The Aristotelian proto-theory of design

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Abstract

In comparing deliberation to the analysis of a geometrical figure, Aristotle made a highly significant theoretical statement on design, which has largely gone unnoticed. Through an interpretation of the accounts given by Aristotle and the Greek geometer Pappus, seven features of the method of analysis can be identified, concerning 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 targeted outcomes. This proto-theory is compared to the current theoretical landscape of design; also it is applied to clarify a current approach to conceptual design. Based on all this, the proto-theory as a theory of design is evaluated. It is concluded that the proto-theory fulfills several of the functions of a theory in a superior and fertile way. Thus, this proto-theory is not only of historical interest, but – still – provides a contribution to the theoretical knowledge on design.

Introduction

In 1993, Cross (1993) stated that the existing design science had contributed little to advances of design practice. After that, similar views have been presented by many. For example, the NSF Report on Engineering Systems Design Workshop (2010) states: "There is a profound need for a normative theory of engineering design [...] Today, without such a theory, our systems engineering methods, processes and tools are a very large edifice built on extraordinarily loose sand."

However, in late Antiquity, the medical doctor Galen (AD 129 – c. 216?), whose influential writings were to be used for fifteen centuries in medical training, praised (what we now would call) a normative theory of engineering design, namely adopting the method of analysis and synthesis from geometry to design. He showed (Galen 1997) how it is applied in the concrete case of designing and making a sun dial, and proposed this theory to be used also in medicine.

Thus, the theory of design has degenerated from being at the leading edge of knowledge at Galen's time to an almost non-existing entity in our times. What on earth happened to it? Is the theory of design known by Galen now hopelessly obsolete, as most of his medical knowledge is, or has it been forgotten?

We contend that the ancient theory of design is not obsolete, but it has been forgotten. In this Chapter, we first address the historical questions: What was the theory of design known and applied by Galen; how was it originated? Then we turn to the question of current interest: Does the ancient theory of design have significance still today?

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Origin of design theorizing

Aristotle as design theorist

We contend that the theory of design referred to, applied and further developed by Galen has its origin in Aristotle. In his Nicomachean Ethics, Aristotle (384-322 BC) states that "the person who deliberates seems to investigate and analyse in the way described as though he were analysing a geometrical construction". Actually, this short statement, along with the sentences surrounding it (Table 1) contains a powerful view on design – however, several layers of interpretation in light of other classical texts are needed for revealing this.

The first question is whether Aristotle means design here. Indeed, he does not use this term for the simple reason that it is of a much more recent origin. Instead, he focuses on deliberation, in the sense of figuring out what to do (Cooper 1975). In his examples, this deliberation occurs in the framework of production (*poiesis*), which has a wide interpretation: it covers medicine, oratory, shoe making, house building, shipbuilding, agriculture, and also artistic activities such as poetry and music.

In the scheme of Aristotle (1924), production has two stages: thinking and making:

> Of the productions or processes one part is called thinking and the other making, - that which proceeds from the starting-point and the form is thinking, and that which proceeds from the final step of the thinking is making.

He exemplifies this through healing by a doctor; the medical knowledge of Aristotle is obsolete but the concepts and method are clearly visible (Aristotle 1924):

> The healthy subject is produced as the result of the following train of thought:-since this is health, if the subject is to be healthy this must first be present, e.g. a uniform state of body, and if this is to be present, there must be heat; and the physician goes on thinking thus until he reduces the matter to a final something which he himself can produce. Then the process from this point onward, i.e. the process towards health, is called a 'making'.

The similarity of logic (means-ends structure) and subject (healing) in the quoted passage and the focused passage in Nicomachean ethics allows concluding that this thinking equates to deliberation. In the case of producing an object, thinking arguably includes the mental operations required before any making is possible, namely designing (in its colloquial sense, specifying the functional principles, form and material of an object) and planning. Thus, when discussing deliberation, Aristotle covers designing.

Table 1. Aristotle's account on deliberation in Nicomachean Ethics (Aristotle s.a.)

We deliberate not about ends but about means. For a doctor does not deliberate whether he shall heal, nor an orator whether he shall persuade, nor a statesman whether he shall produce law and order, nor does any one else deliberate about his end. They assume the end and consider how and by what means it is to be attained; and if it seems to be produced by several means they consider by which it is most easily and best produced, while if it is achieved by one only they consider how it will be achieved by this and by what means this will be achieved, till they come to the first cause, which in the order of discovery is last. For the person who deliberates seems to investigate and analyse in the way described as though he were analysing a geometrical construction (not all investigation appears to be deliberation – for instance mathematical investigations - but all deliberation is investigation), and what is last in the order of analysis seems to be first in the order of becoming. And if we come on an impossibility, we give up the search, e.g. if we need money and this cannot be got; but if a thing appears possible we try to do it.

Analysing a geometrical construction

What, then, does "analysing a geometrical construction" mean? This refers to the method of analysis in geometry, a sophisticated and well-known procedure already at Aristotle's time, although the only written account of it (Table 2), by Pappus (AD c. 290 – c. 350), comes from late Antiquity.

It is useful to briefly outline the procedure contained in the method of analysis (Figure 1). In geometry, one typical problem is to construct a given geometrical figure using a ruler and a compass (this is the problematical analysis of Pappus). The starting point of analysis is to assume the sought figure already done, and to consider through which means it can be created, further through which means this can be achieved, until one comes to something well known, such as a theorem generally known to be true (thus, reasoning in analysis consists of inferences backward). This is the end point of analysis, and simultaneously the start point of synthesis. In synthesis, one follows, in a deductive manner, the steps taken in analysis, but in reverse order, and comes finally to the sought figure. Synthesis contains both the construction of the sought figure and its proof. - It has to be stressed that the sophistication and richness of the method of analysis is not transmitted in such a brief outline.

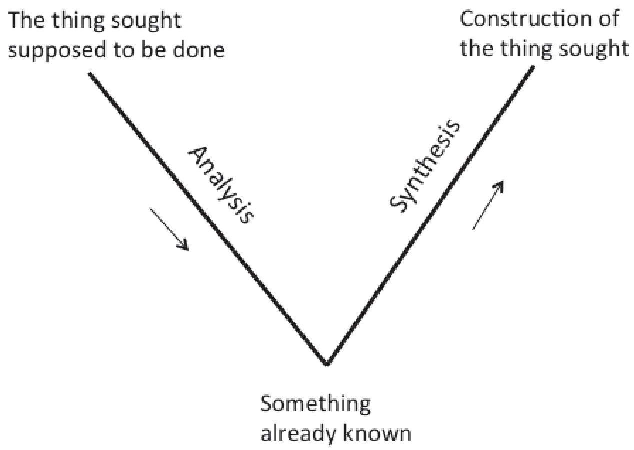

Figure 1. Outline of the method of analysis (problematical analysis).

Table 2. Pappus' account on the method of analysis (from Hintikka & Remes 1974)

Now analysis is the way from what is sought - as if it were admitted - through its concomitants in order to something admitted in synthesis. For in analysis we suppose that which is sought to be already done, and we inquire from what it results, and again what is the antecedent of the latter, until we on our backward way light upon something already known and being first in order. And we call such a method analysis, as being a solution backwards. In synthesis, on the other hand, we suppose that which was reached last in analysis to be already done, and arranging in their natural order as consequents the former antecedents and linking them one with another, we in the end arrive at the construction of the thing sought. And this we call synthesis.

Now analysis is of two kinds. One seeks the truth, being called theoretical. The other serves to carry out what was desired to do, and this is called problematical. In the theoretical kind we suppose the thing sought as being and as being true, and then we pass through its concomitants in order, as though they were true and existent by hypothesis, to something admitted; then, if that which is admitted be true, the thing sought is true, too, and the proof will be the reverse of analysis. But if we come upon something false to admit, the thing sought will be false, too. In the problematical kind we suppose the desired thing to be known, and then we pass through its concomitants in order, as though they were true, up to something admitted. If the thing admitted is possible or can be done, that is, if it is what the mathematicians call given, the desired thing will also be possible. The proof will again be the reverse of analysis. But if we come upon something impossible to admit, the problem will also be impossible.

Comparison of deliberation by Aristotle to the method of analysis by Pappus

A comparison of Aristotle's account of deliberation and Pappus' description of the method of analysis (Table 3) reveals an astonishing similarity, as noted by Hintikka and Remes (1974). Indeed, it can be asked whether Pappus was influenced by Aristotle's account of deliberation, but this is hardly probable as the method of analysis was the paramount methodological resource for Greek geometers and Pappus, a practitioner of the method of analysis, must have absorbed it from his teachers and prior mathematical treatises. Indeed, Menn (2002) argues that the same logical description of analysis that we find in Pappus was already available in Plato's and Aristotle's time.

Table 3. Comparison of deliberation and analysis.

Aristotle's description of deliberation	*Corresponding parts in Pappus' description of the method of analysis*
They assume the end	For in analysis we suppose that which is sought to be already done,
and consider how and by what means it is to be attained;	and we inquire from what it results,
and if it seems to be produced by several means they consider by which it is most easily and best produced,	
while if it is achieved by one only they consider how it will be achieved by this and by what means this will be achieved,	and again what is the antecedent of the latter,
till they come to the first cause, which in the order of discovery is last.	until we on our backward way light upon something already known and being first in order.
For the person who deliberates seems to investigate and analyse in the way described as though he were analysing a geometrical construction (not all investigation appears to be deliberation- for instance mathematical investigations- but all deliberation is investigation),	
and what is last in the order of analysis seems to be first in the order of becoming.	In synthesis, on the other hand, we suppose that which was reached last in analysis to be already done, and […] we in the end arrive at the construction of the thing sought.
And if we come on an impossibility, we give up the search, e.g. if we need money and this cannot be got; but if a thing appears possible we try to do it.	But if we come upon something false to admit, the thing sought will be false, too.

When describing deliberation, Aristotle refers to all the steps of the method of analysis, as later described by Pappus (and presents one additional step not covered by Pappus). Deliberation starts in the same way as analysis, proceeds through the same steps, and even ends similarly. Arguably, Aristotle claims that deliberation and analysis are throughout similar or analogous, from beginning to end. In relation to this claim, several implications and consequential questions arise.

Implications from the viewpoint of design

Thus, in proposing that the person who deliberates seems to investigate and analyse as though he were analysing a geometrical construction, Aristotle presents the first theory – proto-theory – of design. It encompasses the claim that design is similar, or analogous, to geometric analysis. This proto-theory was influential still in late Antiquity, as Galen's example shows, but fell then into oblivion.

Did Aristotle mean that just the topics explicitly mentioned by him are similar between design and geometrical analysis, or does the remark imply an overall, deeper structural similarity? The rhetorical figure he used, from beginning to end, would pinpoint to the latter alternative. Likewise, the character of his writings as lecture notes (Barnes 2000) suggests taking the overall similarity as the hypothetical starting point: it falls to us to establish the extent of similarity.

What, according to Aristotle, is the degree of similarity between design and analysis? Not much can be concluded regarding this question. Several stages of deliberation seem to be similar to their counterparts in analysis; however, the wording "as though he were analysing a geometrical construction" allows a looser analogy, too.

Interpreting the method of analysis as a theory of design leads to the question, whether it is a descriptive or prescriptive theory. Aristotle's wording itself refers to a descriptive account; however, the method of analysis is a prescriptive procedure. Perhaps Aristotle means that expert "deliberators" naturally drift to similar steps as in analysis.

Why was Aristotle concerned with deliberation as it occurs in production? Science of production (*techne*) was one of the three sciences defined by him, all expected to provide information about causes. Aristotle recognized four different causes: efficient, formal, material and final. Now, this account of deliberation may be interpreted as providing explanation on how the final cause comes to be in production. As final cause had the explanatory priority, this was an important piece in the scientific edifice of Aristotle.

Wider questions arising

An account of geometrical analysis and synthesis and of the place given to it by Aristotle in the productive science, as presented above, immediately raises several wider questions. Given the longstanding and wide interest into Aristotle's works, how can the significance of his remark for design theorizing have avoided attention up to now? Why has not the understanding of analysis and synthesis as a precisely defined, ancient method been transmitted to the present day?

That this Aristotle's remark is being focused on only now has its explanation both at the "supply and demand" side. As already mentioned, the interpretation of this remark requires support from other parts of Aristotle's corpus, and its full significance can be grasped only if the method of analysis is understood. This understanding has not been widely diffused through the history. Modern theorizing on design started only in the 1960's. Neither now nor fifty years ago has it been usual to look for Aristotle as a source for theorizing.

The relative disappearance of the original understanding of geometric analysis is due to several factors, which can be only briefly outlined here. Although the method of analysis had been fundamental for the initial development of geometry, philosophy of science (the scientific method) and productive science, all these disciplines failed to maintain understanding on their roots. In geometry and mathematics, the success of the geometric analysis in stimulating further advances, especially infinitesimal calculus, dwarfed Euclidean geometry, and new meanings were given to the term analysis. In natural science, Enlightenment led to an anti-Aristotelian sentiment and the emphasis shifted to empirical studies, from the consideration of classical texts where the geometric roots of the scientific method are explained. In turn, productive science, *techne*, encountered a discontinuation: although productive science was well known in late Antiquity, it was not widely recognised in the Renaissance and fell into oblivion. Altogether, these developments effectively removed understanding on geometric analysis from the public domain.

The current significance of the proto-theory of design

What is the current – rather than historical – significance of this proto-theory of design? This question is examined in four steps. First, we have to settle what we now know about the method of analysis. Secondly, we compare that to the current theoretical landscape of design. Third, we report a case of utilizing understanding on the proto-theory to clarify a current approach to conceptual design. Fourthly, based on all this, we evaluate the proto-theory as a theory of design and draw the conclusions regarding its significance.

What is the method of analysis, understood as the proto-theory of design?

The method of analysis was well known and practiced in Antiquity, but in modern times, the interest has mostly been towards understanding and reconstructing it. Besides Aristotle's and Pappus' accounts, examples of ancient geometric practice (like those presented by Euclid and Pappus) and the interpretation tradition in the Middle Ages (Beaney 2009, Raftopoulos 2003) may give insights to this method. Lastly, current examinations of the method of analysis in mathematics and philosophy of science (for example, Hintikka & Remes 1974, Hintikka 2011, Polya 2004) provide useful directions.

Drawing from these sources (Table 4), although mainly from ancient descriptions, seven features of the method of analysis can be extracted:

Table 4. Justification for the pinpointed features of the method of analysis.

Feature of the method of analysis		*Coverage of the features of the method of analysis in different sources*				
		Aristotle's account of deliberation	*Pappus' account on the method of analysis*	*Mathematical practice, as presented in ancient literature*	*Tradition of interpretation (Beaney 2009)*	*Modern interpretation*
1. Two types of analysis: problematical and theoretical		Problematical analysis implicitly pinpointed	Explicitly described	Commonly found		Described by Polya (2004)
2. Two stages in analysis		Explicit description				
3. Start and end points qualitatively different		Explicit description	Explicitly described	Commonly found		
4. Three types of reasoning in two directions	Regression/ deduction	Explicit description		Commonly found	Scholastic tradition	
	Decomposition/ composition	Explicit description	Explicitly described		Scholastic tradition	
	Transformation			Commonly found (auxiliary lines)	Scholastic tradition	Examined by Hintikka & Remes (1974)
5. The unity of the two directions of reasoning		Vaguely described	Explicitly described	Commonly found		
6. Two strategies of reasoning		Explicitly described for analysis	Explicit description for analysis and synthesis			Discussed by Polya (2004)
7. Two targeted outcomes		Explicit but brief description	Explicit but brief description	*Reductio ad absurdum* as a way of establishing the impossibility of a solution		

1. Two types of analysis: problematical and theoretical.

2. Two stages in analysis: selecting among different means, and completing the analysis regarding the selected means.
3. The qualitative difference between the start point and the end point of analysis.
4. Three types of reasoning in two directions: in analysis, regressive inferences, decomposition and transformation; in synthesis, deductive inferences, composition and (reverse) transformation.
5. The unity of the two directions of reasoning.
6. Two strategies of reasoning: in analysis heuristic and iterative, in synthesis predetermined.
7. Two targeted outcomes: finding a solution or showing that a solution is impossible.

In the following, each of these is described in more detail. For clarity, the same numbering as above will be used throughout the paper.

1. Two types of analysis

According to Pappus, there are two types of analysis: theoretical and problematical. Problematical analysis aims at constructing a wished geometrical figure whereas theoretical analysis aims at proving a theorem. These are, in Polya's (2004) generalised terms, the problem to find (a certain object, the unknown of the problem) and the problem to prove (an assertion true or false).

2. Two stages in analysis

Aristotle states: "if it seems to be produced by several means they consider by which it is most easily and best produced, while if it is achieved by one only they consider how it will be achieved by this and by what means this will be achieved". This suggests that in the common case of several means, there are two stages: first selecting the best means among different alternatives and then completing the analysis regarding the selected means, through a chain of inferences. This feature is related to the general tendency towards economizing. That it is not mentioned by Pappus may be explained by the fact that there is no specific mathematical method in play, rather the question is about a judgment; furthermore, in mathematical problem solving, the need for economizing is not a central issue. Nevertheless, Aristotle seems to have thought that this step of deliberation is also part of the method of analysis.

3. The qualitative difference between the start and end points of analysis

Pappus' description implies that the start and end points of analysis are qualitatively different. Regarding the start point in theoretical analysis, that is the "thing sought", we do not know whether it exists and is true, but assume that. Instead, the end point consists of something admitted, that is, already known. In geometry, axioms and theorems already proven provide a body of admitted things. In turn, synthesis provides the proof that the “thing sought” is existent and true. Correspondingly, in problematical analysis we do not know the “desired thing”, but assume it to be known.

4. Three types of reasoning in two directions

Pappus makes it clear that reasoning in analysis involves inferences backwards and also Aristotle refers to this kind of reasoning in the passage from Nicomachean Ethics. Such inferences backwards are called regressive analysis.

Two other types of reasoning are evident in the interpretation tradition (Beaney 2009) and they can be also deduced from ancient practice. Thus, analysis also comprises transformational aspects, where the original problem is transformed into another form for facilitating its solution (Beaney 2009). In geometric analysis, the use of auxiliary lines is the main form of this type of procedure. Moreover, a decompositional (or configurational) analysis is usually also involved (Hintikka and Remes 1974; Byrne 1997). In geometry, the question is about investigating from which parts (lines, angles, points, etc.) a figure is made up, and which relations exist between those parts.

Regarding synthesis (called proof by him), Pappus says that it is the reverse of analysis. Thus, the three types of reasoning of synthesis are carried out in reverse order compared to analysis.

5. Unity of the two directions of reasoning

According to Pappus, both directions of reasoning are needed: in analysis, backwards for the solution, and in synthesis, forwards for the proof or the construction of the desired figure.

6. Two strategies of reasoning

In Pappus’ description, the method in itself does not provide detailed guidance on which particular moves one should carry out in analysis, except regarding the targeted end point: something admitted which is true or possible or can be done. Thus, analysis is heuristic rather than algorithmic and obviously often leads to an iterative approach of trial and error. In contrast, the synthesis stage is predetermined in the sense that it mirrors the (successful steps of) analysis, even if in reverse order.

7. Two targeted outcomes

Obviously, the main target of an analysis is to find a solution. However, Pappus also claims that the analysis stage can end up showing that a solution to the problem at hand is impossible. Although his wording is laconic and vague, it is reasonable to assume that he refers to *reductio ad absurdum,* a well-known technique in ancient geometry. It creates a proof of a thesis by argumentation that derives a contradiction from its negation (Rescher 2005).

Concluding remark

In summary, it can be stated that these seven features of the method of analysis provide guidance and a flexible methodical arsenal for the geometer on how to approach the task, how to structure it, where to start and where to stop, which are the possible reasoning strategies and moves as well as what to target. It is in this sense that the method of analysis is suggested to provide a proto-theory of design: the thesis is that this guidance and methodical arsenal would apply also to design.

How does the proto-theory compare to the current theoretical landscape on design?

In view of the arguments just made, the crucial question addressed is: Do the features of the proto-theory have similar or analogous counterparts in the current methodical and theoretical landscape of design? Namely, it can be assumed that if the features of the method of analysis are relevant to design, those features would have surfaced in recent methodical and theoretical design literature.

1. Two types of analysis

Briefly stated, the two types of analysis include finding (a solution) and proving (an assertion, say, on the validity of a proposed solution). The main difference of these is that in the former, one endeavours to create a chain of inferences from the problem towards a solution, whereas in the latter a solution is first guessed and then analyzed for its validity. In design literature, analogous approaches have been called problem-oriented and solution-oriented strategies, and it is recognized that completing a design requires the application of both (Wynn and Clarkson 2005). The many stage models of design, some positing that analysis precedes synthesis (Asimow 1962), some that synthesis precedes analysis (Hall 1962), have tried to accommodate and clarify both types, with varying success (it is important to note that in these models the meanings of analysis and synthesis have drastically drifted from the sense these terms are used in geometry).

2. Two stages in analysis

The two stages in analysis, of selecting a means among different alternatives and completing the analysis regarding the selected means, of course correspond to the dichotomy between conceptual design and embodiment/detail design (for example, Roozenburg & Eekels 1995). In the former, one tries to find the best solution in principle; in the latter, one endeavors to translate that into a practical solution. Morphological analysis (Ritchey 2006) and parameter analysis (Kroll & al. 2001) provide examples of approaches that have endeavoured to develop methods for conceptual design.

3. The difference between the start and end points of analysis

The philosopher Schütz (1943) proposed the concept of future perfect in relation to the theory of action: "So we have to place ourselves mentally in a future state of affairs which we consider already as realized…" This proposal, which has been used in the design domain, is similar to Pappus' general description of the start point of analysis: "For in analysis we suppose that which is sought to be already done, and we inquire from what it results…"

However, there is a newer proposal in the design field that comes near this feature. Hatchuel and Weil (2002) take it as their "fundamental proposition" that design reasoning must always make a distinction between two related spaces: the space of concepts and the space of knowledge. A concept (C) is defined as a proposition that has no logical status, i.e., we cannot know whether it is true or false. In turn, propositions in the knowledge space (K) have a logical status, and clearly the most interesting knowledge is what is known to be true. Design is defined as a process by which a concept generates other concepts or is transformed into knowledge. Thus, in the C-K theory, design is conceptualized by its start (C) and end points (K), which have similar characteristics as the start and end points in analysis. The C-K theory expands then knowledge about what occurs between these points.

4. Three types of reasoning in two directions

Regressive and deductive inferences equal, respectively, to backward and forward reasoning, as widely identified in the design domain. As an example, Quality Function Deployment embodies the chain of regressive inferences from the requirements to the product design. Decompositional and compositional inferences refer to breaking down and putting together. Such types of reasoning are often argued to exist in design (e.g. Pahl and Beitz 1996). Indeed, Product Breakdown Structure is a pure application of decomposition. In transformational inferences, the problem is transformed into another problem for facilitating its solution. This idea 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.

5. The unity of the two directions

The Vee model, developed in the framework of systems engineering (Stevens et al. 1998) and recently diffused in software engineering and project management (Forsberg et al. 2005), similarly implies two directions of reasoning.

6. Two strategies of reasoning

The view that the design process is heuristic and iterative, as in analysis, is now wide-spread (e.g. Pahl and Beitz 1996; Hubka and Eder 1987; Cross 2000). However, this was a new idea in the 1980´s, as evident from the observations of many who reported that, in practice, the designers unpredictably move between goals and means, instead of a linear, one-way process (e.g. Cross 2000, Rasmussen et al. 1994). The axiomatic design approach as presented by Suh (2001) represents an attempt to facilitate this heuristic and iterative search through rules. The predetermined deductive process of synthesis, in turn, is present in the right wing of the Vee model.

7. Two targeted outcomes

As all other parts and aspects of the method of analysis are geared towards finding a solution, the interest here in the impossibility of it. In engineering design, it has been found that requirements set based on customer wishes may be unrealistic (Ramaswamy & Ulrich 1993); engineering models are proposed as a means for pinpointing the impossibility of a solution. More generally, a feasibility analysis stage has been suggested (Asimow 1962) for dealing with this issue.

Concluding remarks

Several interesting observations and insights stand out. First, for all the features explicitly, or implicitly, contained in the method of analysis, we can pinpoint modern, corresponding ideas, concepts and methods, many very recently rediscovered (Table 5). This adds to the validity of the method of analysis as a theory of design. Second, without exception, the modern concepts and practices have been forwarded by their originators without any reference to the ancient counterparts – clearly, due to ignorance of them. Further, insights into the breadth and depth of the proto-theory as well as into its use for analyzing the evolution of design methodology can be made – these are discussed below.

Table 5. Proto-theory vs. current theories and methods.

<table>
<tr><th colspan="2">Features of geometric analysis</th><th>Embodied in current methods</th><th>Expanded in current methods</th></tr>
<tr><td colspan="2">1. Two types of analysis</td><td>Problem oriented and solution oriented approaches</td><td></td></tr>
<tr><td colspan="2">2. Two stages in analysis</td><td>Distinction between conceptual design and embodiment/detail design</td><td>Morphological analysis; parameter analysis (expansion of conceptual design)</td></tr>
<tr><td colspan="2">3. Difference between start and end point of analysis</td><td>Future perfect approach</td><td>C-K theory</td></tr>
<tr><td rowspan="3">4. Three types of reasoning in two directions</td><td>Regression</td><td>Quality Function Deployment</td><td></td></tr>
<tr><td>Decomposition</td><td>Product Breakdown Structure</td><td></td></tr>
<tr><td>Transformation</td><td>TRIZ</td><td></td></tr>
<tr><td colspan="2">5. Unity of the two directions</td><td>Vee model</td><td></td></tr>
<tr><td colspan="2">6. Two strategies of reasoning</td><td></td><td>Axiomatic design</td></tr>
<tr><td colspan="2">7. Two targeted outcomes</td><td></td><td>Engineering models (expansion of “proof of impossibility of a solution”.</td></tr>
</table>

Use of the proto-theory for clarification of a current approach to design

In (Kroll & Koskela 2012), research endeavouring to interpret the parameter analysis (PA) methodology of conceptual design (Kroll et al. 2001) through the reconstructed proto-theory of design is reported.

From the viewpoint of parameter analysis, the notions of the proto-theory are found to create added clarity when applied to this contemporary design approach. Especially, they allow interpreting each of the parameter analysis steps separately in terms of the types of reasoning involved. Also it is clarified that reasoning backwards towards a solution and reasoning forwards towards the proof are integrated into one process.

In turn, from the viewpoint of the proto-theory, it is of interest that most features of the proto-theory can be connected to steps or aspects in PA. This, for its part, empirically adds to the validity of the proto-theory. Second, 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 provides 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) could readily be identified when it was compared to the corresponding feature of the proto-theory.

In addition, this research 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. Furthermore, there seem to be steps in PA that do not nicely fall into the proto-theory. Comparison of alternatives belongs 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. This is discussed in the next section.

Evaluation of the proto-theory as a theory of design

In (Koskela 2000), it has been argued that general functions of a theory comprise explanation, prediction, direction (for further progress) and testing (for validity). Furthermore, especially in a managerial science, a theory should also provide the functions of providing tools for decision and control, communication, learning and transfer (to other settings). Due to the novelty of the topic, only a part of these functions can be used as a basis of evaluation: explanation, direction, testing, tools for decision and control and communication.

Explanation

Does the proto-theory provide an explanation on how design can effectively be carried out? If yes, is that explanation better than prior explanations?

The close correspondence of the features of the proto-theory to topics in the current theoretical landscape of design arguably indicates that the proto-theory provides an explanation on design. Some further remarks on the quality of that explanation can be provided.

First, regarding the conceptualization of design, the proto-theory seems to provide a broader explanation than recent design theory proposals, even those with practical success, such as axiomatic design (Suh 2001) or the C-K theory (Hatchuel and Weil 2003). The former deals with the strategy of regressive and decompositional reasoning, for which heuristic (non-proven) rules have been developed. The latter is oriented around the start (C) and end (K) points of analysis (Hatchuel & Weil 2009). In it, the dynamic and interactive nature of the start and end points, concepts and knowledge, is accentuated. By formally representing the start and end points, the space of concepts (C) and the space of knowledge (K), it has been possible to model the revision of object identities in C and the expansion of knowledge in K through four operators, three of which arguably are new. However, despite these advances, both of these approaches orderly cover only one or at most two of the several features of the method of analysis.

Second, this proto-theory can be claimed to be point wise deeper than the present body of knowledge on design. It shows the intellectual origin of such practically used and popular methods as Vee model and Product Breakdown Structure, and gives them an initial explanation by way of a geometric analogue. The theoretical basis for these methods has hitherto been totally missing.

Third, at the outset, the explanation provided by the proto-theory is constrained by any intrinsic differences between the two areas: geometry and design. However, this does not seem to be a serious limitation: in such cases, it is possible to proceed through analogical reasoning towards finding the nearest design counterpart for a geometrical feature as well as to clarify the difference between the two.

Direction

Does the proto-theory give direction for further progress? When comparing current design theories and methods to the proto-theory, an interesting pattern of evolution is initially revealed (Table 5). Many design theories and methods seem to be based on descriptive but somewhat shallow knowledge on some aspect of the design process, equalling one feature of the proto-theory. However, only in such cases where a single feature of the proto-theory has been expanded and operationalised, manifest advances in design theory and/or methodology seem to have been made. Axiomatic design and the C-K theory, as discussed above, provide examples of this.

This leads to the hypothesis that the development of design theory and methodology should concentrate on expanding each feature of the proto-theory, focusing first on those where the theoretical and methodical advances have been meagre, such as “unity of two directions”. Thus, indeed direction for further progress seems to flow from the proto-theory.

Testing

Does the proto-theory allow for testing its validity? As the method of analysis is relatively precisely defined, this should be generally possible. In principle, it would be feasible to empirically test the proto-theory both as a descriptive account (do designers use the seven features in their design activities; to which extent there are activities or aspects that are beyond the seven features?) and as a prescriptive guide (are the design outcomes or the design process improved through the implementation of the proto-theory?). Such studies have not yet been carried out.

However, based on analysis of Aristotle’s seminal remark, the mentioned application of the proto-theory to clarify a current approach, and generally discussed features of design, something can be said regarding the question: Are there limitations related to the method of analysis as a proto-theory of design? At least four important gaps can be discerned.

First, the examples used by Aristotle are on design by one individual, analysis by one mind. However, design is very rarely an activity that is embodied within one individual. Rather, outcomes of design have to be presented to the client, to the producer and to other designers. Each designer needs to persuade others that his output is the best possible in the situation. This interaction, communication and persuasion is not covered by the method of analysis.

Second, the need for plausible (rather than logical) reasoning in design becomes evident for example in the comparison of alternative concepts and solutions. The method of analysis has no means to cover this type of reasoning.

Third, the starting point of analysis is either the task of proving a mathematical theorem or the task of drawing a certain geometrical figure. In both cases, the question is about a self-contained starting point, presented through unambiguous mathematical concepts. Both tasks are universal in the sense that their results are applicable and true everywhere and always. Instead, design is about a particular need of particular user(s). Thus exploration of that particular case is required at the outset of design. Also it is implied that our understanding of a particular case is never complete. The stage of making sense of the particular case in question is missing from geometric analysis.

Fourthly, geometric analysis is about the existence and production of a solution or about the proof. Design, when it comes to esthetical aspirations, is about influencing the audience. This is also missing from geometric analysis.

Interestingly, these gaps (except perhaps the third one) exist also in the theoretical landscape of (engineering) design, if not absolutely, so at least as weaknesses. However, they all point to the need of embracing another ancient discipline into design theorizing, namely rhetoric (Buchanan 1985, Ballard & Koskela 2013, Koskela & Ballard 2013).

Decision and control/communication

Does the proto-theory provide practical tools for design? Does it help in communication? As evidenced in the clarification of the parameter analysis method through the proto-theory, the proto-theory seems to provide a more precise terminology in the field of design, than currently available; this supports communication. But the interpretation of the parameter analysis through the concepts of the proto-theory as such shows that the latter have value in contributing to decision and control in design.

Concluding remark

The conclusion is that the proto-theory fulfills several of the functions of a theory in a superior and fertile way. All in all, it can be contended that this proto-theory is not only of historical interest, but – still – provides a contribution to the theoretical and methodical knowledge on design.

Conclusion: the lessons for design theorizing

Perhaps the most important conclusion for design theorizing is about the significance of history: there has been a fertile legacy for understanding design but it has not been embraced by the movement towards design theorizing that started in the 1960's. It is tempting to draw an analogy to the general history of sciences and philosophy: the forgotten and lost legacy from the Antiquity was reintroduced in Europe during Renaissance and this crucially triggered development towards Enlightenment and the modern period. The intriguing question arises whether we will witness a late Renaissance in the discipline of design. Indeed, if we accept that the proto-theory of design has been rediscovered, we are compelled to see the evolution of design science under a new light. The core theory of design has been missing, and although scholars of design have endeavoured to discover it, the progress has been painfully slow and results fragmented. This missing of the core theory has arguably contributed to the maintenance of disciplinary fragmentation around design. This situation invites sounding whether the proto-theory of design, for its part, could still be used for advancement and unification of design science.

The argument for unified design science is not new. At the outset, there was a unified approach to design and making: the Aristotelian science of production, *techne*. No valid rationale is visible for the current fragmented disciplinary situation in this field, with engineering design, industrial design, systems engineering, new product development and project management having their own communities and knowledge bases. It should be possible to unify the many design disciplines around their common theoretical basis, or at least pinpoint their connections. Indeed, the task ahead is to compile a common conceptual and theoretical core for the various design and production sciences, and to develop associated ways of contextualizing it to specific situations. In this regard, it is interesting to note that the view on the ubiquitous nature of design, as recently highlighted by the initiatives to establish management as a design science (Boland and Collopy 2004), is fully compatible with the original wide scope of *techne*.

Another challenge posed by the proto-theory to current theorizing on design is about the scope of the phenomenon of design. Most current design theories seem narrow in comparison to the proto-theory. On the other hand, the proto-theory cannot be claimed to cover the whole area of design; from Antiquity onwards, it has been contended that there are aspects and stages in design that are best approached through rhetoric. The task of agreeing on the boundaries of the phenomenon of design seems still to be in front of us.

Lastly, the proto-theory renders the terminological problems plaguing the discipline of design visible. The terms analysis and synthesis have maintained a longstanding prestige, and as the understanding of their original meaning has been corrupted, new meanings have been given to them in different knowledge domains. This has led to a fundamental confusion of the role and meaning of analysis and synthesis in design. The current popular understanding in design literature of analysis as a rational stage and synthesis as a creative stage is in direct contradiction with the ancient understanding. In his account on synthesis, Roozenburg (2002) recognises those ancient meanings for analysis and synthesis as they have been transmitted in the philosophy of science, but comments that this use of those words is rather confusing. Unfortunately, it is rather the design field that is using those words in a way that is detached from their historical roots. It is opportune to clarify this confusion, for the sake of the advancement of the field.

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