iteration process stops and programme control is handed back to Step 2 (single-point analysis/parameter survey/optimisation).

Having selected the function 'single-point analysis', the programme terminates when having completed the calculation of the actual (converged) DMS data-base. This indicates that the start configuration complies with the initial design requirements. Having selected the design-function 'parameter survey' or 'optimisation', the initial data set is evaluated in analogy to 'single-point analysis'. In a successive step, a new data set of independent design variables is defined (new configuration concept variant) in programme section Step 2 depending on the evolution of the objective function. The iterative design process is started again in programme section Step 3 for the new data set until a converged DMS data-base is generated. Again, programme control is handed back to programme section Step 2, a new data set of independent design variables is defined, the iterative design process is started again, etc.

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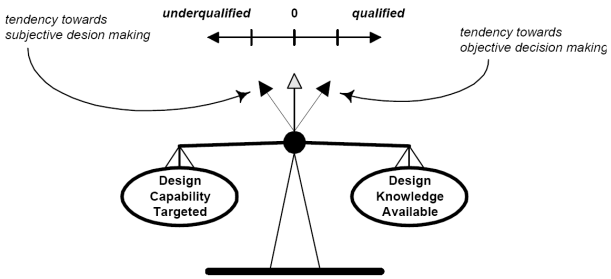


Figure 17. Harmonisation of design capabilities targeted with design knowledge available.

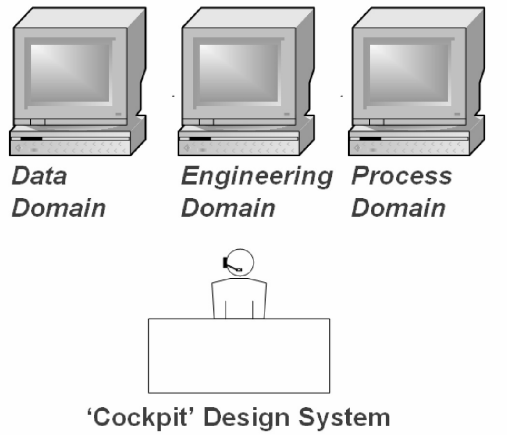


Figure 18. AVDS-PrADO – a 'cockpit' product development framework environment[42].

4. Problem-oriented programme libraries (disciplinary analysis models)

This programme section comprises and manages those programme libraries, which contain the disciplinary physical calculation models and methods for the estimation of aerodynamic-, performance-, mass-, and others design values, which are requested in programme section iterative design orocess (Step 3).

5. Data management system (DMS) (computer-based management system]

The data transfer between all programme sections is managed by the DMS. The DMS administers the data base (DB), which itself stores those design variables which describe the actual aircraft project. The DB is initially filled with input from the user, and it is constantly updated during the iterative design processes. An interface-routine (FORTRAN-library) is integrated into the design modules and programme libraries to enable data-access and data-manipulation (editing, properties, safe/delete, etc.).

Overall, the generic and modular flight vehicle synthesis system PrADO offers a high level of user flexibility. The discussion of new design problems or an adaptation of the design sequence can be easily accomplished by adding or replacing design modules in Step 3 'iterative design process'. The calculation accuracy of individual disciplines can be improved without limit by adding new or improved analysis methods into the programme libraries. At the heart of PrADO lies, however, its unique capability to automatically converge the total flight vehicle in a multi-disciplinary context, a key capability for performing design risk-assessments. Next to its pre-and post processing capability, its software-integration ability to swiftly add external codes and methods to the method library section, its parametric geometry visualisation and optimisation competence; still, key qualification is the implementation of a robust design process being administered by the DMS. What managers and engineers do, and how they do it, can be easily customised, applied, and complemented with PrADO.

4.3 Development and integration of a dedicated aerospace knowledge-based system (KBS)

The final success of any aircraft product is directly related to how much the design team has learned during the design process. The interrelation between design capability targeted and design knowledge available is illustrated in Fig. 17. We have observed that how much the design team will learn is a strong function of how much the design space is being explored. In addition to the availability of an efficient design synthesis capability and proficiency, aerospace product evolution is otherwise primarily dependent on the information and knowledge available to the project lead and design team. The importance of internalising the anatomy of design successes and failures to a design engineer emphasises the task of systematically organising relevant design information and knowledge and making it available to him 'at the fingertips'. Overall, life and money are both too short to have to repeat the learning process in each generation.

Interestingly, no dedicated computer-based design knowledge-based system (KBS) has been developed for the experience-rich aerospace industry world-wide until today. As a consequence, a dedicated flight vehicle design knowledge-based system KBSDESIGN (data and engineering domains) is under development at the AVD Lab, making relevant flight vehicle design knowledge effortlessly available to the design team.

This leads to the quest of organising the workplace of a project manager and design engineer to enable him a 'steep learning curve' while utilising a highly transparent 'digital crystal ball'. Clearly, a synthesis work station has to consist of three separate computer screens next to each other organising the (a) data domain (references, pictures, Jane's information, etc.), (b) engineering domain (design experience, design knowledge, interpretations, etc.), and (c) process domain (synthesis system, design processes, method libraries, etc.), see Fig. 18[77].

4.4 Integration of a virtual flight test and evaluation simulator

The flying characteristics of any aerospace flight vehicle have to comply with design- and certification requirements throughout the flight envelope. The obstacle at the heart of this undesirable situation is the significant multi-disciplinary information requirement (in both quantity and quality), since the flight article has to guarantee satisfactory flying characteristics, which will be confirmed or censured during the flight test phase at the end of the design chain. Clearly, there is a strong incentive to establish a competent link between the first (conceptual design) and the final (flight test) flight vehicle development phase.

Virtual flight testing and evaluation (VT&E) is an engineering technique, which addresses the following emerging problem of aerospace systems analysis: how to check the vehicle's future operational scenarios and flight safety characteristics in a systematic, proactive, efficient, yet affordable way, beginning from the conceptual and preliminary design phases? The proposed solution to this problem employs a concept of autonomous situational modelling and simulation of flight, see Fig. 19. The distinguishing feature of this approach is the use of a generalised mathematical model of the 'pilot-vehicle-operational environment' system dynamics as a substitute for an actual system. In addition to a traditional though advanced non-linear flight dynamics model, the system model also includes a human pilot's tactics model, a flight situation model, and a set of heterogeneous models of demanding operational conditions of flight.

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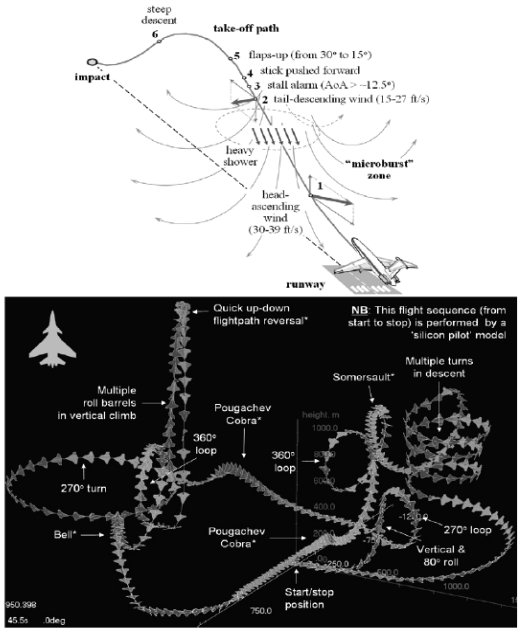


Figure 19. VATES – an intelligent virtual flight testing and evaluation engineering simulator[78].

The integration of the virtual test and evaluation simulator VATES[78] into the AVDS-PrADO product development framework enables the project leader and engineer to systematically 'flight test' any design proposal through a pre-defined flight test sequence. During the aerospace product and mission development phase it is critical to close the link between the first design phase (conceptual design – CD) and the final engineering phase (flight testing – FT). The challenge is to bond both environments via rapid iteration feedbacks to immediately take flight test lessons into account. Such integration supports accident prediction and prevention since hardware or operational decisions can be immediately assessed via rapid feedback to the earlier CD, PD, or DD design phases, if required. However, during the design of the flight article, implications of certification requirements on the overall design and operation of the mission can be readily quantified.

5.0 CONCLUSION AND RECOMMENDATION

The primary research incentives and objectives of the AVD Laboratory have been presented. Focus of all AVD Lab activities is the maturation of the aerospace product development environment AVDS-PrADO. The processes developed by the AVD Lab and partners will enable the customer to reduce cost and risk, and accelerate the design turn-around time, thus achieving higher levels of customer satisfaction. This will be accomplished by creating a true life-cycle synthesis system, capable of simultaneously closing the link between the three primary engineering phases (conceptual design, preliminary design, detail design), with testing, manufacturing, certification, and operations modeling. The highly versatile generic approach will not only contribute to the commercial market, but potentially also to the research and military market enterprise-wide.

This simulation-based acquisition system not only acts as a support tool for the practicing engineer but is primarily of value for decision-making bodies like the chief engineer, project manager, marketing specialist, just to mention some. For the first time, responsible individuals have a transparent decision-support tool available, enabling them to assess the risk of decisions to be made in a simulated environment, where the entire organisation is connected with a single integration framework system. Clearly, programme success correlates well with informed management involvement, where the three programme ingredients management domain, technology domain, and operation domain are seamless blended into a powerful infrastructure.

A true product synthesis environment has to have the functionality of a software integration platform. However, this does not yet enable realistic synthesis capability. Clearly, the challenge and potential of a state-of-the-art synthesis framework has to be seen with the underlying process, strategy, and logic selected to enable reliable identification of the solution space and its capability to proof convergence of the business case considered. Aerospace product development has often been compared with creative arts, a concession acknowledging the weakness to reliably identify the true business case. To be clear, aerospace product development is solving open-ended problems; there may or may not be a single 'optimal' solution available. However, the AVD Lab aims to develop a standard in multi-disciplinary product development, a development which we have seen with CAD systems like CATIA and others. The second century of aerospace not only demands the more intelligent product development framework, but acquisition environments and airlines have a desire to operate such environment for advanced competition analysis and others, accident investigation organisations require to be connected during design and operation with the manufacturer and operator to investigate accidents and their prevention not seen before.

We may ask ourselves the question 'Will the 'digital crystal ball' ever exist, where are we going, what is desirable, how much vision we permit?' Time will show; but, it will happen!

ACKNOWLEDGMENTS

The author acknowledges the support of the AVD Lab research collaborators Ivan Burdun, Aeromechanics, Science & Technology Center, Novosibirsk, Russia, and Wolfgang Heinze, IFL, The University of Braunschweig, Germany. The views and conclusions contained in this report are those of the author.

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