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LEARNING FROM THE DESIGN METHODOLOGY OF FAMOUS AEROSPACE INNOVATORS

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Abstract

Four case studies of innovative designs by expert designers are cast in the framework of a conceptual design method called "Parameter Analysis". We show that the design processes have many characteristics of Parameter Analysis, even though the designers probably did not follow any prescribed method, but rather used their intuition and expertise. The conclusion of the study is that Parameter Analysis is a suitable method for teaching and practicing innovative conceptual design when traditional aerospace design methods are not applicable.

1 Introduction

Traditional aircraft design methods (e.g., [1-3]) work well when designing something that does not deviate much from previous designs or requirements. Such methods consist of highly refined optimization procedures that are based to a large extent on historical data, and using them is efficient and effective when they are applicable. But what should the aerospace designer do when a radically innovative solution is called for? It may well happen that a new aircraft design, totally different from anything done before, is sought to implement a revolutionary idea or invention. A new design may be required also because conventional technologies have reached their limit in satisfying the task requirements, or perhaps the task itself is completely new. Sometimes, an innovative design is needed for a sub-system or component for which no discipline-specific design method exists.

Based on investigating several case studies, the paper shows that famous aerospace designers have implicitly followed a thought process that has some common features. These features can be generalized and formalized as the conceptual design method called "Parameter Analysis", which the paper proposes to apply in teaching and practicing innovative aerospace design.

Engineering design methods historically were developed by first observing designers in action. From such data, a descriptive or explanatory model could usually be formulated by abstraction and generalization. Next, the descriptive model—how design is carried out in practice—is converted into a prescriptive model—how design ought to be done. Prescriptive models are methods that can be taught and practiced after their correctness, usability, effectiveness, etc. have been verified. Well-known methods that underwent this sort of development are the German systematic design [4] and TRIZ [5]. Research into how designers think and work continues in parallel to methods development with the purpose of improving existing practices and discovering new approaches (e.g., [6, 7]). This type of research usually comes from the fields of mechanical engineering, industrial design and architecture.

This paper follows a path similar to other descriptive studies but with one exception: it attempts to show that a specific method—Parameter Analysis—is unknowingly used by leading aerospace designers by looking at accounts of their design processes and casting them within the method's framework. The next section introduces the Parameter Analysis method of conceptual design, followed by brief descriptions of four interpretations of innovative design case studies as Parameter Analysis processes. The paper concludes with a short discussion of the results and proposes to use Parameter Analysis for teaching and practicing conceptual aerospace design.

2 Introduction to Parameter Analysis

Parameter Analysis [8-10] is an empirically-derived method for doing conceptual design. It was developed initially as a descriptive model after studying designers at work and observing that their thought process involved continuously alternating between conceptual-level issues (concept space) and descriptions of hardware (configuration space). The result of any design process is certainly a member of configuration space, and so are all the elements of the design artifact that appear, and sometimes also disappear, as the design process unfolds. Movement from one point to another in configuration space represents a change in the evolving design's physical description, but requires conceptual reasoning, which is done in concept space. The concept space deals with "parameters", which in this context are functions, ideas and other conceptual-level issues that provide the basis for anything that happens in configuration space. Moving from concept space to configuration space involves a realization of the idea in a particular hardware representation, and moving back, from configuration to concept space, is an abstraction or generalization, because a specific hardware serves to stimulate a new conceptual thought.

To facilitate the movement between the two spaces, a prescriptive model was conceived, consisting of three distinct steps, as shown in Fig. 1. The first step, Parameter Identification (PI), consists primarily of the recognition of the most dominant issues at any given moment during the design process. These may include the dominant physics governing a problem, a new insight into critical relationships between some characteristics, an analogy that helps shed new light on the design task, or an idea indicating the next best focus of the designer's attention. Parameters play an important role in developing an understanding of the problem and pointing to potential solutions.

The second step is Creative Synthesis (CS). This part of the process represents the generation of a physical configuration based on the concept recognized within the parameter identification step. Since the process is iterative, it generates many physical realizations, not all of which will be very interesting. However, the configurations allow the designer to see new key parameters, which will again stimulate a new direction for the process. The third component of PA, the Evaluation (E) step, facilitates the process of moving away from a physical realization back to parameters or concepts. Evaluation is important because one must consider the degree to which a specific implementation represents a possible solution to the entire problem. Evaluation also uncovers the weaknesses of the configurations, helps to identify key parameter and points out possible areas of improvement for the next design cycle.

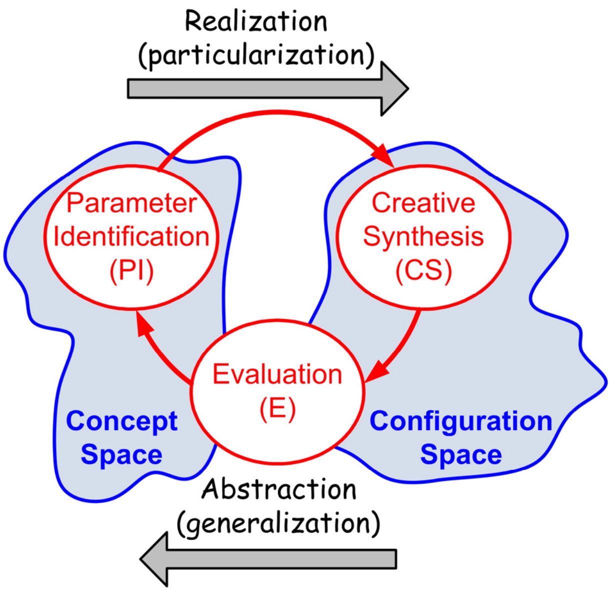

Fig. 1. The prescriptive model of Parameter Analysis consists of repeatedly applying parameter identification (PI), creative synthesis (CS) and evaluation (E). The descriptive model of moving back and forth between concept space and configuration space is also shown.

3 Research Methodology

For the current investigation we adopted the well-established methodology of case study research [11, 12]. It allows us to maintain a holistic view of real life events after they occurred, consider a large number of details and their effect on the design process, perform a meaningful study without controlling the subject, gather insights, and illuminate sets of decisions and their sources.

The case studies chosen for analysis had to meet two requirements: (1) be widely accepted as innovative designs, and (2) be described in enough detail in available resources. The unit of analysis defined for this research was the design process, or design flow, during the conceptual design phase. The design team, the actual features of the product and other aspects were not analyzed. The criteria according to which the data are interpreted were features of Parameter Analysis that could be identified in the case studies.

Correspondence between the case studies and Parameter Analysis was established by first interpreting the design processes as sequences of PI-CS-E triplets, followed by looking for as many of the following characteristics as possible:

1. A three-step (concept→configuration→evaluation) reasoning process whose essence is the repetitive application of stating an idea, a concept; implementing the idea in hardware representation, a configuration, through calculations, sketching, prototyping, etc.; and assessing the evolving artifact.
2. An iterative, non-linear cognitive path to the solution with occasional backtracking when evaluation suggests that a better solution may exist or if failure occurs.
3. A thought process that alternates between ideas (concepts) and their implementation (configurations), as opposed to reasoning mostly in the physical domain.
4. Focusing on one or a few critical and dominant issues at the conceptual level at any moment, as opposed to addressing many aspects concurrently.
5. Applying constant evaluation to the evolving artifact, as opposed to developing the design extensively before applying any critical assessment.
6. Generating minimalistic, back-of-the-envelope configurations, just what is needed for evaluation and not more than that at intermediary cycles of concept development.
7. Extensive use of the underlying physics and other first principles when generating ideas, as opposed to relying on historical data, empirical mathematical relations, etc.
8. "Steepest-first" development of the design: trying to solve problems so as to minimize the uncertainty in the steepest manner, as opposed to simultaneous, breadth-wise development or random ordering of the problematic aspects.

It should be noted that the first characteristic on this list is automatically present in the case study if the latter can be stated as a sequence of PI-CS-E triplets.

4 Case Study I: Wallis' Bouncing Bomb

During World War II, Sir Barnes Wallis designed 5- and 10-ton "Earthquake" bombs to destroy strategic German targets. These bombs were dropped from ~40,000 ft and could penetrate up to 40 meters of soil before detonating and producing powerful shock waves. Next he addressed the problem of destroying river dams. The description here is based on [13, 14]:

PI: Use the water near the concrete dams to conduct the shock waves from the bomb explosion to the structure.

CS: Calculations show that a 10-ton bomb exploding 15-meters from a dam (15-m precision seemed attainable) will create a 30-m opening in the structure. Experiments start on small specially-built dams but result in many failures.

E: A 30-ton bomb will be needed, and this is clearly impossible (no aircraft to carry it).

PI: A much smaller bomb can be used if it exploded while touching the dam, but this requires very precise dropping of the bomb.

CS: This can be done with torpedoes or by flying very low and hitting the dam directly.

E: The dams are protected by torpedo nets in the water. Dropping the bomb from very low may make it bounce off the water surface because the trajectory is almost horizontal, and miss the dam.

PI: Use precise bouncing of the bomb to hit the dam, sink to its bottom, and then explode.

CS: Experiments begin in a small pond with a home-made throwing device, and at the same time, exploding charges adjacent to a dam model. Results show that 3 tons of explosive (new RDX) will blow up a dam. Add 1.5 tons for the casing, and the bomb is less than 5 tons. It is possible to carry it by a Lancaster. Many experiments continue, bomb diameter set to 210 cm, and the bomb spun "backwards" at 500 rpm before dropping it to ensure it reaches the bottom of the dam and not "climb" over it (Fig. 2).

E: If the height when releasing the bomb is not precise, the bomb can explode when hitting the top of the dam and possibly damage the airplane, or bounce over the dam.

PI: The airplane's altimeter is not accurate enough (and also, the barometric conditions over the target are unknown), radar altimeters are not accurate enough either. Suspend a rope with a weight at its end and watch it touch the water surface.

CS: Experiments with such a device are carried out.

E: The rope becomes almost horizontal during flight and does not touch the water. Another method is needed.

PI: Use the method of triangulation with two lamps whose spots can be seen on the water surface, as already known by the RAF.

CS: Set-up established for the height spotlights on the Lancaster to allow flying at 60 ft when the light circles touch and form a figure eight.

E: This will work but what about releasing the bomb at the exact distance from the target?

PI: Use the known distance between the dam towers for a mechanical device based on the principle of similar triangles.

CS: A wooden device with two nails and an eyepiece is designed for measuring the 400-450 yd range. It is tested with eight training bombs.

E: An average miss of 3.5 yd in testing means that the solution is satisfactory.

It is quite clear from this short presentation of a relatively long development process that it follows the 3-step (concept→configuration→ evaluation) characteristic and also demonstrates an iterative nature of trying various solutions and backtracking when failure occurs. Basic physics and mathematics principles are also used in the design. Dominant and critical issues are clearly used at each stage, and the order of addressing them follows the steepest-first characteristic.

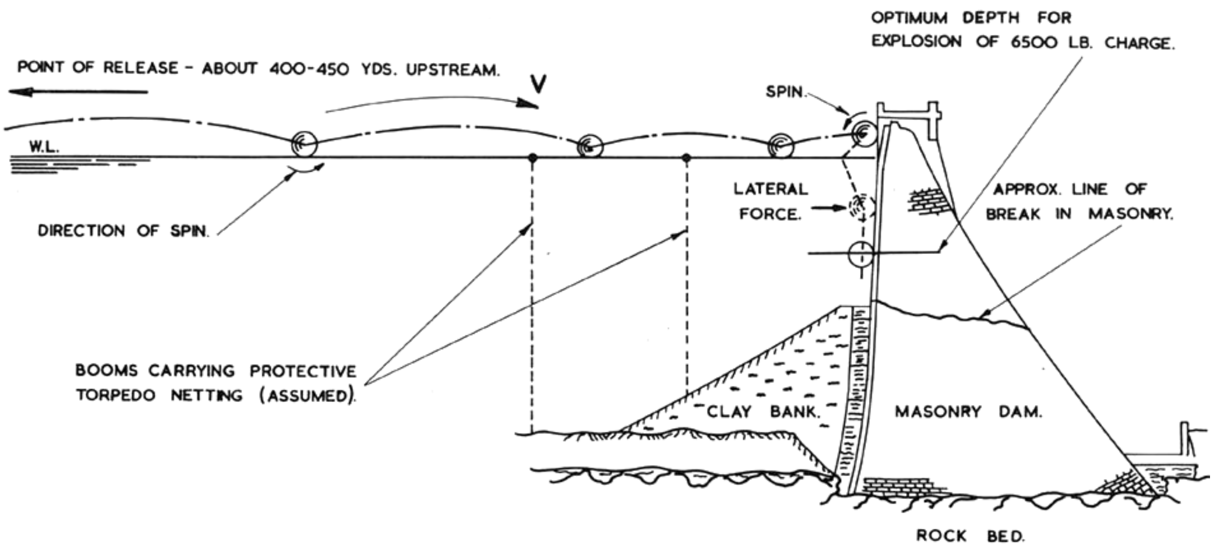

Fig. 2. Method of attack on large gravity dam (adapted from [15]).

5 Case Study II: Gossamer Condor Human-powered Plane

Paul MacCready's human-powered Gossamer Condor won the Kremer prize in 1977 for flying a figure eight course around two markers one half mile apart, starting and ending at least 10 ft above the ground. The following reconstruction of part of the design process is based on [16-18]:

PI: Human power output vs. time has been studied in the past and is given as (Fig. 3):

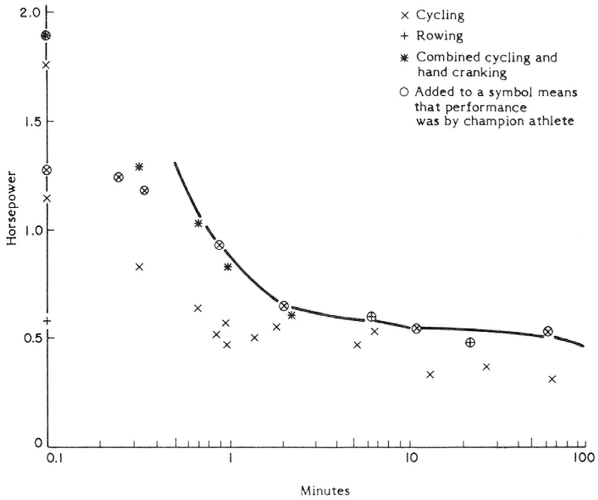

Fig. 3. Power output vs. time for human cycling, rowing, and combined cycling and hand cranking, adapted from [16].

Flying slowly would take longer to complete the course, but the required power would be considerably reduced. Locate the operating point on the asymptote.

CS: The course is about 1.5 miles long. If the speed is set at ~8 mph, the duration would be ~10 min and the required power ~0.4 hp. Takeoff and climb would require more power, but for very short duration.

E: A cycling pilot can produce the required power, but can the airplane be designed around this operating point?

PI: The power P needed for sustained level flight can be expressed, among several other ways, as $P = \frac{2W^2K}{\rho\pi e b^2 U} + \frac{1}{2}\rho U^3 A_l$ where W is the weight, K is a ground effect factor, ρ is the air density, e is a span efficiency factor, b is the wing span, U is the speed, and A_l is the equivalent flat-plate drag area. It clearly shows how power depends on weight, span, speed and drag. The first, induced-drag, term shows the importance of low weight and large span while the second, parasite-drag, term shows that speed should be low.

CS: With the speed set at 8 mph, the span is set at 95 ft (so the aircraft can fit in the available hangar) and the cord at 12 ft.

E: Assuming reasonable powertrain and propeller efficiencies, calculations show that there is a good power margin at the required duration. But can such a large, light and efficient airplane be built?

PI: Use lightweight materials and efficient structures.

CS: Wire-braced aluminum tube structure inspired by hang-gliders and a single-surface airfoil made of Mylar in a canard configuration is built and tested (Fig. 4):

Fig. 4. The structure of the Gossamer Condor (adapted from [17])

E: Aerodynamic and structural principles have been well demonstrated, but the wing is found to be too sensitive to AOA, not rigid enough, and the airplane cannot turn.

PI: Make the wing a full two-surface airfoil…

From this relatively short portion of the design process we can clearly see the 3-step reasoning process (concept→configuration→evaluation), use of minimalistic configurations during development, focusing on single dominant conceptual issues ("parameters") at any moment, relying on first principles and basic physics, and addressing the most difficult issues first (steepest-first development).

6 Case Study III: Rutan's Boomerang

This 1996 unique asymmetric configuration claimed increased safety and fuel efficiency over other twin engine planes. Chapter 2 in [19] and [20] quote Rutan in explaining the design process, part of which we formulate here as Parameter Analysis:

PI: Start with a conventional twin-engine configuration of an existing plane and improve engine-out safety and cabin noise by relocating the engines asymmetrically to the fuselage and away from the cabin.

CS: Left engine moved outboard to improve symmetry at high AOA and to reduce cabin noise (Fig. 5a).

E: Minimum control speed (MCS) is too high.

PI: Reduce MCS by moving the engines inboard.

CS: Right engine moved forward to clear fuselage and left engine moved aft to balance (Fig. 5b).

E: Right engine is not supported well by the right wing; left engine interferes with the fuselage.

PI: Solve these problems by skewing both wings.

CS: Wing skewed to support engines and to reduce left engine interference (Fig. 5c).

E: This configuration is too heavy and would not have the desired speed and range.

PI: Make the structure lighter by using composites.

CS: The wings are more slender so the configuration is nose-heavy. To move the center of pressure forward, the left wing is swept forward (Fig. 5d).

E: The plane is still nose-heavy.

PI: Thanks to the lighter composite structure, smaller engines and tail area can be used.

CS: Smaller and lighter engines and reduced tail area are employed (Fig. 5e).

E: High aspect ratio tail has flutter problem.

PI: Stiffen the tail by adding beam support.

CS: Nacelle boom added (Fig. 5f).

E: There is added baggage room in the boom, but weight, cost and drag are too high.

PI: Solve these problems by moving the right engine to the fuselage.

CS: Right engine moved to fuselage and entire wing moved to the left for lateral balance (Fig. 5g).

E: MCS is now well below stall, but left engine is too close to the fuselage (prop interference) and cabin (noise).

PI: Move the left engine outboard.

CS: Left engine moved outboard and entire wing moved left for balance (Fig. 5h).

E: Low-speed handling is not good enough.

PI: Add vertical tail surface to improve handling.

CS: Twin small vertical tails are added, fuselage rounded and some other details improved (Fig. 5i).

E: The design is satisfactory.

In summary, we can see a clear flow of the 3-step (concept→configuration→evaluation) process, the iterative nature, alternating between concept and configuration spaces, use of explicit parameters (dominant conceptual-level issues) to drive the evolution of the design, controlling the process with constant evaluations, maintaining minimalistic representations of the configurations, and using first principles (e.g., understanding the P-factor that yielded the initial asymmetrical configuration, and supporting the horizontal tail beam at two points instead of at the center). All in all, seven out of the eight characteristics exist in this case study.

7 Case Study IV: Rutan's SpaceShipOne (SS1)

This suborbital spacecraft won the Ansari X Prize in 2004 for reaching a height of 100 km twice within two weeks. The following partial description of its design process is based on Chapter 4 in [19], [21] and [22]:

PI: The traditional method of launching spacecraft from the ground with a rocket is expensive, not easy to reuse, and requires

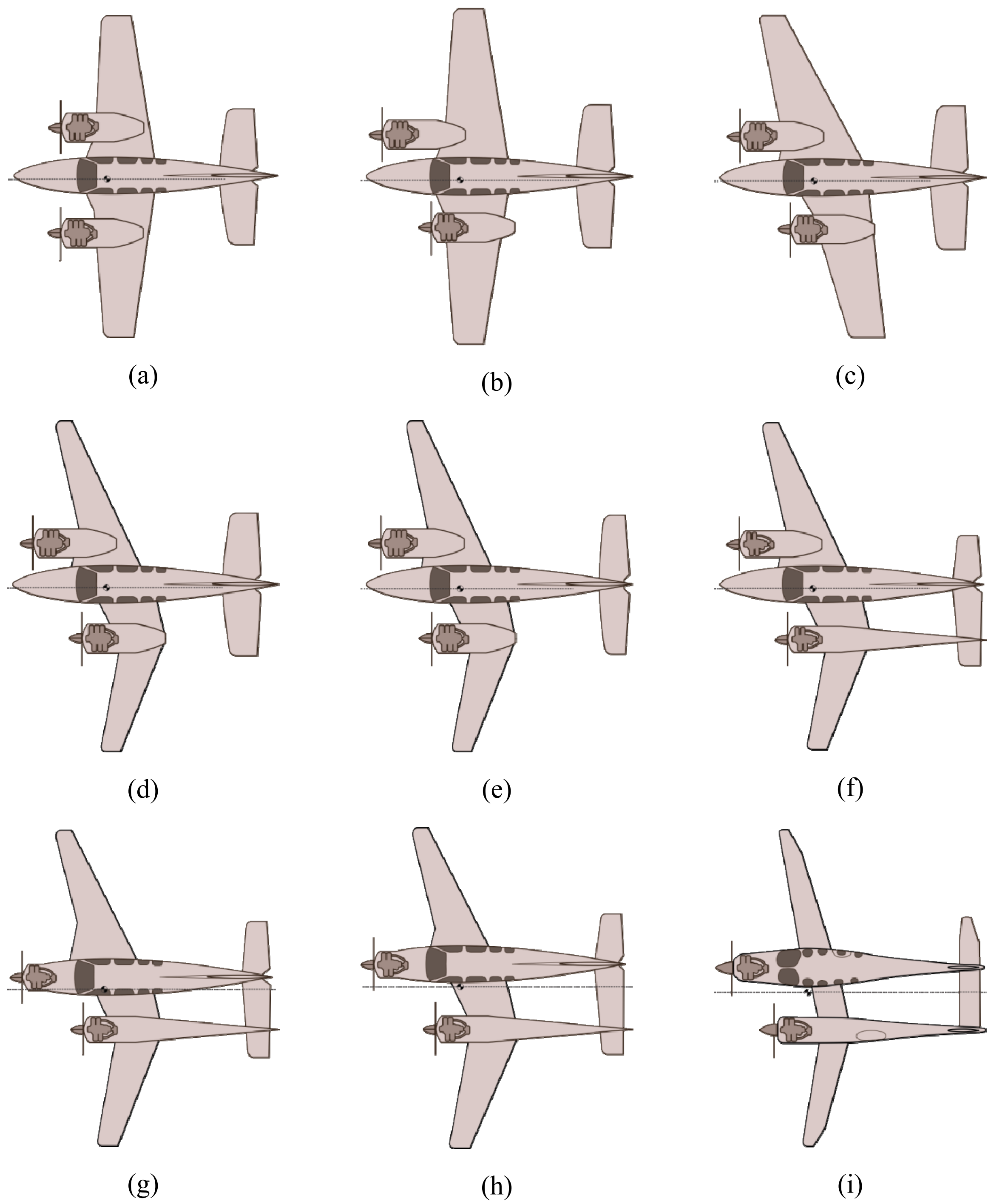

Fig. 5. Evolution of the Boomerang configuration (adapted from [20]).

complex control by thrust vectoring. A spacecraft can alternatively be raised to a considerable altitude by a Helium-filled balloon or another airplane, and launched from there. Use a carrier aircraft.

CS: The White Knight carrier aircraft designed to launch SS1 at about 50,000 ft (Fig. 6).

E: This may work for launching the spacecraft, but how will it land?

PI: There are several possibilities. Parachutes are simple and low-cost, but controlling the exact landing site is difficult and hitting the ground may be rough. Landing at sea requires expensive equipment and manpower for recovery. Propulsion-assisted

Fig. 6. The White Knight turbojet aircraft with SpaceShipOne attached below (Courtesy of Scaled Composites, LLC)

descent permits controlling the landing location, but will add considerably to the launch weight. Finally, gliding may be a good option.

CS: Gliding descent and landing is investigated.

E: It proves successful, inexpensive, and minimalistic in terms of weight. But how will the spacecraft re-enter the atmosphere?

PI: The traditional approach of adding an insulating or ablative heat-shield will add weight and expense. A better way is to create large aerodynamic drag at high altitude where heat buildup is relatively small.

CS: A feathering configuration that folds the whole back half of the wings, including the outboard tail sections, is developed. For safety, it includes redundancy in the actuators and locking mechanisms (Fig. 7).

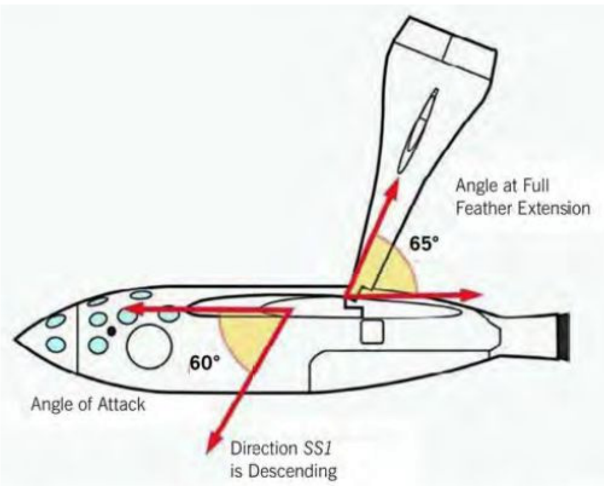

Fig. 7. Feather extended prior to re-entry [19].

E: This will work, but how will the spacecraft accelerate after launch?

PI: Air-breathing engines will not work at the relevant altitudes, so a rocket motor needs to be used. Solid-fuel rockets are simpler, but cannot be turned off, so safety is hindered. Liquid-fuel rockets require cryogenic storage and equipment (pumps, valves, etc.) and this would increase the cost and reduce reliability. Use a hybrid motor with solid fuel and liquid oxidizer.

CS: A specific motor is developed, using synthetic rubber fuel and N_2O oxidizer, producing 16,800 pounds of thrust.

E: The efficiency of the motor is not that high, but it satisfies the requirements and provides a simple, inexpensive, safe and re-usable solution.

We can see that four major design aspects were dealt with in this example—launch, landing, re-entry and propulsion—clearly demonstrating parameter identification: focusing on critical issues one at a time and ignoring others. Also obvious is the steepest development characteristic: addressing the most demanding tasks first. Each cycle of development has an unmistakably-stated concept, idea, at the beginning, followed by realization in specific hardware, and this shows the alternating spaces characteristic. Use of basic physics principles has also been demonstrated in considering the speed change required by ground-based launch vs. aerial launch, and by using heating and aerodynamic drag considerations for decelerating upon re-entry. Finally, the 3-step reasoning process is evident from our formulation of the process as concept→configuration→evaluation triplets.

8 Discussion and Conclusion

A summary of the prominent characteristics of Parameter Analysis as exhibited by the four case studies is shown in Table 1. At least five out of the eight characteristics were identified in each case, leading us to conclude that Parameter Analysis is indeed a prescriptive model of how innovative conceptual design ought to be carried

Table 1. Presence of notable Parameter Analysis characteristics in the case studies.

	[1] Characteristics							
	3-step process	*Iterative nature*	*Alternating spaces*	*Focus on dominant issues*	*Constant evaluation*	*Minimalistic configurations*	*First principles*	*Steepest development*
Case study I	√	√		√			√	√
Case study II	√			√		√	√	√
Case study III	√	√	√	√	√	√	√	
Case study IV	√		√	√			√	√

out if we want to learn from successful expert designers.

It is interesting to note, however, that the constant evaluation characteristic was explicitly present only in one of the four case studies. Our interpretation of this finding is that the literature and other sources used did not put an emphasis on describing the evaluation activities, although assessing the extent to which the evolving artifact meets the requirements and works properly is obviously a major driver in any design process.

The four case studies presented here are quite different from each other. Wallis's Bouncing Bomb project took several years and involved many people. Design steps that show as a short sentence here may represent months-long efforts of ideation, construction and testing. The Gossamer Condor design was first of a kind, and had to rely on first principles for many of its aspects. Rutan's Boomerang may seem like an optimization process, with many steps producing small changes in the configuration. However, the fact that the final aircraft is so unusual and different from the initial conventional twin-engine configuration means that it is actually a process of conceptual design. Finally, SpaceShipOne is an outstanding demonstration of a successful attempt to solve a unique problem by adopting known as well as novel solution concepts and integrating them into a whole.

Parameter Analysis consists of fundamental activities that can be expected in any design method: looking for solution ideas, implementing them in hardware representations, and evaluating the evolving artifact. It is therefore not surprising that many design processes can be cast within this intuitive framework, given a detailed accounting of how they unfolded. However, the pedagogical and practical importance of Parameter Analysis is in its formal statement as a prescriptive model, and researching many phenomena in design from this perspective.

Studying the usefulness and validity of a design method can be done in several ways [23], including controlled experiments on students and designers at work, or analyzing the outcomes of their design processes. However, such empirical approaches have their limitations, and are not applicable to our current purpose. Instead, we chose to analyze several case studies (four of them presented in this paper) that had adequate coverage in various sources such as books, articles, and online videos.

The disadvantages of the case study research methodology should also be acknowledged. First, there is the danger of a confirmation bias, that is, the tendency to look only for case studies that support our hypotheses. Second, we had to rely mostly on third-party descriptions of the design processes, and these may tend to put more emphasis on success and minimize reports of failures. Thirdly, analysis of case studies is still an investigation based on just a few cases, with no wider statistical validation.

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