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ASPECTS OF NONLINEARITY IN CONCEPTUAL DESIGN

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ABSTRACT

Systematic Design methods present a sequential model of conceptual design, whereby function structures are established, solution principles sought, and then combined to form the product concept. We argue that in reality, design is seldom such a linear process, and that linear design process models may hinder creativity and innovation. Two main aspects of conceptual design are used to support this argument: high-level functional reasoning and emergence of new concepts during – not just at the outset – of the conceptual design stage. A simple model that captures the nonlinearity and is therefore more suitable for describing the thought process of conceptual design is the Parameter Analysis methodology. We review it briefly and apply it to a case study of designing small aerodynamic decelerators. Several innovative concepts generated by Parameter Analysis are shown to be an unlikely result of a Systematic Design process.

Keywords: Systematic design, parameter analysis, nonlinearity, conceptual design

1 INTRODUCTION

Systematic Design methods, such as Pahl & Beitz's [1], dictate a very linear nature for the design process: After clarifying the task, the designer uses abstraction to identify the essential problems, decomposes the task into main functions, continues to decompose the functions until s/he reaches elementary or simple subfunctions, finds concepts (solution or working principles) that fulfill each elementary function, combines those into concepts for the whole product (often with the help of a Morphological Chart or Matrix), and finally, embodies the concepts as (descriptions of) physical configurations and selects the best solution. In other words, the double mapping in design, *function → concept → configuration*, is executed linearly, or consecutively.

Obviously, backtracking often occurs in real design, even if carried out according to the Systematic Design model, in case the developed artifact fails to satisfy the requirements or some other type of dead-end is encountered. This backtracking breaks the linear process, but in this paper our interest is in the linearity exhibited by the conceptual design stage when everything proceeds normally, and not when it fails. While addressing of one part of the design problem at a time and recursion may be considered deviations from strict linearity, the design development can still be viewed as a "crudely" linear procedure [2].

Conceptual design according to the Systematic Design method is sequential and linear in several respects:

1. Once the design requirements, or specifications, have been established, they do not change.
2. Once the functional decomposition is finished, no further functional-level thinking takes place.
3. Concepts for each subfunction are sought independently. No higher-level reasoning about function–concept combinations, contradictions, tradeoffs, etc. takes place.
4. Once concepts for all the subfunctions have been listed, only combinations thereof can constitute the overall product concept.
5. Once overall product concepts ("working structures") are chosen, the design proceeds at a configurational level only, with no high-level conceptual reasoning.

Over the last few years there has been some criticism of the linear model of the design process. According to Brooks [3], "…the rational model of the design process…such as Pahl & Beitz…is dead wrong and seriously misleading." He further argues that this design model is not followed by expert designers, does not capture the dynamics of the design process, and results in "bizarre" results [4]. Some of the criticism focuses on Systematic Design's implicit assumptions that a solution-neutral function structure can be developed without thinking of solutions, that all the subfunctions are independent and discrete, and that each concept in the working structure satisfies one and only one subfunction [5,6]. These characteristics are actually a consequence of assuming that design is a linear process, and hence, the property of superposition should exist. An empirical study by Leenders *et al.* [7] found that the excessive functional decomposition in Systematic Design leads to a lack of freedom for the designer and adversely affects innovation and creative performance. Condoor *et al.* [8] discuss the presence of and difficulties in handling nonlinearity in consumer product designs. They argue that the nonlinearity results in a richer learning environment in an educational setting.

Hatchuel and Weil [9] propose their C-K design theory to model the design process as an interplay between concept space (C) and knowledge space (K), and note "the ambiguity of classical design phases when design is innovative" in that functions, concepts and solutions are not always distinguishable. They also demonstrate that Pahl and Beitz's recommendation to model *all* the main functions in the first design phase was impossible in the case of their innovative design example.

The Axiomatic Design approach [10] builds on the Systematic Design method and addresses some of the problems discussed earlier. In this approach, the designer first identifies functional requirements (FRs) and then s/he proposes a design solution in terms of design parameters (DPs) to solve the FRs. Once the FRs and DPs are identified, the designer determines whether the mapping between the FRs and DPs is optimal. An optimal mapping exists when there is a one-to-one correspondence between FRs and DPs, similar to the mapping between functions and concepts in Systematic Design. Once an optimal mapping is achieved, the designer moves to the functional domain, decomposes the FRs further into lower-level FRs, and as the process continues, the design solution evolves.

In Axiomatic Design the designer continually decomposes functional requirements and therefore, indulges in some level of functional reasoning. However, the functional thinking is focused on the decomposition process and not on abstraction or backing off from the task at hand to identify the real need and/or expand the design envelope. Thus, it does not particularly encourage the restructuring of the original functional requirements. Also, the approach requires a complete list of functional requirements, which is almost impossible in most design tasks [11].

This type of linearity, where the output of each design stage becomes the input of the next, is also exhibited by early design methodologies from the area of software engineering, such as the "waterfall" or linear sequential model. The waterfall model can be used to address "righteous" problems, where the problem can be defined well [11]. Software engineering is shifting away from the linear models. According to Pressman [12], page 848:

> *It is reasonable to characterize the first two decades of software engineering practice as the era of "linear thinking." Fostered by the classic life cycle model, software engineering was approached as a linear activity in which a series of sequential steps could be applied in an effort to solve complex problems. Yet, linear approaches to software development run counter to the way in which most systems are actually built. In reality, complex systems evolve iteratively, even incrementally. It is for this reason that a large segment of the software engineering community is moving toward evolutionary models for software development.*

The waterfall models are not good at dealing with "wicked" or ill-structured problems, which do not have definite formulations and where the problem is fully grasped only after the solution is discovered. In other words, the problem definition and solution evolve at the same time [11]. The same theme is echoed in the co-evolution model of design [13,14], where the design requirements and the solutions evolve, with each affecting the other.

We shall not deal in this paper with the issue of changing requirements during the design process, as we wish to focus on what happens *within* the conceptual design stage, as opposed to looking at the whole design process. Our focus is on two aspects of non-linearity: (1) The need for higher-level functional reasoning, and (2) the emergence of totally new concepts, both occurring *during* the development of the design artifact. The two aspects will be demonstrated on a case-study of designing small aerodynamic decelerators. We shall show how Systematic Design fails to result in a good solution, and then propose another conceptual design methodology, Parameter Analysis, as a more appropriate thought process.

2 DESCRIPTION OF THE CASE STUDY

It was desired to design the means for deploying a large number of airborne sensors for monitoring air quality and composition, wind velocities, atmospheric pressure variations, and so on. The sensors were to be released at altitudes of some 3,000 m from an under-wing container carried by a light aircraft. Typically, some 500 sensors would be discharged and they should stay as long as possible in the air, with the descent rate not exceeding 3 m/s (corresponding to the sensor staying airborne for over 15 minutes). The sensors contained a small battery and a radio transmitter, and were packaged as ϕ10x50 mm cylinders weighing 10 g each, with their center of gravity located about 1 cm from one end. It was necessary to design the aerodynamic decelerators to be attached to the payload (the sensors), and the method of their deployment from a minimum weight and size container.

During the need analysis stage, some preliminary, back-of-the-envelope calculations showed that at Re $> 10^4$ (this Reynolds number corresponds to a few centimeters characteristic length and a velocity of 3 m/s), the drag coefficient C_D of a parachute shaped decelerator is about 2, so to balance a total weight of 12-15 g (10 g sensor plus 2-5 g assumed for the decelerator itself), the parachute's diameter would be ~15 cm. If the decelerator is a flat disk perpendicular to the flow, the C_D reduces to ~1.2, and if it is a sphere, then $C_D \cong 0.5$, with the corresponding diameters being about 20 and 30 cm, respectively.

It also became apparent at that point that such large decelerators would be difficult to pack compactly in large numbers, that they should be strong enough to sustain aerodynamic loads, particularly during their deployment, when the relative velocity between them and the surrounding air is high, and that being disposable, they should be relatively cheap to make and assemble. Further, the sturdier the decelerator is made, chances are that it would also be heavier. And the heavier it is, the larger it would have to be in order to provide enough area to generate the required drag force.

3 THE NEED FOR HIGHER-LEVEL FUNCTIONAL REASONING

In a typical Systematic Design process, major functions are identified and expanded in a solution-neutral manner into more and more elementary subfunctions, to form what is known as a function structure. This decomposition usually terminates when the designer is unable to break the subfunctions any further, or when the subfunctions are recognized by the designer as being implementable by single, basic solution principles [15]. Next, each subfunction is considered independently of other subfunctions, and concepts for its realization are sought. The important point here is that this functional analysis is done once and not revisited at all during the rest of the design process. As the model assumes that the functions are independent and discrete with no overlapping, there is no further reasoning about the relationships/interdependence among the subfunctions, or among the subfunctions and their solution concepts.

In a sense, this design stage is carried out as a sort of breadth-first type of search, where the terminal subfunctions (the "leaves" of the function structure when using a tree analogy) are all at the same, top level (see Figure 1). Next, the concepts for each subfunction are added as the next level, and only when this step is complete, the process continues with combinations of subfunction concepts that are generated to establish the next hierarchical level. Due to the combinatorial explosion expected at this point, the much needed converging component of any design process is now applied, when the designer chooses the most promising combinations for further development. This selection is carried out using heuristics, such as examining "what combinations make sense", "avoiding 'Rube Goldberg' type of solutions", etc. Note, however, that at no instant after finishing with the function structure does the methodology direct the designer to reconsider functional aspects of the design. Let us examine this kind of design process in light of the case study.

A Systematic Design-style functional decomposition, followed by identification of suitable concepts for each subfunction, led a student design team to proposing a conventional parachute (i.e., made of flexible material so that it can be folded for packing), a "rigid parachute" (pyramid or conical shape, for example), and a balloon filled with lighter-than-air gas (utilizing both its buoyancy and aerodynamic drag) for the function of "provide aerodynamic resistance" (see Figure 2). Another function, "allow compact packaging in a container", resulted in concepts such as "shapes that are enclosed in small volumes", "folding structures", and "shapes that can nest one inside the other".

One combination concept chosen by the team for further development consisted of a conical shape (chosen because of its high drag coefficient) similar to Figure 2b, but because it occupied a large volume and could not provide the nesting property, folding was selected instead. For the structure to fold, it had to be made of a flexible sheet material stretched over rigid members, with many hinges, sliding contacts and an opening mechanism, just like an umbrella (Figure 3). This resulted in a very complex design (with some accompanying reliability problems), which did not lend itself to automated manufacturing or assembly, and consequently, to a potentially prohibitive cost.

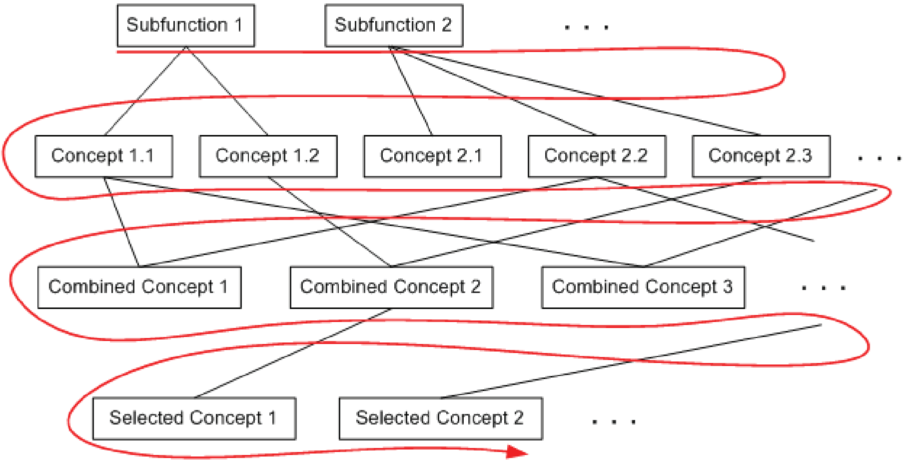


Figure 1. Starting with the terminal subfunctions from a function structure, the Systematic Design methods proceed in a breadth-first manner, shown by the arrowed red line

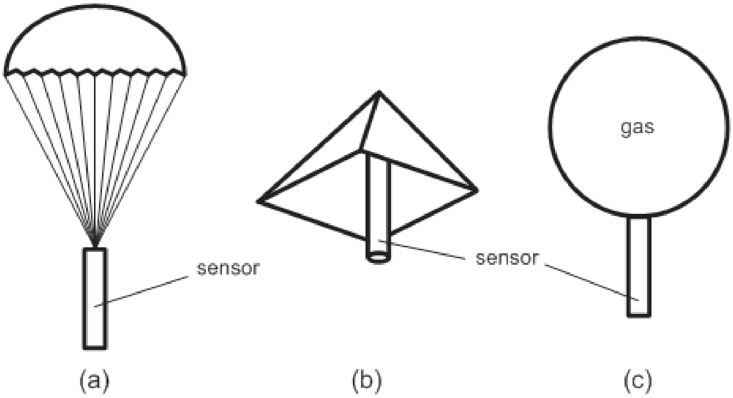


Figure 2. Three concepts for providing aerodynamic resistance: (a) "flexible parachute", (b) "rigid parachute", and (c) gas-filled balloon

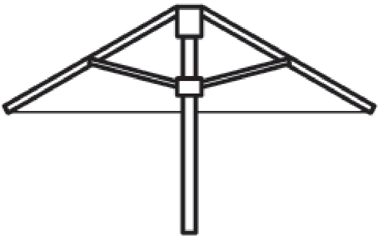


Figure 3. Schematic of a proposed umbrella-type decelerator

4 THE EMERGENCE OF TOTALLY NEW CONCEPTS

Systematic Design calls for the designer to search for concepts for realizing each subfunction in the function structure, and then form combinations of such concepts to constitute the overall product concept. Among the many possible combinations, several are selected for further development. The important feature of this process is that only those concepts found initially for the subfunctions are the ones that will appear in the final design. There is no mechanism in the design process model for introducing new, innovative concepts *while* developing the design. As pointed out in [5], two key drawbacks of this approach are the difficulties in generating a function structure without thinking of solutions and of developing a complete list of discrete (non-overlapping) functions.

In actual design work, the designer is gaining considerable knowledge *during* the product development, particularly in the case of an innovative design, that is, a design with no precedence in the form of similar products. When some initial concepts prove infeasible, the designer is led, in reality, to gaining new perspectives on the problem, identifying new relationships that dominate the design task and shed new light on it, and helping to reformulate and refine the problem and design requirements.

The primary sources of innovation in a Systematic Design process are:

1. Identification of novel concepts for realizing a particular subfunction. The concepts are novel if they stem from new technologies or existing technologies that have never been applied in the particular problem domain.
2. Novel arrangements (combinations) of existing concepts for the subfunctions.

The Systematic Design process applied to the case study of this paper resulted in the three concepts shown in Figure 2. The designs were refined and some of them even tested as prototypes (see Figure 4), but none proved to be a very good solution. The lack of innovation in the resulting design can be attributed, at least partially, to the inability of the team to go beyond the initial formulation of the problem in terms of the two main functions and their accompanying concepts.

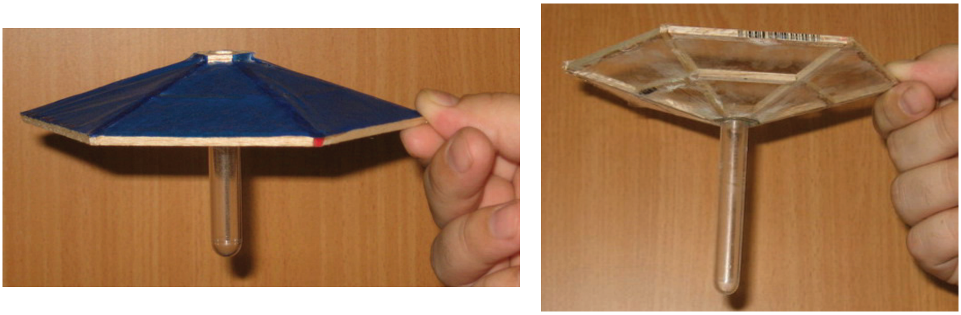


Figure 4. Prototype "rigid parachute" designs built of Balsa wood for aerodynamic testing. The model on the left was unstable during descent, so the "positive dihedral" model shown on the right was constructed. It was stable, but its drag coefficient lower

5 A DIFFERENT DESIGN PROCESS MODEL

The failure of Systematic Design to produce potentially good concepts, as described in the previous two sections, is attributed to its linear nature, and in particular to two major aspects of linearity: The lack of functional reasoning *throughout* the conceptual design stage, and the impossibility of deriving new concepts that are different than those identified initially. We propose a different model for the thought process during conceptual design, called Parameter Analysis [16]. Parameter Analysis was originally formulated as a methodology for dealing with the conceptual design stage. Later, its relevance to embodiment design as a means for systematically incorporating design principles was also shown [17]. For sustainable landscape design, Osmond [18] independently cited: "Parameter analysis provides a useful model for a non-linear process".

The Parameter Analysis methodology emphasizes the discovery of a few critical issues (referred to as 'parameters') at a time, calls for implementing these conceptual issues as configurations, and directs the designer to keep evaluating the evolving design to identify new, emerging, dominant issues. The methodology (see Figure 5) consists of back-and-forth movement between the two spaces of design knowledge: concept space and configuration space. As the name suggests, the configuration space consists of descriptions of hardware, shapes and forms. 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 or concepts that provide the basis for anything that happens in configuration space.

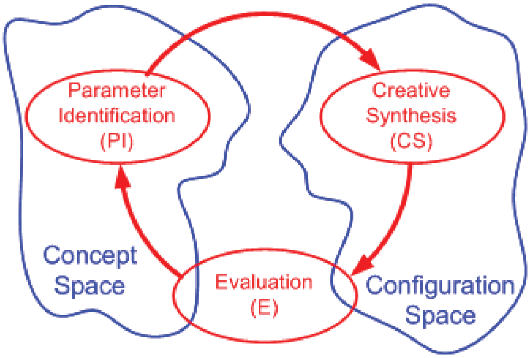


Figure 5. Schematic of the two spaces and three repeated steps used in the Parameter Analysis conceptual design methodology

Repeatedly moving between concept and configuration spaces is carried out by breaking the thought process into three distinct steps: *parameter identification, creative synthesis,* and *evaluation*. The three steps are applied time and again during Parameter Analysis, dealing with contingent, constantly evolving information associated with the design artifact. At each cycle of this process, the critical issues identified are different, as are the changing configurations and the results of the evaluations.

The first step, parameter identification, consists primarily of the recognition of the most dominant issues at any given moment during the design process. In Parameter Analysis, the term 'parameter' specifically refers to issues at a conceptual level. The parameters within a problem are not fixed; rather, they evolve as the process moves forward. Parameter Analysis shifts the burden of truly innovative activity from creative synthesis to parameter identification, the creation of new conceptual relationships or simplified problem statements, which lead to desirable configurational results. Thus, the task of creative synthesis is only to generate configurations that, through evaluation, will enlighten the creative identification of the next interesting conceptual approach. Each new configuration does not have to be a good solution, only one that will further direct the discovery process. Evaluation should not usually resort to analysis of physical configurations that goes any deeper than is required to create a fundamental understanding of its underlying elements. The main purpose of evaluation is not to find fault or filter out ideas, but rather, to generate constructive criticism. A well-balanced observation of the design's good and bad aspects is crucial for pointing possible areas of improvement for the next design cycle.

6 PARAMETER ANALYSIS APPLIED TO THE CASE STUDY

Several student design teams were assigned the task of designing the aerodynamic decelerators system using Parameter Analysis. We shall not present the full design processes here, but rather focus on their highlights and show how innovative solutions were found.

One team started with the concept of a "rigid parachute" (as shown in Figure 2b). They chose a high C_D shape (in the parameter identification, or PI for short, step), that of a hemisphere, and identified the relationship between the drag force produced and the size, or diameter of the decelerator (creative synthesis, CS). In the evaluation (E) step they recognized the fact that the configuration did not lend itself to compact packaging (while hemispherical shapes can be nested inside each other, the sensors themselves prevent this), so the next parameter (PI) was "a high C_D shape that can be folded around the cylindrical sensor in a simple way". Note that this parameter, or concept, combines three functional issues – providing aerodynamic resistance, allowing compact packaging, and being simple. This is in contrast to Systematic Design's treatment of each function separately. The configuration (CS) proposed for realizing the last concept is shown in Figure 6.

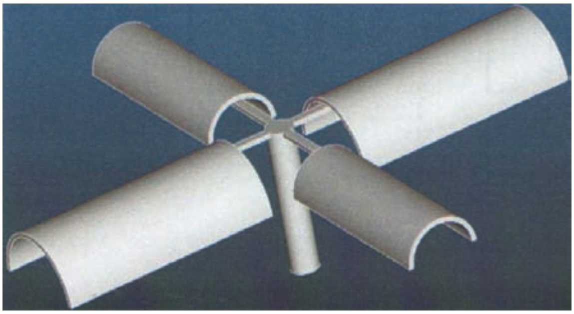


Figure 6. A proposed design with two pairs of "wings" that can fold around the cylindrical sensor to allow compact packaging

Another design team chose the "flexible parachute" concept (Figure 2a) to start with (PI). Sizing the parachute (CS) led them to realize that the payload's light weight might not guarantee opening of the folded parachute, and that the cords could also get tangled during deployment (E). This resulted in the team's re-examining the physics of the problem as follows (PI). They recognized the fact that the design actually called for dissipating the potential energy of an object released at an altitude. Aerodynamic drag perpendicular to the descent direction (i.e., a force pointing vertically upward) would dissipate energy by frictional work that depended on the size of the decelerator. However, if energy dissipation by frictional (drag) work was the dominating physics, then the physics of work should be studied carefully. Work is the product of force and distance. In vertical descent the distance was the altitude, so the focus in the design was on creating a large vertical drag force, one that was equal to the weight of the falling object. Such a large force dictated a large size decelerator. But what if we could make the distance longer? Then we would be able to dissipate much energy by a combination of long travel distance and small force, and the latter might equate to a smaller object, that could be packed compactly in large quantities. And so the concept of a "glider" was born. Two configurations for realizing this last concept are shown in Figure 7. They were further refined to introduce an imbalance in the design so that when deployed, the glider would follow a spiral trajectory with a diameter of approximately 30 m.

Note that the glider solution is very different from the initial concept. In Systematic Design, starting with the "flexible parachute" concept would most likely yield a final design that can be quite refined, but still clearly a type of folding parachute. In Parameter Analysis, on the other hand, the glider concept emerged from the parachute concept through high-level conceptual reasoning *during* the development of the concept.

A third design team also realized that the physics of the problem did not necessarily require a simple drag-force device (i.e., a parachute), and through energy considerations decided to attempt dissipating additional potential energy of the falling object by forcing it to rotate in a windmill style (PI). Figure 8 shows a model made on a rapid prototyping machine of a skeleton with a thin plastic film (Saran Wrap) stretched and glued onto it, and a weight simulating the sensor attached below (CS). The rotating wings, or propeller blades, act against air resistance in the horizontal plane in addition to the vertical drag. A rotating device of this sort probably could not have emerged from Systematic Design had the concept of a "windmill" not been identified at the stage of searching for solution principles.

Interestingly, rotating wings have also been proposed by design teams who used analogies to nature. The physical model of the decelerator of Figure 9a was inspired by the Samara fruit (as found on elm and maple trees, for example) shown in Figure 9b.

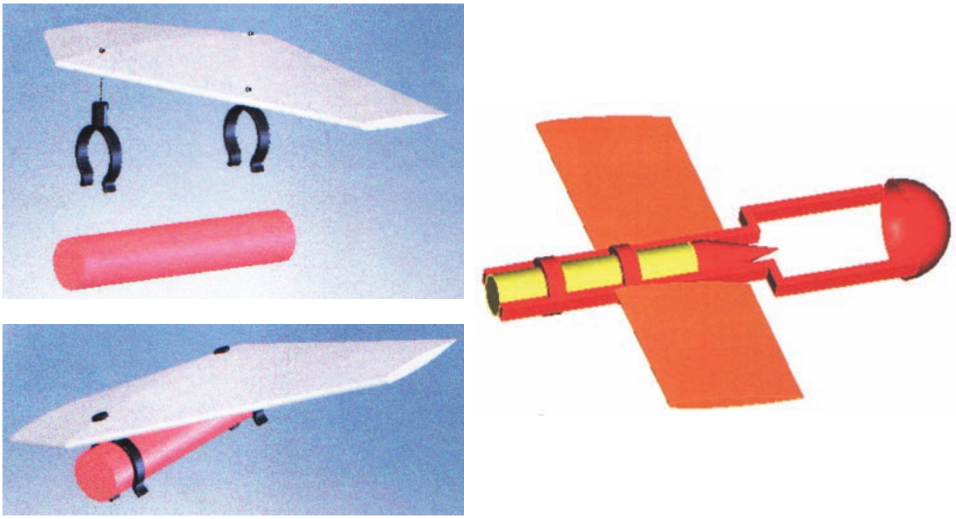


Figure 7. Two "glider" designs showing the simplicity of the concept

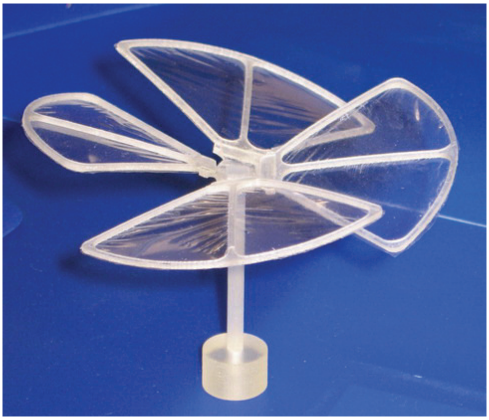
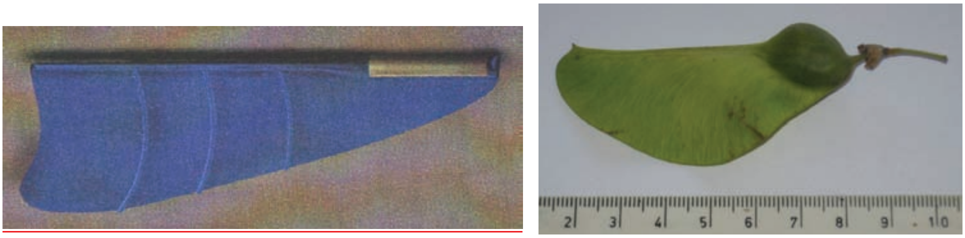


Figure 8. A prototype made for testing the "windmill" or "propeller" concept



(a) (b)

Figure 9. A model of a decelerator (a) inspired by a single winged Samara fruit (b)

7 CONCLUSION

As Albert Einstein put it [19], “Innovation is not the product of logical thought, although the result is tied to logical structure.” We often look at the logical structure of the solution, and assume that the design process could have linearly progressed from a functional description to a concrete solution. While in hindsight it may be easy to say that some insight could and should have been gained during need analysis (the task clarification stage that precedes conceptual design), in reality, it is *during* conceptual design that the designer discovers the underlying relationships while dwelling into design solutions to fit the needs.

Linear models of the design process suffer from several drawbacks and are inappropriate for design tasks that require a high level of innovation. While they may be beneficial during the redesign of an existing design, they impede the discovery of new formulations during the conceptual design process. Further, the linear models gradually shift the focus from functional considerations to detailed configurational issues. The configurational spotlight provides instant gratification in terms of perceived progress towards the final design, but tends to fixate the designers and prevent the consideration of new functional issues.

Parameter Analysis was proposed as an effective tool to help designers gain crucial insights into the problem, thereby aiding them to reformulate the problem. Further, it does not force the designer to completely specify the functional requirements before proceeding with the conceptual design. Each Parameter Analysis cycle uses a transitory configuration to acquire better understanding and facilitate the discovery of the innate conceptual relationships governing the design, and based on them, the problem definition evolves and increases the likelihood of innovation. Thus, Parameter Analysis offers the designer a practical means for handling the nonlinearity of the design process using repeated application of three simple steps.

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