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INTERPRETING PARAMETER ANALYSIS THROUGH THE PROTO-THEORY OF DESIGN

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1. Introduction

This paper reports on initial outcomes of ongoing research, where the parameter analysis (PA) methodology of conceptual design is interpreted through the notions provided by the reconstructed proto-theory of design, based on Aristotle's remarks [Koskela and Kagioglou 2006], [Koskela 2010], [Koskela et al. under review]. Two research questions are addressed: (1) What further clarification and explanation to the approach of PA is provided by the proto-theory? (2) Which conclusions can be drawn from the study of an empirical design approach through the proto-theory regarding usefulness, validity and range of that theory?

The origin of PA is in work done at MIT in the 1970s [Li et al. 1980] as a way to train innovators. It has since been developed into a methodology for teaching and practicing conceptual design, i.e., a prescriptive model used for conceiving innovative ideas and developing them into workable designs [Kroll et al. 2001], [Condoor and Kroll 2008], [Kroll 2011]. PA is based on a descriptive model according to which conceptual design is done by back-and-forth movement between two spaces: concept space and configuration space. Concept space contains ideas and other conceptual-level issues, such as fundamental physics, analogies and important relationships, called "parameters". Configuration space consists of the evolving hardware representation.

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) (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 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 (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.

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 [Hintikka 1969], who outlined the long history of the method of analysis and its significance in the method of science. This contrasts to the common but ahistorical usage of the terms analysis and synthesis in engineering; the historical background is never clarified. Then, Niiniluoto [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.

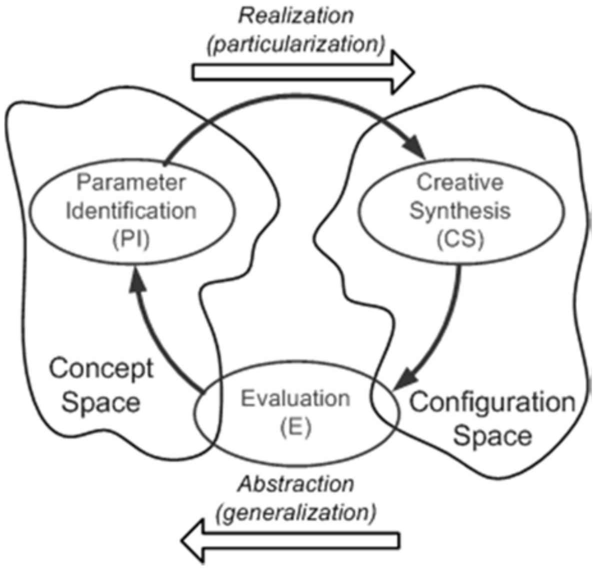


Figure 1. The 3-step prescriptive model of parameter analysis drawn on top of the 2-space descriptive model

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 and Kagioglou 2006]. After that, two significant findings were made. First, it was found that already Aristotle had pinpointed the close resemblance of designing and analyzing a geometrical figure. 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. However, this part of the legacy of Antiquity was not addressed during Renaissance, and fell into oblivion.

In its further developed form [Koskela et al. under review] the proto-theory of design refers to a proposed interpretation of the method of analysis of the ancient geometers, in which five features are related to our understanding of modern design methods. These features are the types of analysis, its start and end points, the types of reasoning involved, the relation of the two directions of reasoning, and the strategy of reasoning.

Studying a specific method with the aid of a theory is common in scientific areas. 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.

The PA methodology and the proto-theory of design are described in the next sections, followed by a partial demonstration of applying PA to a conceptual design task. 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 model, and an explanation for the overall design strategy used by PA. The paper ends with some general conclusions on the benefits of theory-based analysis of a pragmatic design method, and on future research directions.

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 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. 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.

The first step, parameter identification, 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, 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 second step in PA is creative synthesis. This part of the process represents the generation of a physical configuration based on the concept recognized within the parameter identification step. Since the process is iterative, it generates many physical 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 creative synthesis to parameter identification, the creation of new conceptual relationships or simplified problem statements, which will lead to desirable configurational results. Thus, the task of creative synthesis 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.

The third component of PA, the evaluation 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.

3. Overview of the proto-theory of design

Drawn mainly from ancient descriptions, five features of the method of analysis can be extracted [Koskela et al. under review]:

- Two types of analysis: problematical and theoretical
- The qualitative difference between the start point and end point of analysis
- 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
- The strategies of reasoning: in analysis heuristic and iterative, in synthesis predetermined.

Remarkably, for all the five features of the method of analysis, comparable ideas exist in the current theoretical and methodical landscape of design, developed essentially since the 1960s. These features and their counterparts in design are briefly explained in the following, based on [Koskela et al. under review].

In the method of analysis, problematical analysis refers to the problem to find (a geometrical construction) and theoretical analysis to the problem to prove (an assertion or theorem). In design, a corresponding dichotomy between conceptual design and detail design is widely recognized. In the former, one tries to find a solution in principle; in the latter, one endeavors to show that the found solution fulfills all the requirements.

The start and end points of geometric analysis are qualitatively different. Regarding the start point, we do not know whether it exists and is true, but assume that. In contrast, the end point consists of something admitted, that is, already known. A recent counterpart in design is the C-K theory (developed by Hatchuel and his group), where design is conceptualized by its start (C) and end points (K). These have similar characteristics as the start and end points in analysis. A concept (C) is defined as a proposition, regarding which we cannot know whether it is true or false. In turn, propositions in the knowledge space (K) have a logical status, and contain knowledge that is known to be true or false. (Note that the meaning of the C-K theory's spaces is different from PA's, in spite of the identical use of the term "concept space".)

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, as identified in the design domain. Decompositional and compositional inferences refer to breaking down and putting together. Such types of reasoning are often argued to exist in design. In transformational inferences, the problem is transformed into another problem for facilitating its solution. This idea is used in TRIZ, where a particular problem to be solved is abstracted to a more general level, at which the knowledge about inventive opportunities lies.

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. The Vee model, which has originated in systems engineering and recently diffused into software engineering and project management, similarly implies two directions of reasoning.

The method of analysis does not advise on the precise strategy through which the solution can be found. Rather, the method leads to a heuristic and iterative approach. The iterative nature of design has been emphasized in recent design theorizing.

The close correspondence of the method of analysis and recent design theorizing adds to the justification for holding the method of analysis as the proto-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 point wise deeper than the present body of knowledge on design. For example, it shows the intellectual origin of the practically used and popular Vee model, and gives it an initial explanation by way of a geometric analogue. All in all, the prospect of creating a core theory of design (which has been missing up to now), 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 demonstration 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 evaluation stage – this is diametrically opposite to the ancient usage. Due to the nature of the topic, it has been necessary to apply both usages in this paper.

4. Example of parameter analysis application

Figure 2 depicts a portion of the conceptual design process of small aerodynamic decelerators, which are required to keep 10-g sensors airborne for about 15 minutes when released in large quantities from a container attached to a light aircraft at an altitude of 3,000 m. The sensors will be used for monitoring air quality and composition, wind velocities, atmospheric pressure variations, etc. Each sensor contains a small battery, electronic circuitry and radio transmitter, and is packaged as a ϕ10x50 mm cylinder. The sensors and decelerators are disposable, so their cost should be low.

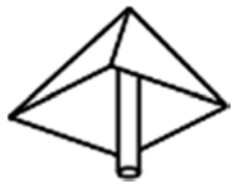
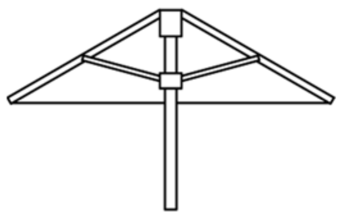
Reasoning process	Outcome
PI_1: Use the chosen technology as the solution concept; i.e., a flexible parachute.	*Identified parameter: Produce a large enough drag force with a flexible parachute.*
CS_1: The required drag force F equals the weight during the descent at a constant v = 3 m/s. The payload 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 $F = \frac{1}{2}\rho C_D(\pi d^2/4)v^2$. This parachute will be connected to the sensor by cords.	
E_1: The drag force is ok and folding for packaging 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 packaging is impossible because these units cannot nest inside each other.	*The packaging 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 packaging 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.*
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.	
E_3: Drag and packaging 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.*

Figure 2. Portion of a 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 (continued on next page)

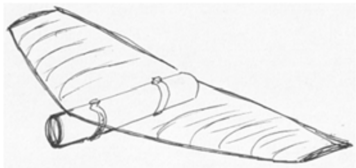
PI_4: Let's re-examine the physics of the problem: we need to dissipate the potential energy of an object released at an altitude. Aerodynamic drag in the direction opposite to the descent (i.e., a force pointing vertically upward) would dissipate energy by frictional work that depended on the size of the decelerator. However, if energy dissipation by frictional (drag) work 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 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 the distance could be made longer? Then it would be possible to dissipate the 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.	*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 could produce a 30-mdiameter spiraling glide. The sensor would be the fuselage and the wing attached to it by plastic clips.	
E_4: ...	

Figure 2. Continued

The design process started with a technology identification stage that is omitted here, but described elsewhere [Kroll et al. 2001], [Kroll 2011]. It refers to the process of looking into possible fundamental technologies that can be used for the design task at hand, thus establishing several starting points, or initial conditions, for parameter analysis. In this example, the technologies identified were flexible parachute, rigid parachute, gas-filled balloon and hot-air balloon. A cursory listing of each candidate technology's pros and cons resulted in the designer picking the flexible parachute idea as the one that seems most likely to result in a successful design.

The first concept described in Figure 2 (PI_1) is therefore based on a small conventional parachute that will provide the necessary drag force while allowing compact packaging 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 – packaging – in the evaluation (E_2). A folding, semi-rigid parachute is the next concept realized and evaluated, resulting in a 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 spiralling 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 that when the "umbrella" concept failed (E_3), the designer 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).

5. Interpretation of parameter analysis through the proto-theory

In the following, the presented partial example of applying PA is interpreted, clarified and explained through the relevant features of the proto-theory – not all features become visible in this examination of a part of the whole PA process. Because design is ultimately the creation of a configuration, and this is done in the CS step of PA, the evolving configuration will be at the center of the discussion:

- At any intermediate point in the parameter analysis process we have a partially specified configuration (a member of configuration space). We examine this configuration and evaluate it (the E step). This is clearly a **deductive reasoning** step of "given structure, find behavior", which corresponds to ancient synthesis (and modern analysis).
- The previous evaluation reveals a problem with the configuration (either it would not work as desired, would not meet the requirements, or pose new problems). This is true for all E steps except the last. To address this problem the designer identifies a new dominant issue/solution principle 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 Fig. 1. 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 point of analysis**), and (b) it is explored through **regressive reasoning**, which concept could bring forth that solution. The 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 facilitating its solution, and this is similar 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: (a) particularization (the opposite of generalization), as depicted in Fig. 1, which is a **regressive reasoning** step of "given (desired) behavior, find structure", corresponding to the ancient analysis (and modern synthesis), and (b) integrating the current particular hardware with the overall configuration, and this **compositional reasoning** step fits the ancient synthesis.

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

Table 1. The type of reasoning and ancient name of each parameter analysis step

Parameter analysis step	Type of reasoning	Ancient name
Evaluation (E)	deductive	synthesis
Parameter Identification (PI)	regressive transformational/interpretational	analysis
Creative Synthesis (CS)	regressive + compositional	analysis + synthesis

But there may be an even more interesting clarification of PA as a process, to which the proto-theory contributes. The long chain of PI–CS–E steps is different from Pahl & Beitz's model [Pahl et al. 2007] or system engineering's Vee model [Forsberg 2005], with their decomposition followed by composition, or one stream of reasoning towards the solution and another towards its proof/validation, respectively. Rather, PA exhibits a type of mixed reasoning: a step of regressive transformational reasoning (PI) followed by a step of regressive and compositional reasoning (CS), then a step of deductive reasoning (E), and so on. This mix of ancient analysis and synthesis steps 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.

One possible conclusion from comparing the schematic of PA (Fig. 1) and Table 1 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 (see Figure 3).

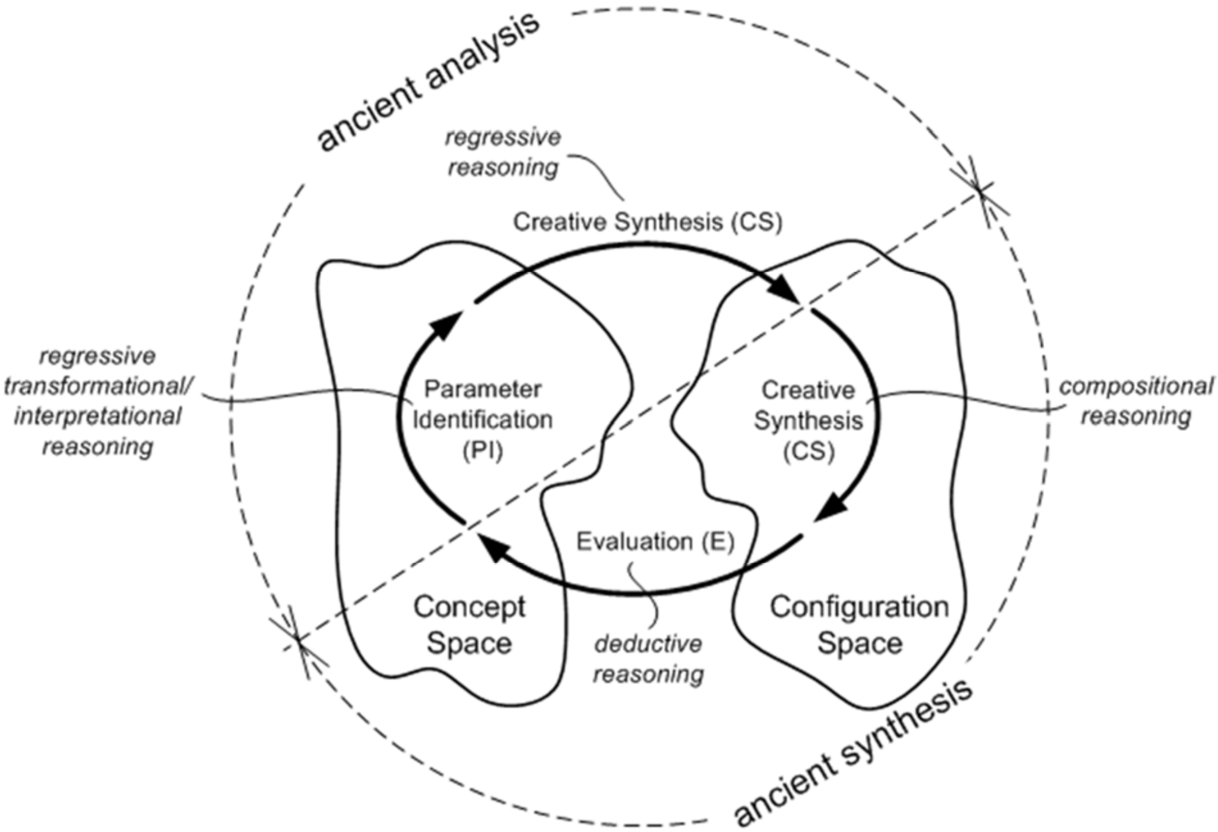


Figure 3. Redefining the operators of parameter analysis

Another possible pragmatic conclusion of the above 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. A solution-oriented strategy means that the designer starts with the goal, 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, to create as quickly as possible 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’. PA, on the other hand, is solution oriented, 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 proto-theory of design may tell us that analysis and synthesis carry with them much ambiguity, and that real design is done by a close partnership of both reasoning directions.

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. In this situation, there are several good reasons for reconnecting back 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.

6. 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, all features of the proto-theory can be connected to steps or aspects in PA (the example given above is partial and not all features were discussed; however, they are covered in ongoing work). 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 remain 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; not discussed in this paper) could readily be identified when it was compared to the corresponding feature of the proto-theory.

In the ongoing work, two further issues are considered. Initial work 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 is to comprehensively capture such differences. Furthermore, there seem to be steps in PA that do not nicely fall into the proto-theory. Gathering of requirements information for the initial stage (and subsequent stages) and 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; here another suggestion of Aristotle can be taken on board, namely to see certain types of design as rhetoric.

All in all, the outcomes of this exercise, where the proto-theory of design encountered parameter analysis, clearly support the suggestion made in [Koskela et al. under review] to explore whether the proto-theory could offer a conceptual and theoretical basis for the design domain.

7. 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 methodology 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 further work, a more comprehensive interpretation of PA through the proto-theory is targeted. In turn, regarding the proto-theory of design, it was found that all its notions can be found in PA, that these notions help to clarify parts or aspects of this methodology and that they provide a helpful reference point. In further work, the differences between design and geometric reasoning will be addressed as well as the question whether the proto-theory covers all parts and aspects of PA.

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