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Abstract

This paper reports on the outcomes of applying the notions provided by the reconstructed proto-theory of design, based on Aristotle's remarks, to the parameter analysis method of conceptual design. Two research questions are addressed: (1) What further clarification and explanation to the approach of parameter analysis is provided by the proto-theory? (2) Which conclusions can be drawn from the study of an empirically-derived design approach through the proto-theory regarding usefulness, validity and range of that theory? An overview of parameter analysis and an application example illustrate its present model and unique characteristics. Then, seven features of the proto-theory are explained and demonstrated through geometrical problem solving and analogies are drawn between these features and the corresponding ideas in modern design thinking. Historical and current uses of the terms analysis and synthesis in design are also outlined and contrasted, showing that caution should be exercised when applying them. Consequences regarding the design moves, process and strategy of parameter analysis allow proposing modifications to its model, while demonstrating how the ancient method of analysis can contribute to better understanding of contemporary design-theoretic issues.

Keywords: design theory; conceptual design; parameter analysis; design method; reasoning

1. Introduction

Parameter analysis (PA) is a method for teaching and practicing conceptual design, i.e., a prescriptive model used for conceiving innovative ideas and developing them into workable designs (Kroll, Condoor, & Jansson, 2001; Kroll, 2011; Kroll, 2013). PA is based on a descriptive model according to which conceptual design is done by back and forth movement between two spaces: the concept space and the configuration space. The concept space contains ideas and other conceptual-level issues, such as fundamental physics, analogies and important relationships, called "parameters". The configuration space consists of the evolving hardware representation.

While a descriptive model aims at understanding *how designers design*, that is, what processes, strategies and methods they use, a prescriptive model specifies *how the design process ought to proceed*. To instruct the designer as to what needs to be done at any given time during conceptual design, PA's prescriptive model states that moving between concept and configuration spaces is carried out by breaking the thought process into three distinct steps: parameter identification (PI), creative synthesis (CS) and evaluation (E), as shown in Figure 1. The three steps are applied time and again, dealing with contingent, constantly evolving information associated with the design artifact. At each cycle of this process, the critical issues (parameters) identified are different, as are the changing configurations and the results of the evaluations.

Although PA has been in use for over 20 years, its fundamental notions are still based on observing designers in action (Li, Jansson, & Cravalho, 1980) and not on deep-seated theory. In addition, the 3-step model may be somewhat ambiguous and difficult to understand because the steps are depicted schematically as the inputs and outputs of the arrows, instead of being the arrows themselves with a meaning of design "moves" (Figure 1). The current effort therefore attempts to examine the reasoning process behind PA and offer modifications to this model in light of the explanations provided by the proto-theory of design. As this proto-theory has been only recently rediscovered, a secondary objective is to evaluate its validity and usability when confronted with a contemporary approach to design.

The development of the proto-theory of design was inspired by two puzzling observations made when reading philosophical literature. The initial excitement with this topic was raised by Hintikka (1969), who outlined the long history of the method of analysis and its significance in the method of science. This contrasts with the common but ahistorical usage of the terms analysis and synthesis in engineering[1], as elaborated in Section 4.4; the historical background is never clarified. Then, Niiniluoto (1990) was found to make, *en passant*, an explicit connection between the ancient geometric analysis and engineering and architectural design. Such a connection is not recognized in mainstream literature on design.

Based on subsequent research on these intriguing puzzles, the proto-theory of design, drawing on the similarity of design and geometric analysis, was first suggested in (Koskela & Kagioglou, 2006). After that, two significant findings were made. First, it was found that already Aristotle had pinpointed the close resemblance of designing on the one hand, and analyzing a geometrical figure on the other hand. Second, it turned out that this linkage was still known several centuries after Aristotle: the well known philosopher and medical doctor Galen (129 – c. 210 AD) explicitly referred to it. Galen discussed how the method of analysis can be used in the design and making of sundials and water clocks as well as in confirming their correctness (Singer, 1997). However, this part of the legacy of Antiquity was not addressed during the Renaissance, and fell into oblivion. As a consequence, although there has been recent interest in Aristotle's works from a design viewpoint (for instance, Wang, 2013), the interesting analogy between design and geometry is still not generally known.

In its further developed form (Koskela, Codinhoto, Tzortzopoulos, & Kagioglou, 2014) the proto-theory of design refers to a proposed interpretation of the method of analysis of the ancient geometers, in which seven features are related to our understanding of modern design methods. These features are the types of analysis, its stages, its start and end points, the types of reasoning involved, the relation of the two directions of reasoning, the strategy of reasoning, and the existence of a solution.

Studying a specific method with the aid of a theory is common in design research. It allows investigating the method to further our understanding of how and why it works, identify its limitations and area of applicability, and compare it to other methods using a common theoretical basis. At the same time, interpreting and demonstrating the method from the theoretic perspective can provide empirical validation of the theory. Similar studies have used the C–K theory of design (Hatchuel & Weil, 2009) to analyze the advanced systematic inventive thinking (ASIT) method (Reich, Hatchuel, Shai, & Subrahmanian, 2012), the infused design method (Shai, Reich, Hatchuel, & Subrahmanian, 2013), and parameter analysis (Kroll, Le Masson, & Weil, 2014).

The PA method is described and partially demonstrated in the next two sections, followed by elaborating the proto-theory of design with its seven features and their analogues in contemporary design ideation. The often confusing difference in usage of the terms analysis and synthesis between ancient and modern times is also discussed. The reasoning process of PA is interpreted next with the notions of the proto-theory to reveal new insights on the design "moves" used, a possible new depiction of the 3-step process model, and an explanation for the overall design strategy used by PA. The usefulness of the proto-theory, as

[1] Of course, from the early days of modern engineering, engineering students have encountered the term "analysis" in mathematics. It was originally used to refer to algebraic analysis (Monge, 1807), and infinitesimal analysis (Cauchy, 1821). These senses connected to the historical tradition in mathematics, although the meanings of the term had already drifted from what it was in classical geometry. However, this usage of "analysis" refers narrowly to the mathematical treatment of an engineering problem rather than to parts of the engineering design process itself. It is worth noting that the tendency of giving new meanings to the terms ”analysis” and ”synthesis” has been quite common. Thus, Otte & Panza (1997) list no fewer than 18 different interpretations, in which these terms have been used in the history of mathematics.

demonstrated in this paper, includes the re-interpretation of some aspects of PA by the features of the theory, the added clarity of the pragmatic design approach of PA provided by the proto-theory, and the identification of PA's unique reasoning strategy when compared to the method of analysis. Some issues that remain for future research are also listed.

2. Overview of parameter analysis

As the name suggests, the configuration space of PA 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 reasoning about ideas, which is done in concept space. The concept space deals with "parameters", which in this context are ideas or concepts 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. This model of the design process is in coherence with Schön's reflective practice paradigm (Schön, 1991), including the notion of dynamically framing the problem to discover new aspects of it, generating moves towards a solution, and reflecting on the outcomes.

The first step, parameter identification (PI), consists primarily of the recognition of the most dominant issues at any given moment during the design process. In PA, the term "parameter" specifically refers to issues at a conceptual level. 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 and its solution, 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 parameters within a problem are not fixed; rather, they evolve as the process moves forward. The temporal nature of design parameters is consistent with the notion of situatedness, i.e., the dynamic character of the context in which designing takes place (Gero & Kannengiesser, 2004).

The second step in PA 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. Physical configuration here usually means a sketch, although it often also entails calculations for rough dimensioning and even crude physical prototyping. Since the process is iterative, it generates many (representations of) physical configurations, not all of which will be very interesting. However, the physical configurations allow one to see new key parameters, which will again stimulate a new direction for the process. PA shifts the burden of truly creative activity from CS to PI, the creation of new conceptual relationships or simplified problem statements, which will lead to desirable configurational results. Thus, the task of CS along the way 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. This role of CS is in line with IDEO's design thinking philosophy, which emphasizes the creation of rapid physical prototypes (Kelly, 2001), and studies of designers and architects in action. For example, Suwa, Gero, & Purcell (1999) found, through protocol analyses of freehand sketching during design, that only after designers synthesize a solution are they able to detect and understand important issues and requirements of the problem. Such “unexpected discoveries” and “situated-inventions” are claimed to be strongly associated with creative outcomes.

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 physical realization represents a possible solution to the entire problem. Evaluation also points to the weaknesses of the configurations. 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. Evaluation in PA is not a filtering mechanism. The main purpose is not to find fault, but rather, to generate constructive criticism. A well-balanced observation of the design’s good and bad aspects is crucial for pointing out possible areas of improvement for the next design cycle.

Real design processes are rarely linear in nature, and PA is compatible with this situation. It may seem that a complete design process can begin with a certain concept in a PI step, proceed through a sequence of PI, CS and E steps, and terminate with an E step that says the design is complete. However, failures of various types may occur in the process, and even if everything proceeds as expected, there is often a need to repeat the process to generate several alternative designs, not just one. For these reasons it was necessary to add a stage, called “technology identification”, that precedes PA in the conceptual design process model, as shown in Figure 2.

Technology identification refers to the process of looking into possible fundamental technologies or physical principles that can be used for the design task at hand, thus establishing several starting points, or initial conditions, for PA. Often, several such core technologies can be used in a particular design. Technology identification plays a similar role to functional decomposition and morphology in systematic design (Pahl & Beitz, 1984), except that it focuses on the working principles for the most important function of the designed artifact, and ignores the less significant aspects. The similarity, however, is in the fact that the designer is not particularly directed to try to innovate at this stage, but rather to list solution principles that are mostly known to have been used in comparable applications. A cursory listing of each candidate technology’s pros and cons is usually all that is required at this stage to allow the designer to pick the one that seems most likely to result in a successful design. If a PA process reaches a dead end at some point, and it is realized by the designer that a major change is required, not merely backtracking to an earlier decision point and redoing part of the process, then another technology identified at the outset can be used as the new starting point for PA. And if the development of several alternative conceptual designs is desired, they can all be developed from different such core technologies.

3. Example of parameter analysis application

The following is a real design task that had originated in industry and was later changed slightly for confidentiality reasons and assigned to teams of students (3-4 members in each) in mechanical engineering design classes. The students had been instructed to use PA for its solution. The design process presented here is based on one team's written report, and has been described in a somewhat different context also in (Kroll et al., 2014).

The design task was 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, about 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). Each sensor contained a small battery, electronic circuitry, and radio transmitter, and was packaged as a ϕ10x50 mm cylinder weighing 10 g, with its center of gravity located about 10 mm 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. The sensors and decelerators were disposable, so their cost should be low. The following focuses on the decelerator design only.

The design team began with analyzing the need, carrying out some preliminary calculations that showed that at $Re>10^4$ (this Reynolds number corresponds to several tens of millimeters 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 ~150 mm. If the decelerator were a flat disk perpendicular to the flow, the C_D would reduce to ~1.2, and if it were a sphere, then $C_D \cong 0.5$, with the corresponding diameters being about 200 and 300 mm, respectively.

It was also clear that the decelators should allow compact packing in large numbers and 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 will also be heavier. And the heavier it is, the larger it will have to be in order to provide enough area to generate the required drag force.

The conceptual design process started with a technology identification stage, whose detailed description is omitted here for brevity. The team identified the deceleration technologies of flexible parachute, rigid parachute, gas-filled balloon and hot-air balloon. The flexible parachute can easily be folded for compact packing, and represents a very common technological solution for slowing down the descent of airborne objects. The rigid parachute can be made in various shapes; e.g., pyramids, cones and flat surfaces, and is also used in some existing applications. The balloons use both buoyancy and aerodynamic drag, and can be packed compactly, but inflating or heating during or after deployment seem difficult. The concept chosen by the designers for further development was therefore the flexible parachute.

Figure 3 shows the PA process applied to this task, presented as distinct reasoning steps that produce clear outcomes. The wording and illustrations have been slightly modified for better clarity, but in essence they follow the original students' work.

The first concept described in Figure 3 (PI_1) is based on a small conventional parachute that will provide the necessary drag force while allowing compact packing in its folded state in an under-wing container. The following creative synthesis step (CS_1) realizes this idea in a specific hardware by sketching the configuration and sizing it with the help of some calculations. Having a configuration at hand, evaluation can now take place (E_1), raising doubts about the operability of the solution. The next concept attempted (PI_2) is the rigid parachute from the technology identification stage, implemented as a square pyramid configuration (CS_2), but found to introduce a new problem – packing – in the evaluation (E_2). A folding, semi-rigid parachute is the next concept realized and evaluated, resulting in the conclusion that parachutes are not a good solution. This brings a breakthrough in the design: dissipating energy by frictional work can also be achieved by a smaller drag force over a larger distance, so instead of a vertical fall the payload can be carried by a “glider” in a spiraling descent (PI_4). The resulting configuration (CS_4) shows an implementation of the last concept in words and a sketch, to be followed by an evaluation and further development.

It is interesting to note a few points in this process: First, when the designers carried out preliminary calculations during the need analysis stage, they already had a vertical drag device in mind, exhibiting the sort of fixation in which a seemingly simple problem triggers the most straightforward solution. Second, technology identification yielded four concepts, all still relevant for vertical descent, and all quite "standard". A third interesting point is that when the flexible parachute concept was evaluated (E_1), the designers knew about problematic aspects of parachute deployment and were able to reason about the feasibilty of the concept. Had they not happened to already possess that knowledge, an experiment with a prototype might have been used for the purpose of evaluation. Conversely, they could also have failed to identify this problem at all and proceeded with the flexible parachute concept. Finally, when the “umbrella” concept failed (E_3), the designers chose not to attempt another technology identified at the outset (such as gas-filled balloon), but instead used the insights and understanding gained during the earlier steps to arrive at a totally new concept, that of a “glider” (PI_4). And while in hindsight, this last concept may not seem that innovative, it actually represents a breakthrough in the design process because this concept was not apparent at all at the beginning.

4. Overview of the proto-theory of design

4.1 Introduction to the method of analysis

The proto-theory of design is an adaptation of the method of geometric analysis to the field we now call ‘design’, based on Aristotle’s remarks. In his Nichomachean Ethics, Aristotle states: *For the person who deliberates seems to investigate and analyse in the way described as though he were analysing a geometrical construction* […]. It has been shown that design falls into that deliberation as meant by Aristotle (Koskela et al., 2014). He is thus suggesting that design and the method of analysis are similar or analogous.[2] The passage further details several aspects of deliberation that are similar to their counterparts in analysis, starting from the assumptions done at the outset, and ending, usually with the wished solution, but sometimes also with the realization that it is impossible. This suggested range of similarity, from beginning to end, can be interpreted to mean that the analogy between design and the method of analysis is general, rather than limited to a few aspects. That Galen (Singer, 1997), roughly five centuries later, knew, expanded and applied this analogy settles definitely the objection that perhaps we are interpreting more into a few sentences by Aristotle than historically justified.

Before progressing further, a linguistic note is warranted. The central terms analysis and synthesis, which existed also in the everyday Greek language, were given a precise technical meaning in the ancient method of analysis. The original meanings of analysis (αναλυση) in classical Greek (Panza, 1997) are argued to be: “back from solution”, “toward the solution”, “close to the conclusion” “what brings to the solution (or dissolution or even destruction)”, or “what makes it possible to unknot something”. Synthesis (σύνθεση) could be “the act of putting (something) together” or “the act of stating (something) with accord.” According to the same source, analysis and synthesis seem to have been used to refer to particular sorts of separation and composition, however without the idea of a natural opposition of these terms.

Now, we can turn to the question: What is the importance of this analogy between design and the method of analysis today? Even if our interest is current, again we have to draw on historical materials, as the method of analysis was developed, known and practiced in Antiquity, and in modern times, the interest has mostly been towards understanding and reconstructing it. Besides Aristotle’s mentioned account, there is only one more detailed description on the method of analysis from Antiquity, namely by Pappus (Hintikka & Remes, 1974). Examples of geometric practice and the interpretation tradition in the Middle Ages

[2] We use ‘analogous’ in its everyday meaning of being comparable and related; not in the more specific sense of design analogies.

may give additional insights. Lastly, current examinations of the method of analysis in mathematics and philosophy of science (Hintikka & Remes, 1974) provide useful directions.

Drawing from these sources (although mainly from ancient descriptions), seven features of the method of analysis can be extracted, as argued in more detail in (Koskela et al., 2014). For the purposes of this presentation, these features can be briefly introduced as follows:

- Two types of analysis: in problematical analysis, the task is to find (construct) a geometrical figure whereas in theoretical analysis, the task is to prove an assertion.
- Two stages in analysis: selection among different means, and completing the analysis regarding the selected means.
- The qualitative difference between the start point and end point of analysis: the start point is assumed to exist or to be true, whereas the end point is something already known.
- Three types of reasoning in two directions: in analysis, regressive inferences, decomposition and transformation; in synthesis, deductive inferences, composition and (reverse) transformation.
- The unity of the two directions of reasoning: analysis must be complemented with synthesis that provides the construction of the wished figure as well as the proof.
- The strategies of reasoning: in analysis heuristic and iterative, in synthesis predetermined.
- Impossibility of a solution as one special end point of analysis.

These features and their counterparts in design are explained in section 4.3; further elaboration can be found in (Koskela et al., 2014). However, as a background to that, it is instructive first to explore how the method of analysis practically operates in geometry.

4.2 Demonstration through geometrical problem solving

The demonstration below of the method of analysis is through example problems from Euclidean plane geometry, following the classical method of constructing figures with only a compass and an unmarked straightedge.

Problem 1: An angle PQR is given and it is desired to find (construct) its bisector (Figure 4a).

Problem 2: An angle PQR and an interior point C that is located at equal distances from the legs are given and it is desired to prove that QC is a bisector of ∡PQR (Figure 4b)

The solution of both problems according to Pappus (Hintikka & Remes, 1974) is by assuming the thing sought to be known or true and working backward to the conditions, assuming next that they are known or true, and continuing until arriving at something known to be possible/impossible or true/false, respectively, and this is called ‘analysis’. If we arrived at something possible or true, then the solution itself (construction or proof, respectively) will be by ‘synthesis’, which is reversal of the analysis. Thus, analysis can be regarded as devising a plan of action to arrive at the desired result, while synthesis is the actual implementation of the plan (Polya 1985).

For Problem 1, the first part of the solution, the analysis, may be: Assume a line from Q to some interior point C is indeed the bisector of ∡PQR (Figure 5a). It follows that ∡PQC = ∡RQC. It follows that we could have congruent (SAS; side-angle-side) triangles having the common side QC, ∡PQC = ∡RQC, and another side built on the original angle’s legs, which we can call QA and QB. It follows that QA = QB. Building equal length lines is known to be possible.

Now we need to complete the solution process by synthesis, that is, generate the sequence of construction for the bisector by reversing the previous analysis. We begin with the given ∡PQR and draw an arc of arbitrary length that crosses its legs at A and B and we have QA = QB (Figure 5b). To have ΔQAC ≅ ΔQBC (by SSS) we need AC = BC which we can do by drawing two equal arcs of arbitrary length from A and B and call their crossing point C. From the congruency of the triangles we get ∡AQC = ∡BQC, which is identical to ∡PQC = ∡RQC, so QC is the sought bisector.

For Problem 2, the solution process may begin with the following analysis stage: Assume that QC is indeed the bisector (Figure 6). It follows that ∡PQC = ∡RQC. It follows that we could have congruent (SAS) triangles having the common side QC, ∡PQC = ∡RQC, and another side built on the original angle's legs, which we call QA and QB, where CA and CB are perpendiculars from C to PQ and RQ respectively. It follows from the congruency that CA = CB, but this is already known to be true: it is given in the problem that C is equi-distant from the legs of the angle.

The proof by synthesis is the reversal of this sequence: From the given point C draw perpendiculars to PQ and RQ. Because it is given that CA = CB, if follows that ΔQAC ≅ ΔQBC by LH (hypotenuse leg of a right triangle). It follows that ∡AQC = ∡BQC, so QC is a bisector.

4.3 The seven features of the method of analysis and their interpretation in design

In the following, the seven features of the method of analysis are presented in more detail, as well as their correspondence to comparable ideas in the current theoretical and methodical landscape of design, developed essentially since the 1960s.

4.3.1 Problematical and theoretical analysis

In the method of analysis, problematical analysis refers to the problem to find (an unknown geometrical construction) and theoretical analysis, to the problem to prove (establish whether an assertion or theorem is 'true' or 'false'). "Problem to find" and "problem to prove" are terms coined by Polya (1985) and are exemplified by the aforementioned Problem 1 and Problem 2, respectively. An intriguing issue here is from where a theorem to be proven emerges. As originally argued by Peirce (Burch, 2013), the question is about abduction, a type of inference producing a conjecture or hypothesis.

In design, a corresponding dichotomy between problem-oriented and solution-oriented strategies is widely recognized (Wynn & Clarkson, 2005; Kruger & Cross, 2006). In the former, one tries to derive a solution proceeding logically from what is required; in the latter, one endeavors to propose a solution straightaway and then tries to show that it fulfills all the requirements. The German systematic design method (Pahl & Beitz, 1984) is well-known to be problem-oriented, as it entails a thorough, hierarchical decomposition of the desired function into subfunctions. Brainstorming may be considered a solution-oriented approach where the focus is on rapidly generating many solutions.

Another distinction in the "machine design" area of mechanical engineering is between "open-ended" and "closed-ended" problems. An example of the former is: design a shaft to transmit a certain power at a given speed with a prescribed minimum factor a safety against failure. This problem is about finding a solution (problematical analysis) where many solutions are of course possible, with different materials, diameters, surface finishes, etc. On the other hand, a "closed-ended" problem is: given a shaft (with all its construction details), its loading and the desired factor of safety, determine whether the design is satisfactory. This is a theoretical analysis problem whose answer is 'yes' or 'no'.

4.3.2 The two stages in analysis

Aristotle can be interpreted to refer to two stages in analysis: selecting among alternative means the one most easily and best produced, and then completing the analysis regarding the selected means. For example, we have seen two different ways to bisect an angle: as in Figure 5b and as in Figure 6. Which one shall we choose? Figure 6 requires constructing perpendiculars, which themselves require a separate construction effort, so perhaps Figure 5b's fewer operations should be preferred.

The two-stages feature may correspond to the dichotomy between conceptual design and the downstream stages (embodiment and detail design). In the former, one tries to find the best solution in principle; in the latter, one endeavors to translate that into a practical solution (Pahl & Beitz, 1984). Many systematic design procedures insert a concept selection step at the end of conceptual design to facilitate the choosing of the concept to be developed further. Of course, alternatives and choices exist at any stage or level of the design process, but overall when a selection is made, it is kept and the process continues until alternatives are generated for a new aspect of the artifact within the previously-made selected means.

The two stages in analysis can be recognized also in individual phases or tasks of many design models, each time the designer decides to choose one alternative over another, and proceeds with the chosen alternative. For example, in systematic design's morphology a choice is first made among the working principles that satisfy each subfunction, followed by creating overall ('principal') solutions by combining only those working principles that are compatible (Pahl & Beitz, 1984). Finally, Aristotle's criterion for selection, being "most easily and best produced" immediately brings to mind the modern quest for ease of manufacturing and assembly.

4.3.3 The start and end points in analysis

The start and end points of geometric analysis are qualitatively different. Regarding the start point, we do not know whether it exists or is true, but assume that. In contrast, the end point consists of something admitted, that is, already known. The aforementioned Problem 1 and Problem 2 clarify this property. This feature foreshadows the C–K (concept–knowledge) design theory (Hatchuel & Weil, 2009), where design is conceptualized by its start (C) and end (K) points. These have similar characteristics to the start and end points in analysis. A concept is defined as a proposition, regarding which we cannot know whether it is true or false ("undecidable"). In turn, propositions in K-space have a logical status, and contain knowledge that is known to be true or false. The design process in the C–K theory is defined as transforming undecidable propositions to true propositions in K.[3]

4.3.4 Three types of reasoning

In analysis, there are regressive, decompositional and transformational inferences, and in synthesis, their counterparts in the opposite direction: deductive, compositional, and reversely transformational inferences. Regressive and deductive inferences equal, respectively, to backward and forward reasoning, demonstrated by the above analysis and synthesis processes of Problems 1 and 2. These types of reasoning are ubiqituous in design. Backward reasoning

[3] Note that the meaning of C-space in the C–K theory is epistemologically different from PA's "concept space". C–K's concepts are tentative descriptions of the design artifact, while PA's concepts are ideas to be incorporated in the artifact. The former includes the latter as attributes, but will also have structural characteristics that come from PA's "configuration space" (Kroll, 2013).

is, of course, the main type of inference when deriving a structure (form) to provide some desired behavior (function). Forward reasoning may be seen, say, in the act of evaluating an artifact for function and performance by such methods as simulation, finite element analysis and computational fluid dynamics. In responding to the evaluation by introducing changes in the design, such as adding material to make it stronger or subtracting material to make it lighter, backward reasoning is again used.

Decompositional and compositional inferences refer to breaking down and putting together. In the geometrical Problems 1 and 2 we can find decomposing of figures into their constituent points, lines, and arcs, and vice versa. At somewhat higher level of decomposition and composition we can identify taking some constructions, for example drawing a perpendicular to a line from a given point, as given or known and using them as elementary entities. Such types of reasoning are often argued to exist in design; for example, functional decomposition followed by combining solutions through morphology (Pahl & Beitz, 1984).

In transformational inferences, the problem is transformed into another problem for facilitating its solution. Thus, the problem of bisecting an angle in Problem 1 was transformed into a problem of constructing congruent triangles; in fact, any use of auxiliary lines can be regarded as transforming the problem. Another possibility is to view the problem literally in a new perspective; say, a problem represented in two dimensions is seen in three dimensions (Hoffman, 1999). In design the idea of transformation is used in TRIZ (Cavallucci, 2002), where a particular problem to be solved is abstracted to a more general level, at which the knowledge about inventive opportunities lies. Abstraction to broaden the scope of the task has also been recommended by (Pahl & Beitz, 1984) as a first step in conceptual design. Ullah (2008) introduces an inference mechanism called ‘extension’ that transforms a specific problem to a more general one and thus allows generating a new solution. This is required in cases where existing design knowledge has no logical agreement with a design requirement and needs to be modified. Another type of transformational inference can be seen in analogical reasoning, restating the problem, variation of the problem, framing of the situation, etc., which can be generalized as interpretational. Modern use of such methods in design is, of course, quite common; for example, (Chan, Fu, Schunn, Cagan, Wood, & Kotovsky, 2011), (Singh, Skiles, Krager, Wood, Jensen, & Sierakowski, 2009) and (Dorst, 2011).

4.3.5 Unity of the two directions of reasoning

In geometric analysis, both directions of reasoning are needed: in analysis, backwards for the solution, and in synthesis, forwards for the proof or for the construction of the desired figure. This interwoven nature of solving geometrical problems has been demonstrated with Problem 1 and Problem 2 for both problematical and theoretical analyses, respectively. The Vee model (Forsberg, Mooz, & Cotterman, 1996), which has originated in systems engineering and recently diffused into software engineering and project management, similarly implies two directions of reasoning: the left “leg” represents system decomposition and definition from the customer needs through concept and subsystem development to low-level configuration items (and this corresponds to analysis); the right “leg” stands for integration and verification from the part level through subassemblies and subsystems to the whole system level (similarly to synthesis).

4.3.6 Two strategies of reasoning

The method of analysis does not advise on the precise strategy through which the solution can be found. Rather, as explained by Polya (1985), the method leads to a heuristic and iterative approach in the analysis stage and to a predermined procedure in the synthesis stage. Heuristic here means intuitive, non-algorithmic, and because using heuristics does not guarantee a solution, the possibility of iterations follows. Consider again the problematical analysis of bisecting a given angle. The person who has gone through solving this problem as demonstrated by the construction of Figures 5b and 6 may have developed a “feel” for this problem and its solution by drawing congruent triangles. He or she may now intuitively suggest the following construction (Figure 7): From vertex Q of the given angle draw two arbitrary-length arcs, crossing the legs at A, B, C and D. Now connect A and D with a line and connect B and C with a line. Call the crossing of AD and BC, E. Connect E and Q and EQ will be a bisector.

How has this construction come into being? It seems that the reasoning is heuristic, by abduction to a hypothesis (solution candidate). Of course, to prove that this construction is correct would require theoretical analysis as a follow up. In contrast, the predetermined nature of synthesis has been clearly demonstrated by Problems 1 and 2 above, where the order of analysis is reversed. However, it should be noted that this reversal need not always be precise: in the analysis related to Figure 5a an SAS congruency was used, while reversing the order for the synthesis of Figure 5b used SSS congruency.

The iterative nature of design has been emphasized in recent design theorizing; for instance (Pahl & Beitz, 1984). In turn, the predetermined strategy in synthesis has its counterpart in the right leg of the Vee model, as discussed above, or in the way solution principles for each subfunction are combined in morphological approaches.

4.3.7 Impossibility of a solution

In the method of analysis, the analysis stage can end up showing that a solution to the problem at hand is impossible; for example, by applying the well-known *reductio ad absurdum* reasoning method. Some geometrical problems, such as trisecting an arbitrary angle (with unmarked straightedge and compass), have been shown to have no solution. In engineering design, it has been found that requirements set based on customer wishes may be unrealistic (Ramaswamy & Ulrich, 1993) and engineering models are proposed as a means for identifying the impossibility of a solution. At a more general level, feasibility studies have a similar aim. And of course, design solutions that either violate natural laws or require non-existing technological capabilities are considered impossible.

4.4 Discussion

The close correspondence of the method of analysis and recent design theorizing suggests that the proto-theory of design is not only of historical interest, but can possibly contribute to the current research in theory of design. Somewhat surprisingly, in terms of the conceptualization of design, the proto-theory seems to provide a broader explanation than recent design theory proposals that can be interpreted to be typically oriented around one feature of the proto-theory. In addition, this proto-theory can be claimed to be pointwise deeper than the present body of knowledge on design. For example, it shows the intellectual origin of the practically used and popular Vee and morphological models, and gives them an initial explanation by way of geometric analogues. All in all, the prospect of advancing a core theory of design, based on the proto-theory, emerges.

Of course, the terms analysis and synthesis have often been used in treatments of design, but in dislocated and narrow meanings in comparison to the ancient usage. In the method of analysis, the analysis stage refers to a process of discovery, whereas the synthesis stage is the proof or construction of what was found in analysis. The most common usage of these terms in engineering today holds synthesis as the creative stage and analysis as the rational stage – this is more or less diametrically opposite to the ancient usage. Due to the nature of the topic, it has been necessary to apply both usages in this paper.

To further illustrate the confusing terminological mismatch of analysis and synthesis in ancient and modern times, consider that we now use the term analysis in two different meanings. The first of these is to describe studying the design task to extract customer requirements and converting customer requirements to engineering specifications—'needs analysis' according to Asimow (1962), and carrying out functional analysis/decomposition as in the German systematic design. Secondly, analysis is also used nowadays for evaluating a proposed solution, as in deducing the behavioral consequences of a hypothesized structure; a process often termed 'engineering analysis'. The latter use may add to the confusion because now we have analysis (of the problem situation) and analysis (of proposed solutions) in the ubiquitous analysis-synthesis-evaluation model of the design process (Jones, 1970), with modern synthesis of course referring to the creative or ampliative stage of generating something new.

The ancient usage, on the other hand, emphasizes the creative and intuitive aspect of analysis, where a plan is being devised by working backwards from the unknown or the conjecture toward something known. Ancient synthesis refers to the reversal of analysis, and therefore is predetermined and rational.[4] It is also worth noting that evaluation does not seem to be an explicit part of the ancient method of analysis, requiring perhaps notions of rhetoric to support it (Koskela & Ballard, 2013).

5. Interpretation of parameter analysis through the proto-theory

In the following, the method of PA is interpreted, clarified and explained through the relevant features of the proto-theory. The interpretation consists of looking at the following three aspects of the PA method: individual operators, process logic, and design strategy.

5.1 Parameter analysis design operators

Because design is ultimately the creation of a configuration, and this is done in the CS step of PA, the evolving configuration will be the starting point of the discussion of the individual steps, moves, or operators:

- At any intermediate point in the PA process there is a partially specified configuration (a member of configuration space). This configuration is examined and evaluated in the E step. This is clearly a **deductive reasoning** step of "given structure, find behavior", which corresponds to ancient synthesis (and modern analysis). This is followed by a decision whether to attempt improving the design or altogether abandoning the main technology on which it is based.
- The previous evaluation reveals a problem with the configuration: either it would not work as desired, would not meet the design requirements, or pose new problems. This is true for all E steps except the last. To address this problem, a new dominant issue/solution principle is identified in the PI step. So, going from a problem (related to a specific configuration and its behavior) to concept for solving it involves generalization and abstraction as depicted in Figure 1. Consider for example an evaluation that reveals that the artifact is too heavy. We ask, what is the reason for

[4] Does this imply that a proof does not require creativity? Actually, the terms "proof" or "proving" may be used in two senses, to refer to the whole process of preparing a proof, or to the part in the method of analysis that delivers the proof, namely synthesis. The latter meaning was used already by Euclid; the Elements mostly consists of (ready) proofs in the form of synthesis. Now, in theoretical analysis, the task is to prove an assertion, theorem, conjecture. That endeavor has two parts, analysis and synthesis, where analysis is the creative part but synthesis is predetermined by the path taken in the successful analysis stage. Consequently, the preparation of a proof, as a whole, requires creativity, but the synthesis stage (usually) not.

that? Is it because we used a high-density material, or perhaps we used a solid section? We may generalize and abstract to come up with a new solution concept; for example, use composite material instead of metal or use a square-tube section instead of the solid one. The particular type of composite or the section dimensions are not specified yet, but an idea for improving the artifact has been proposed. From the proto-theory perspective this step has two aspects: (a) the problem is assumed to be solved (this is related to **the qualitative difference between the start and end points of analysis**), and (b) it is explored through **regressive reasoning**, which concept could bring forth that solution. The facilitating mechanism for this exploration is mainly **transformational or interpretational reasoning**, where the original problem is converted into another form or examined from a different perspective for enabling its solution, and this is analogous to the use of auxiliary lines in geometric analysis.

- Having decided on a solution concept in the PI step, the designer now realizes it in hardware, that is, he or she updates the artifact's configuration by implementing the last concept ("parameter") in it. This CS step consists of two operations. First, there is a **regressive reasoning** operation of "given (desired) behavior, find structure", corresponding to the ancient analysis (and modern synthesis). As depicted in Figure 1, it can also be characterized as particularization (the opposite of generalization). Second, there is an operation for integrating the current particular hardware within the overall configuration. From the point of view of the method of analysis, the question is about **composition**; however, this is slightly different from the predetermined composition as in ancient synthesis, as in PA there has not been a complete stage of analysis of the whole configuration, along with corresponding decomposition that could be reversed. Rather, the designer has more degrees of freedom when carrying out composition, perhaps either based on prior experience or, more rarely, through a creative leap.

To summarize, the proto-theory of design allows us to interpret each of the PA steps separately in terms of the type of reasoning involved, as shown in Table 1.

5.2 The process of parameter analysis

The proto-theory may contribute to an even more interesting clarification of PA as a process, as opposed to looking at the individual steps. The long chain of PI–CS–E steps is different from the Pahl & Beitz (1984) model or system engineering's Vee model (Forsberg et al., 1996), with their decomposition followed by composition, or one stream of reasoning towards the solution and another towards its proof/validation, respectively. Indeed, linear design process models usually include a feedback loop between stages to facilitate iteration; but this is for cases in which some sort of failure occurs and previous decisions need to be changed. Ideally, if everything goes well then the process may proceed linearly. This reasoning process may be explained by the focus of these so-called "rational models": they are not particularly intended for applications that require original or radical designs.

In contrast, PA exhibits a type of mixed reasoning: a step of regressive transformational[5] reasoning (PI) followed by a step of regressive and compositional reasoning (CS), then a step of deductive reasoning (E), and so on. Therefore, the cyclic or repetitive nature of the PA steps is always present, even when the process is ideally successful, and it follows from the different design philosophy of handling one aspect or issue at a time. This conclusion is supported by Lawson's "analysis through synthesis" (Lawson, 2005), the phenomenon of

[5] "Regressive transformational" means that the backwards reasoning, from ends to means, transforms an original problematic issue into another or re-interprets the current situations as a new one.

designers not following a sequence of analysis, synthesis and evaluation only once in their design process, but rather applying these steps repeatedly, in a rapid cycle. This mix of ancient analysis and synthesis steps, as shown in Figure 8, can be identified to be based on the principle **of the unity of the two directions of reasoning**, that is, reasoning backwards towards a solution (ancient analysis) and reasoning forwards towards the proof (ancient synthesis). Both are necessary in design and can be integrated into one process rather than separated to two distinct streams.

It should also be noted that while the evaluation step in PA is essentially deductive, its findings are followed by a decision on how to proceed. The actual decision-making requires reasoning that is not deductive and therefore is represented separately from the evaluation in Figure 8, and is not shown at all in the diagram of Figure 9. Detaching the decision from the evaluation step follows Asimow's (1962) four-stage model of design with analysis-synthesis-evaluation-decision.

5.3 The design strategy of parameter analysis

A pragmatic conclusion of the study of PA in light of the proto-theory of design is that PA uses solution-oriented and problem-oriented strategies in one design process; in the vocabulary of the method of analysis, both **problematical and theoretical analysis** modes are used. A solution-oriented strategy means that the designer starts with a solution, with what needs to be achieved, as opposed to starting with the problem as in the problem-oriented thinking of scientific approaches. Pahl & Beitz's systematic design, for example, tries, after an exhaustive capture of requirements and detailed functional decomposition of the main problem to be solved, to create (through backward reasoning) many combinations of sub-solutions, screen them for the feasible ones, and select the best among them. This is a problem-oriented approach whose main reasoning mechanism in modern terms is 'analysis' (in the specific sense of problem analysis). This strategy may have advantages in conducting an orderly systems engineering process in large projects, or when applied by students and novice designers (as evident from the many adaptations in design textbooks). Drawbacks of problem-oriented paradigms are highlighted by works on design as co-evolution of problem and solution (Dorst & Cross, 2001; Maher & Tang, 2003; Wiltschnig, Christensen, & Ball, 2013), claiming that ill-structured problems cannot be understood fully at the outset and need the added appreciation gained by attempting to solve them.

PA, on the other hand, while flexibly proceeding either from problem or intermittent solution onwards, covers both orientations. On the whole, though, the solution-oriented aspects tend to accentuate in PA: striving to quickly create a partial (virtual) prototype that can be evaluated and improved in successive steps; along these steps, the relevant requirements also become more visible. In modern terminology, this is referred to as 'synthesis'. However, the interpretation through the proto-theory of design suggests that the problem-oriented and solution-oriented strategies should not be seen as alternatives but that designing, when the prescriptions of PA are followed, is done by a close partnership of both strategies.

A unique aspect of PA's strategy is its depth-first strategy, combined with moving in the "steepest" direction. Depth-first means that a central solution principle is pursued, even in the face of difficulties, as long as the designer feels that this is a promising path. The path itself is generated by identifying at any given moment the most critical issues with the evolving artifact, those whose resolution would reduce the uncertainty most steeply. This strategy is efficient in two respects: first, it allows reaching a solution quickly, with no effort wasted on developing multiple paths; and second, it accomodates the notion that solving minor subproblems may be futile if the central issues are not addressed first, and that the solution to the former is likely to depend on the latter.

Depth-first is not a new notion in search and planning problem-solving; neither it is obvious in design. Some systematic methods recommend developing the design breadth-wise, with many alternative paths in parallel. The proto-theory of design, being descriptive in nature, does not specify a strategy for designing; however, its **two stages in analysis** feature seems compatible also with the notion of depth-first: select among alternatives and continue only with the selected means, as opposed to simultaneous development of multiple paths.

6. Summary of the modified parameter analysis model

One possible conclusion from comparing the schematic of PA in Figure 1 and both Table 1 and Figure 8 is that perhaps the operators of PA should be redefined to reflect better the transition from concept space to configuration space (the "realization" direction) by means of (ancient) analysis followed by synthesis, and the transition in the opposite direction, from configuration space to concept space ("abstraction"), by a combination of (ancient) synthesis and analysis, as shown in Figure 9. Additionally, the diagram associates the PI and CS steps to problematical analysis (working towards finding the solution) and the E step, to theoretical analysis (moving in the direction of proving or validating the solution).

The diagram of Figure 9 contains the original descriptive model of back and forth movement between concept space (where the elements are "parameters", i.e., ideas, concepts, issues at the conceptual level) and configuration space (where hardware representations reside), and the original repeatedly-applied sequence of PI–CS–E operators. However, it now prescribes more precisely what needs to be done when applying these reasoning steps, and this has a significant pedagogical benefit when teaching PA to design students: the exact nature of each step is less vague and can be explained more rationally.

Creative synthesis (CS) begins in concept space, from an identified parameter, whose content is usually an idea of how to overcome a specific problematic aspect of the evolving artifact. So the first step in CS is the realization of this idea in hardware, thus establishing a configuration, a hardware representation, that solves the specific problematic issue. Now in configuration space, this last piece of hardware needs to be integrated into the overall artifact, and this is shown as the second CS arrow, lying entirely within configuration space.

Evaluation (E) now takes over, starting with the current configuration and deducing its specific behavior (would it work? if not, how can it be fixed? would it perform as required? is there anything still missing?), followed by a decision whether to attempt to improve the current design or abandon this conceptual path and start over with a different technology. Whatever the decision, its outcome locates the reasoning process again in concept space.Parameter identification (PI) at this point takes place, seeking a new idea, a conceptual-level issue that now dominates the design. If the previous E step concluded that a different technology should be used, then the identified parameter is using that technology as a basis for the design. If, however, a decision were made to improve a problematic aspect of the current design, then the challenging task of the designer now becomes finding ideas of how to do that. The logic of the process is summarized in the flow chart of Figure 10.

One of the important aspects of PA is the explicit discovery and statement of parameters in the PI step. Until now it was considered something that depends on the designer's experience and intuition, but the mechanism for doing it was not very clear. The current understanding, using the proto-theory, that this is done by transformational/interpretational reasoning, offers additional grounding of this notion. For example, Polya (1985) emphasizes the importance of heuristic reasoning, the use of methods and rules of discovery and invention, and traces it back to Pappus. Among Polya's heuristic suggestions are restating the problem and variation of the problem (by decomposing and recombining its elements, by analogy, by discovery of a more accessible auxiliary problem, and more). We can therefore suggest that in general, the main mechanism of identifying parameters—ideas and other conceptual-level issues that are critical to the progression of the design process—is that of transforming and interpreting the current design situation using heuristics and intuition.

The emphasis put by PA on using heuristic methods may also point to some of its possible weaknesses. First, being less formal and mechanistic in nature than systematic design's functional decomposition and morphology, it may require more talent and experience and therefore be less suitable for use by novice designers. Second, PA works mostly in the depth-first direction by quickly finding a solution (configuration), even if not a very good one, just so that it can be evaluated and improved; however there is always the danger of missing something useful by not covering the whole breadth of alternatives. A third weakness of PA may be its requisite high-level abstract reasoning during the PI step, which may necessitate training and practicing before reaching a satisfactory level of performance.

7. Conclusions on the usefulness, validity and range of the proto-theory

Regarding the validity, usefulness and range of the proto-theory, three insights and two pointers for further work flow from the examination of PA through it. First, several features of the proto-theory can be used for interpretation of steps or aspects in PA. This, for its part, empirically adds to the validity of the proto-theory. Second, the notions of the proto-theory seem to create added clarity when applied to a contemporary design approach. The proto-theory is helpful in pinpointing aspects or parts of a suggested design process that have remained implicit or not fully elaborated. Arguably, this is related to the prevailing relative lack of precise notions to describe design reasoning in detail. Third, the examination of PA provided evidence on the role of the proto-theory as a useful reference: for example, a novel strategy of reasoning in PA (focus on those parts of the problem where uncertainty can be most steeply reduced, by identifying the most critical issues at each PI step) could readily be identified when it was compared to the strategy of reasoning in the method of analysis.

Two further issues are considered as topics for future investigation. This research has highlighted certain differences of design reasoning in comparison to geometric reasoning. For example, in design, reasoning is more often based on informal logic than in geometry. This stresses the analogical (rather than strictly identical) relation that the practically implemented features of the proto-theory of design have to their counterparts in geometric analysis. The target should be to comprehensively capture such differences. Furthermore, there seem to be steps in PA that are not explained and supported by the proto-theory. Comparison of alternatives belong to such steps. This may indicate that for some aspects and stages of design, notions and explanations that go beyond the proto-theory are needed. However, the whole legacy of Antiquity for the design domain has not been exhausted though the proto-theory; as mentioned above, here another ancient idea can be taken on board, namely to see certain types of design as rhetoric. Indeed, Koskela and Ballard (2013) argue that rhetoric and the method of analysis provide different lenses to see design and lead to different prescriptions; however, in a practical design project the mobilization of ideas from both these sources is needed.

All in all, the outcomes of this study, where the proto-theory of design encountered parameter analysis, clearly support the suggestion made in (Koskela et al., 2014) to explore whether the proto-theory could suggest a conceptual and theoretical basis for the design domain.

Finally, one might ask whether it is worthwhile to introduce new meanings of the terms "analysis" and "synthesis" into the vocabulary of the design research community as there is a danger of added confusion. However, as the preceding discussion has shown, the design community is using the terms "analysis" and "synthesis" in a way that is totally separated from the origin and the subsequent, origin-informed usage of these terms. This may contribute to a general diminishment of the communicative value of these terms. Indeed, Polya (1985) states when referring to the term ‘analysis’ (p. 200): *Unfortunately, the word has acquired very different meanings ... and therefore, it is regretfully avoided in the present study.* A similar explanation is provided for the avoidance of ‘synthesis’ (p. 202). In this situation, there are several good reasons for reconnecting back in the design domain to the original meanings of the terms: terminological precision is added; an opportunity to understand the point of origin of design theory is created; and communication with fields, where the original meanings are still used, is enabled. Table 2 summarizes the differences in the meaning of analysis and synthesis between ancient and modern times.

8. Conclusion

The outcomes of this study clearly show that theoretical decoding of an empirically derived design method is beneficial both for clarification and explanation of the method and for validation and further development of the (still nascent) theoretical foundations of design. The application of the notions of the proto-theory to the reasoning process embedded in the PA method of conceptual design uncovered interesting findings. It showed that the CS design move of realizing a concept as a configuration actually involves two successive reasoning steps, and it also helped understanding the nature of the E move. Most of all, the proto-theory helped in beginning to grasp the PI move, which refers to the thought processes that take place within concept space. In turn, regarding the proto-theory of design, it was found that many of its notions can be found in PA, that these notions help to clarify parts or aspects of this method and that they provide a helpful reference point.

Although the insights outlined in this investigation are specific to the design method studied, the activities of coming up with solution ideas for required functions, implementing them as a form, and evaluating the designed artifact, together with the ideas presented regarding the processes and strategies involved in designing, are all fundamental to design in general. Some of the insights regarding PA were new, and others had been known before and perhaps only explained better by the proto-theory. However, this research shows that the proto-theory encompasses many known, general notions in design under one framework, and this leads us to suggest that it may be a more unified theory than some of its competitors. The question of how far this model of ancient analysis can be pushed to explain design methods in creating a theory of design still remains open.

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Figure and Table Captions

Figure 1. The 3-step prescriptive model of parameter analysis drawn on top of the 2-space descriptive model.

Figure 2. Block diagram of the two stages of conceptual design: technology identification and parameter analysis.

Figure 3. Portion of the parameter analysis process for small aerodynamic decelerators; PI = parameter identification, CS = creative synthesis, E = evaluation. The outcome of each reasoning step, described in the right-hand column, consists of identified parameters, configurations, and evaluation results.

Figure 4. Examples of (a) finding (constructing) the bisector of ∡PQR; and (b) proving that QC is a bisector of ∡PQR given that C is equi-distant from QP and QR.

Figure 5. Examples of (a) analysis and (b) synthesis in Problem 1.

Figure 6. Example of analysis and synthesis in Problem 2.

Figure 7. An intuitively suggested construction of an angle bisector.

Figure 8. Parameter analysis as a sequence of steps with comparable parts to ancient analysis and synthesis.

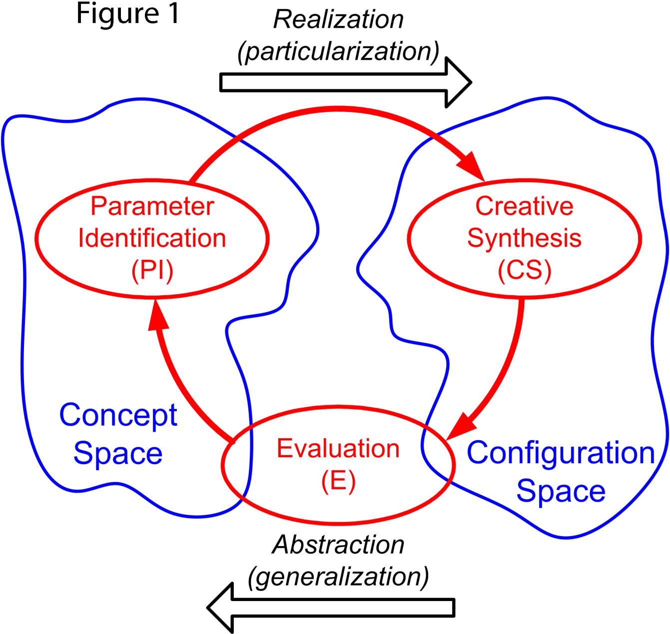
Figure 9. The modified model of parameter analysis showing the transitions from ancient analysis to ancient synthesis.

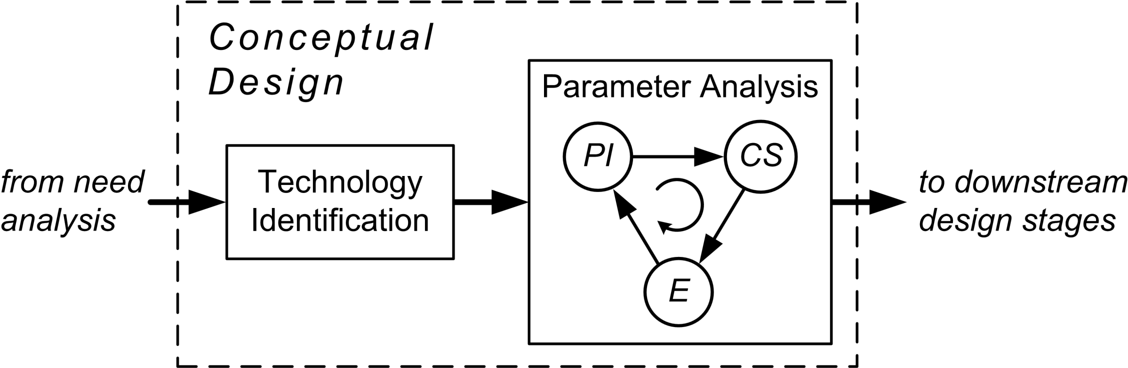
Figure 10. Flowchart of parameter analysis: beginning with the identified technologies, repeatedly cycling through the PI–CS–E steps will eventually yield a final configuration; this diagram therefore depicts a successful design process.

Table 1. The type of reasoning of each parameter analysis step; the comparable stage in the method of analysis is also indicated.

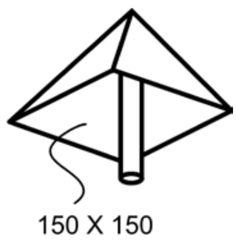
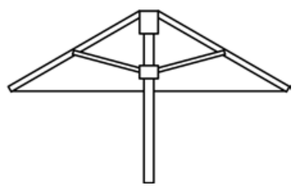
Table 2. Summary of ancient and modern characteristics of analysis and synthesis.

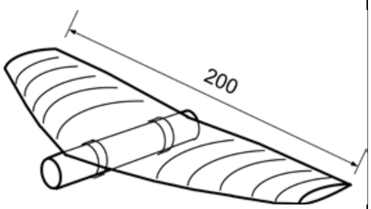
Figure 1

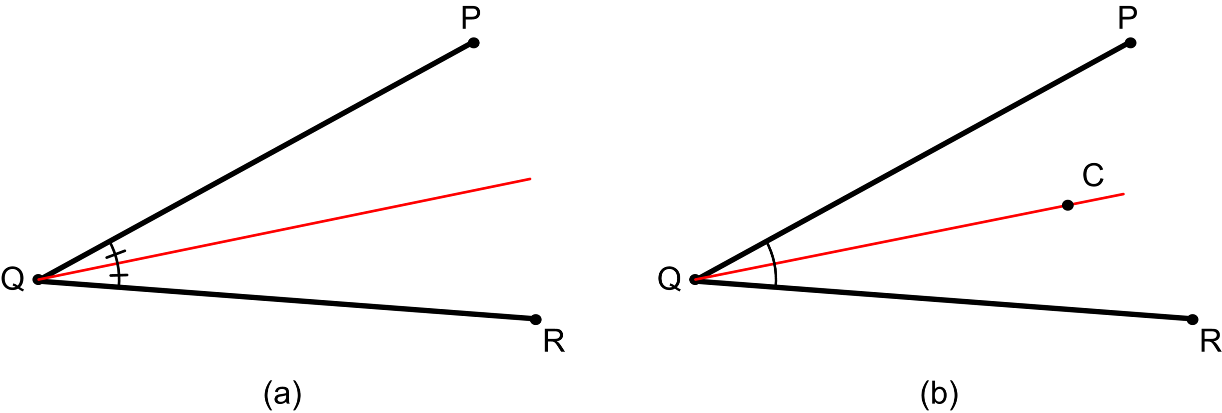

Realization
(particularization)
Parameter
Identification
(PI)
Creative
Synthesis
(CS)
Concept
Space
Evaluation
(E)
Configuration
Space
Abstraction
(generalization)

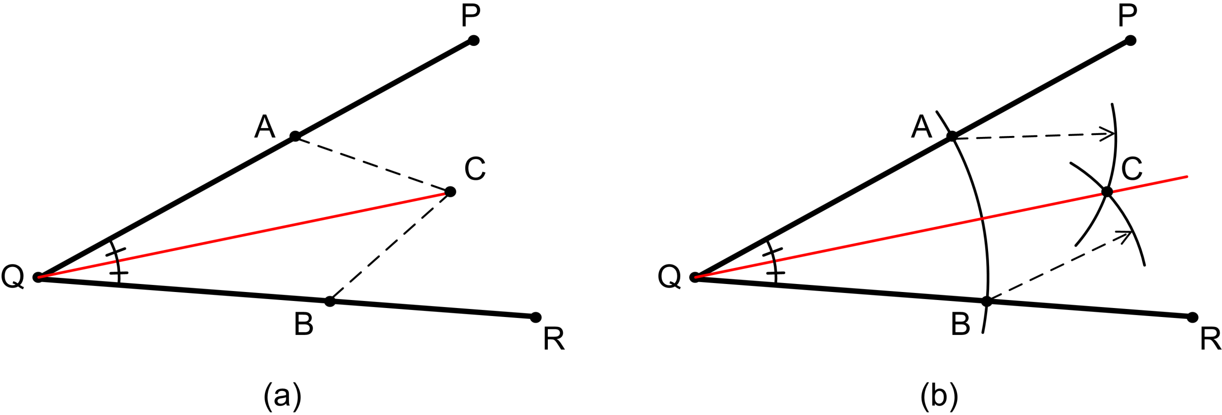


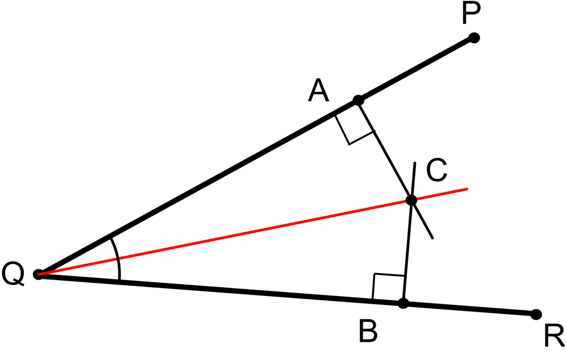
Conceptual Design
from need analysis
Technology Identification
Parameter Analysis
PI
CS
E
to downstream design stages

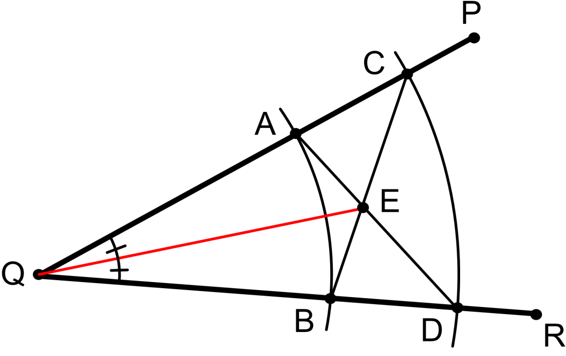
Reasoning step	Outcome
PI_1: *Use the chosen technology as the solution concept; i.e., a flexible parachute.*	*Identified parameter: Produce a large enough drag force with a flexible parachute.*
CS_1: *The required drag force F equals the weight during the descent at a constant v = 3 m/s. The payload weighs 10 g, and 2-5 g can be assumed for the decelerator. The drag coefficient* C_D *is ~2, and air density at 3,000 m altitude is* $\rho \approx 1$*, so the required parachute diameter is* $d \approx 150$ *mm from* $F = ½\rho C_D(\pi d^2/4)v^2$*. This parachute will be connected to the sensor by cords.*	
E_1: *The drag force is ok and folding for packing is possible. But there might not be enough "pull" on the cords to open the parachute when deployed. It might not open at all, or the cords might tangle.*	*The deployment problem needs to be solved.*
PI_2: *How can we get rid of the problematic elements (flexibility of parachute and cords) but retain the good ones (large drag force)?*	*Identified parameter: Use a rigid parachute.*
CS_2: *A square pyramid with a 150X150-mm base with the sensor attached to it.*	
E_2: *The drag is ok, but compact packing is impossible because these units cannot nest inside each other.*	*The packing problem needs to be solved.*
PI_3: *How can the last configuration be improved? Combine the idea of flexible parachute that can be folded for packing with a rigid parachute that doesn't have cords and doesn't require a strong "pull" to open.*	*Identified parameter: Use "frame + flexible sheet" construction that can fold like an umbrella and opens with a spring.*
CS_3: *Light weight skeleton made of plastic or composite with "Saran wrap" stretched and glued onto it. Hinges and slides allow folding around the sensor and a spring facilitates opening.*	
E_3: *Drag and packing are ok, but the structure is unreliable because of all the moving parts and expensive to manufacture.*	*Parachutes, flexible or rigid, seem problematic so we need to look for other ideas.*

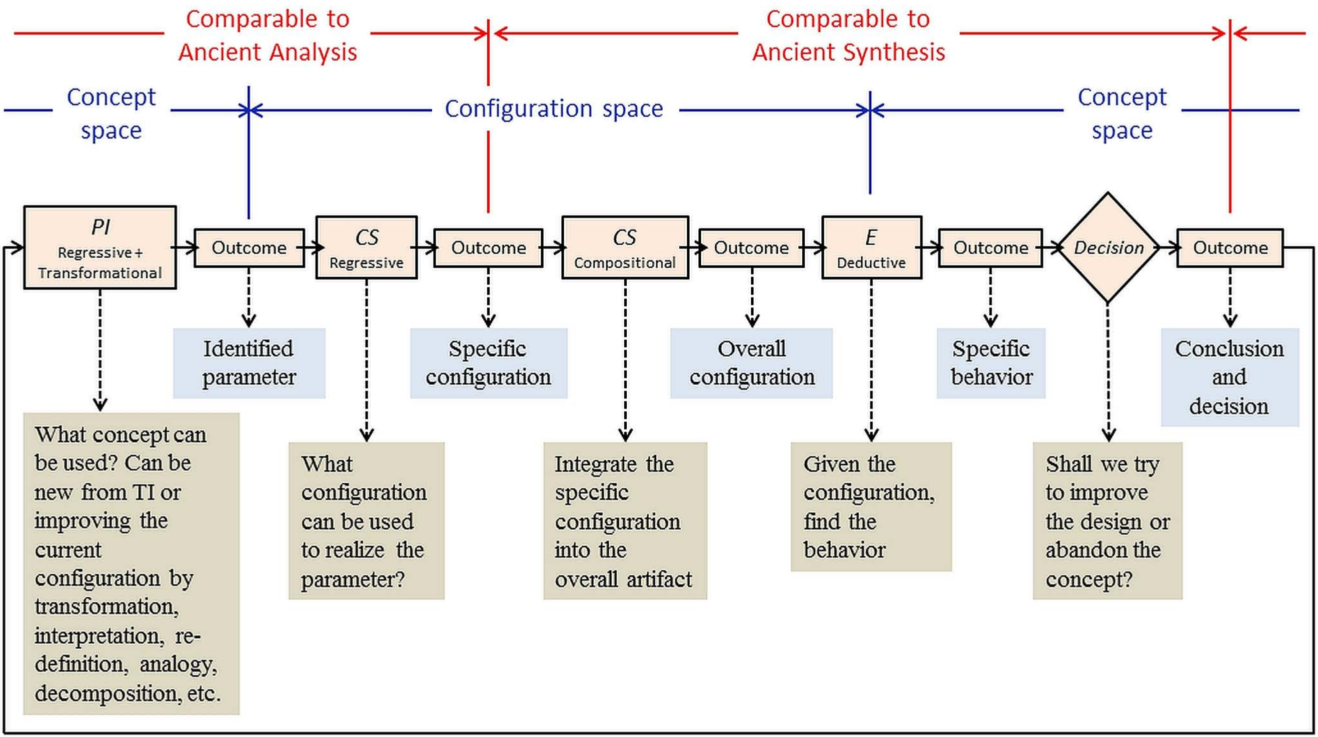
PI_4:	*Let's re-examine the physics of the problem: we need to dissipate the potential energy of an object released at an altitude. Aerodynamic drag opposite to the descent direction (i.e., a force pointing vertically upward) dissipates energy by frictional work that depends on the size of the decelerator. However, if energy dissipation by frictional (drag) work is the dominating physics, we should study the physics of work more carefully. Work is the product of force and distance. In vertical descent the distance is the altitude, so the focus in the design so far has been on creating a large vertical drag force, one that is equal to the weight of the falling object. Such a large force dictates a large size decelerator. But what if the distance can be made longer? Then it should be possible to dissipate the energy by a combination of long travel distance and small force, and the latter may equate to a smaller object that can be packed compactly in large quantities.*	*Identified parameter: Use a small "aircraft" that glides down slowly in spirals.*
CS_4:	*Light wings, perhaps made of Styrofoam, with a span of 200 mm and a slight imbalance can produce a 30m diameter spiraling glide. The sensor will be the fuselage and the wing attached to it by plastic clips.*	
E_4:	*...*	


P
Q
R
(a)
P
C
Q
R
(b)

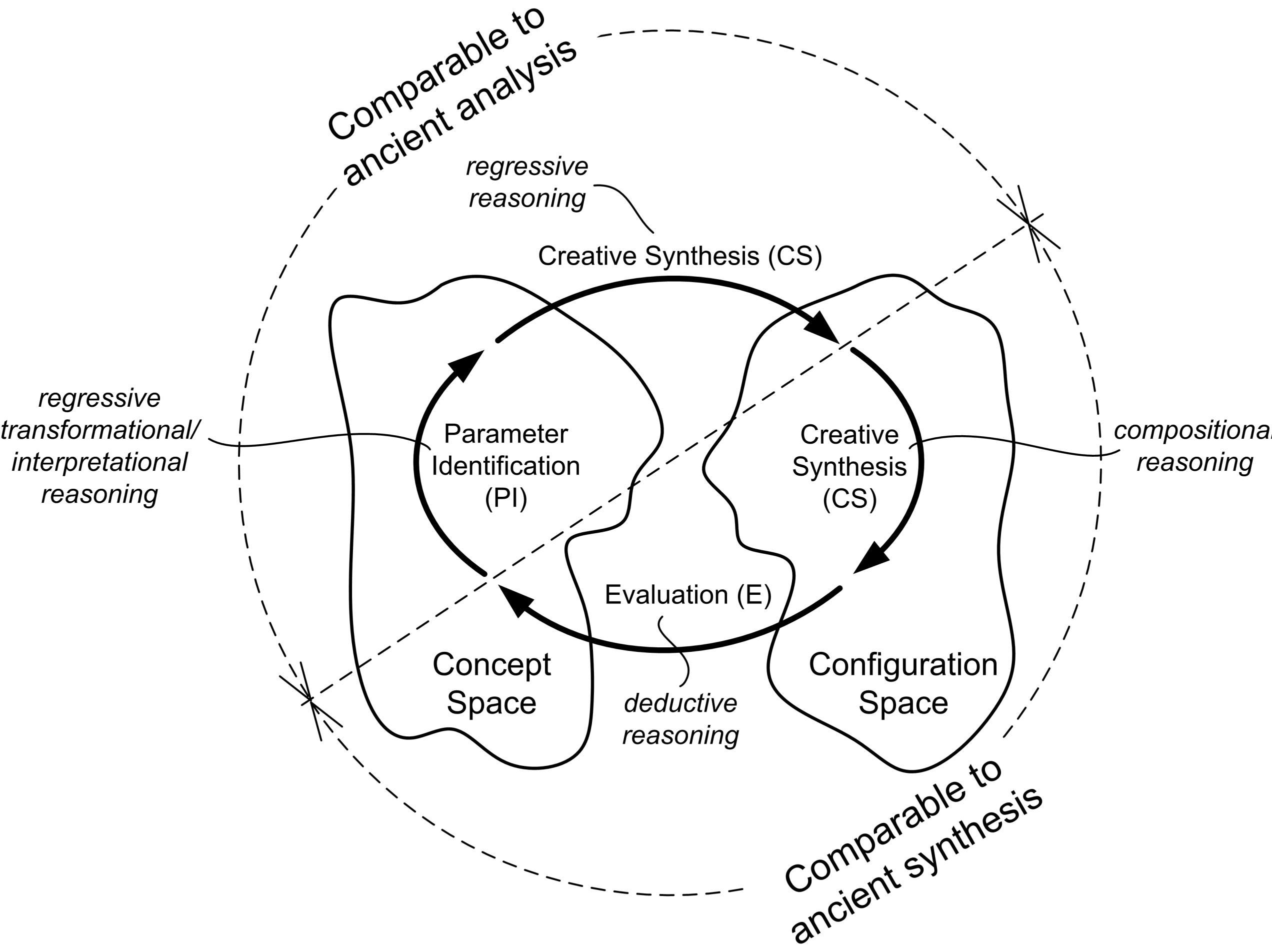

P
A
C
Q
B
R
(a)
P
A
C
Q
B
R
(b)

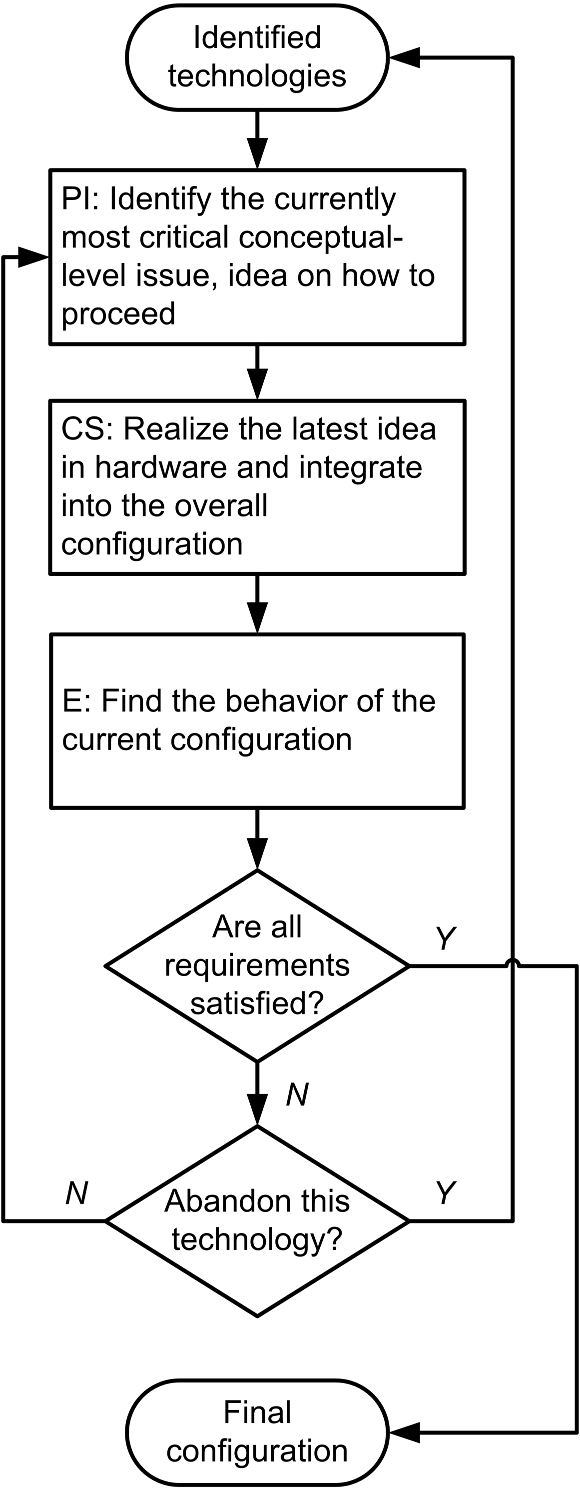

P
A
C
Q
B
R


P
C
A
E
Q
B
D
R



Comparable to Ancient Analysis
Comparable to Ancient Synthesis
Concept space
Configuration space
Concept space
PI
Regressive + Transformational
Outcome
CS
Regressive
Outcome
CS
Compositional
Outcome
E
Deductive
Outcome
Decision
Outcome
Identified parameter
Specific configuration
Overall configuration
Specific behavior
Conclusion and decision
What concept can be used? Can be new from TI or improving the current configuration by transformation, interpretation, re-definition, analogy, decomposition, etc.
What configuration can be used to realize the parameter?
Integrate the specific configuration into the overall artifact
Given the configuration, find the behavior
Shall we try to improve the design or abandon the concept?


Comparable to
ancient analysis
regressive
reasoning
Creative Synthesis (CS)
regressive
transformational/
interpretational
reasoning
Parameter
Identification
(PI)
Creative
Synthesis
(CS)
compositional
reasoning
Evaluation (E)
Concept
Space
Configuration
Space
deductive
reasoning
Comparable to
ancient synthesis



Identified technologies
PI: Identify the currently most critical conceptual-level issue, idea on how to proceed
CS: Realize the latest idea in hardware and integrate into the overall configuration
E: Find the behavior of the current configuration
Are all requirements satisfied?
Y
N
Abandon this technology?
N
Y
Final configuration

Table 1. The type of reasoning of each parameter analysis step; the comparable stage in the method of analysis is also indicated.

Parameter analysis step	*Type of reasoning*	*Comparable stage in the method of analysis*
Evaluation (E)	Deductive	Synthesis
Parameter Identification (PI)	Regressive transformational/interpretational	Analysis
Creative Synthesis (CS)	Regressive + Compositional	Analysis + Synthesis

Table 2. Summary of ancient and modern characteristics of analysis and synthesis.

		Analysis	*Synthesis*
Ancient method of analysis	Nature	Creative, intuitive	Rational
	Aspects of geometric problem-solving covered	Devising, in a heuristic and iterative manner, a plan to find or prove	Implementing the predetermined plan by construction or proof
Modern usage in design	Nature	Rational	Creative, intuitive
	Aspects of design covered	Needs analysis (requirements development), evaluation of proposed solutions (deduction of behavior from structure, engineering analysis)	Generating something new, proposing solutions