

## USING PARAMETER ANALYSIS FOR INCORPORATING DESIGN PRINCIPLES DURING CONCEPTUAL DESIGN

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### 1. Introduction

During conceptual design, the exact form or shape of the design artifact is still unknown, impeding a quantitative evaluation of loads, strength, stiffness and material requirements. What is available to the designer are structural design principles, such as the principle of direct and short transmission path and the principle of functional symmetry. These principles can provide useful guidance to the designer when dealing with a product configuration that is not fully defined yet. The layout of the design can be created in such a way as to comply with the design principles, or the principles can be used as criteria for comparing alternative solutions, thus assisting the designer in making choices.

Novice designers often do not use design principles sufficiently due to a lack of knowledge about the very existence of the principles, an inability to identify situations where the application of the principles is appropriate, or difficulty in incorporating the principles even when the relevance is recognized [French 1992a]. In all cases, the problem may stem from the opportunistic nature of the use of principles: There is no methodology for systematically integrating the knowledge embodied in design principles into the design artifact.

To assist all designers in considering design principles, we propose the use of the parameter analysis methodology [Kroll *et al.* 2001]. Parameter analysis formalizes the “natural” way of thinking during design – repeatedly identifying dominant issues at the concept or idea level, implementing the concept as a configuration, and evaluating the design.

The case study presented in this paper demonstrates the steps of parameter analysis that are required for the incorporation of a single design principle, in a similar manner to what is shown in [Condoor and Kroll 2008]. It is anticipated that other design principles can be applied using a similar process. A novice designer can greatly benefit from a formal methodology for incorporating design principles as opposed to merely being presented with a brief discussion about the design principle and a few examples that compare two embodiments with no reference to the development of the design. The experienced designer too may use parameter analysis for the application of design principles and avoid the pitfalls of the opportunistic manner.

### 2. The Principle of direct and short transmission path

Each design principle represents a comprehensive and fundamental doctrine to tackle a certain type of design tasks. Design principles originate as a list of *do*'s and *don't*s based on observations and experience. Over time, they harden into design principles that are applicable to a range of problems within a specified scope. They represent a simplification or generalization of design knowledge. The

principles are useful in defining the task in abstract terms, identifying potential design improvements, synthesizing new designs, and comparing design alternatives.

French [French 1992a] identifies two major problems related to design principles:

1. Design principles are little known and not well developed.
2. In a given situation, it is often difficult to identify and/or apply the relevant principles.

To address these issues, French recommends the documentation of the principles with examples and an emphasis on the circumstances in which it is both appropriate and inappropriate to apply them. He also provides an annotated list of design principles using a simple classification [French 1994].

Holgate [Holgate 1986] emphasizes that design principles, if taken at face value, represent a great over-simplification. According to him, “abstract principles are of some value in helping us to take our bearings when confronted by a problem and give us an idea of the localized influence of certain parameters, as long as we do not forget their inherent limitations.”

The current paper focuses on the principle of direct and short transmission path, which is of paramount importance in structural design tasks. Pahl and Beitz [Pahl and Beitz 1996] state the principle of direct and short transmission path as follows: “If a force or moment is to be transmitted from one place to another with the *minimum possible deformation*, then the *shortest and most direct* force transmission path is the best.” This principle ensures not only the least possible amount of deformations but also the minimum use of material.

The application of the principle of direct and short transmission path relies on a technique called ‘force flow visualization’ or ‘force flow analogy,’ wherein loads are imagined to ‘flow’ through components and streamlines are drawn and labeled. The density of the flow lines indicates the magnitude of the stresses.

It is interesting to note that many books mention the method of force flow visualization and illustrate its use by short, intuitive examples, but they do not present a consistent “theory” of the best methods of drawing the force diagrams. For example, an orderly procedure for identifying critical sections of parts using the concept of force flow is proposed in [Juvinal and Marshek 2000], but the authors propose to determine the force paths by “simple inspection” (page 58). Ullman [Ullman 2003] explains the method with five rules for drawing force flow diagrams and determines the flow line direction at each point according to the maximum principal stress at that location (section 10.2.4). He also offers two alternatives to labeling the type of force on the diagram. French [French 1992d] considers the concept of a force path to be a very useful abstraction, but warns that “the idea is useful, so long as we keep it vague: attempts to express it in precise terms are likely to end in fruitless complexities” (pp. 102-103).

Typically, designs that use the principle of direct and short transmission path avoid bending and exploit uniaxial (tensile or compressive) loading. The uniaxial loads result in a uniform stress distribution irrespective of the component’s sectional geometry, stiffer structures, and efficient material utilization. Thus, applying the principle of direct and short transmission path is consistent with the common design knowledge that *designers should prefer uniaxial loads and avoid bending loads.*

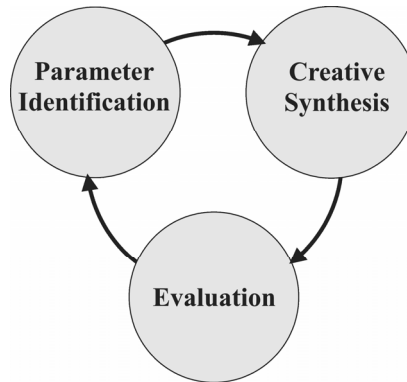
### 3. Parameter analysis

#### 3.1 Overview

Parameter analysis [Kroll *et al.* 2001] is a systematic methodology for conceiving innovative ideas and developing them into workable designs. The parameter analysis methodology emphasizes the discovery of one or a few critical conceptual issues (referred to as ‘parameters’) at a time, calls for implementing these concepts as configurations, and directs the designer to keep evaluating the evolving design to identify new, emerging, dominant issues at the conceptual level. The methodology consists of going through cycles of three distinct steps: parameter identification, creative synthesis, and evaluation (see figure 1).

Every design process must incorporate the three major stages of (1) identifying and analyzing the need, (2) generating concepts to satisfy the need, and (3) evaluating the alternatives to select the best

solution. But while parameter analysis does involve these elements, it should not be confused with the conventional stages of the design process. Rather, parameter analysis takes over after the need has been identified and analyzed and before the designer has selected from among the competing concepts. Parameter analysis is used primarily during the conceptual design stage to develop a concept from a rough idea all the way to a viable embodiment. The three unique steps applied repeatedly during parameter analysis deal with contingent, constantly evolving information associated with the design artifact. At each cycle during the process, the critical issues identified are different, as are the changing configurations and the results of the evaluations.



**Figure 1. Schematic of the *parameter analysis* methodology**

### 3.2 Parameter identification

The first step, *parameter identification*, consists primarily of the recognition of the most dominant issues at any given moment during the design process. In parameter analysis, the term ‘parameter’ specifically refers to issues at a conceptual level. 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. Theoretically, the most significant conceptual issues – the dominant parameters – are identified early in the design process, and as we proceed downstream, we encounter and handle more detailed conceptual issues. However, as design is rarely such a linear process, the progress from conceptual to more detailed parameters is not simply gradual.

When used during conceptual or embodiment design, parameters (i.e., concepts) may include any design principle together with the ideas, at the conceptual level, for implementing them. In the context of the principle of direct and short force transmission path, the parameters deal with issues relating to the directness and length of the transmission path and the relationship between the transmission path and loads, deformations and stiffnesses. Even a simple design can incorporate several transmission paths, and these can vary considerably in their character. The designer can identify critical parameters, i.e. the more important transmission paths – those that may need special attention – using the following guidelines:

- *Directness and length:* More indirect and longer transmission paths are critical, because they usually result in an ineffective use of material and eventual failure.
- *Magnitude:* Forces and moments of great magnitude usually have a greater influence on the success of the evolving design.

During the development of the design artifact, the exact form remains unknown, so it is difficult to address any minute details of the transmission path, particularly at the interfaces between components. It is therefore recommended that the designer identify and attend to major transmission paths first before proceeding to handle their minor features.

### 3.3 Creative synthesis

The second step in parameter analysis is *creative synthesis*. This part of the process includes 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 stimulate new directions for the design process.

Parameter analysis shifts the burden of truly creative activity from creative synthesis to parameter identification, the creation of new conceptual relationships or simplified problem statements, which lead to desirable configurational results. Thus, the task of creative synthesis is only to generate configurations that, through evaluation, will enlighten the creative identification of the next interesting conceptual approach. Each new configuration does not have to be a good solution, only one that will further direct the discovery process.

A design principle plus its implementation concept can serve as impetus for the next creative synthesis step, wherein a physical realization is conceived. Here the designer should create or modify configurations to address the critical transmission path. A transmission path may be made more direct or shorter by strategically relocating components, changing part shapes, re-assigning functions among components, and adding new components.

### 3.4 Evaluation

The third component of parameter analysis, 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 parameter analysis 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 up possible areas of improvement for the next design cycle.

The extent to which the configuration succeeds in achieving the desired effect constitutes a useful criterion for evaluating and/or comparing design alternatives. The designer should systematically identify and map various transmission paths of forces and moments in the evaluation step. This activity provides critical insights into 'when,' 'where,' and 'which' transmission paths are critical. The qualitative analysis is often enough to provide a good understanding of the design. However, the designer may sometimes need to compute the loads experienced by various structural elements.

Any knowledge that exists in the form of a design principle can be incorporated into the design process using the parameter analysis methodology. As opposed to just providing the designer with a list of principles, parameter analysis constitutes a systematic manner by which the principles can be implemented. First, a relevant principle is chosen and, together with a concept for its realization, it becomes the temporal parameter. Next, a configuration is created to embody the parameter, and finally, an evaluation is carried out. The evaluation examines the latest configuration in light of the current parameter, and also against the design requirements and other principles.

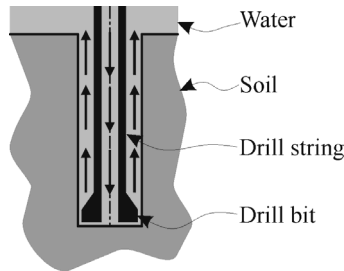
## 4. Case study: running tool design

This section on the conceptual design of a running tool demonstrates the synergy between the parameter analysis methodology and the principle of direct and short transmission path.

### 4.1 Background

The task involves the design of a device known as running tool, used in offshore oil drilling in the unconsolidated soil of the Gulf of Mexico. In a typical drilling operation, the drill string rotates the drill bit against the soil to create a hole (see figure 2). Water circulated through the drill string removes the dirt and cools the drill bit. After reaching the desired depth, the drill string is removed, a casing

(called conductor casing) is inserted into the hole and cemented in place. The casing forms the foundation for the subsea equipment and further tubing by transferring their weight to the soil.



**Figure 2. A schematic of the drilling operation**

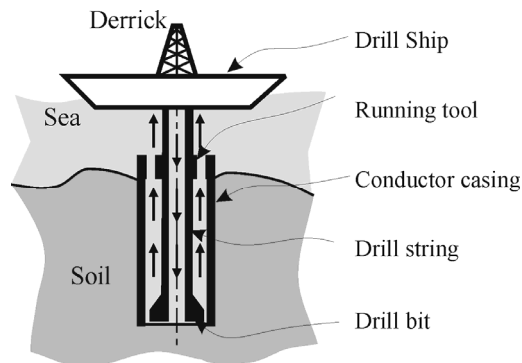
Drilling in loose soils/sands poses two problems:

1. Enlargement of the hole at the top due to the continuous flow of water,
2. Caving-in of the hole when the drill string is removed.

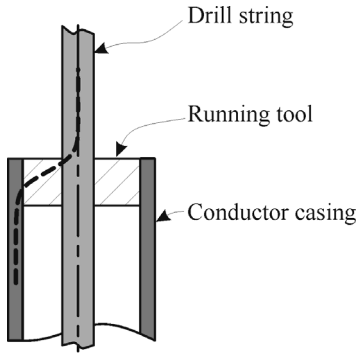
To address these problems, another operation, known as jetting-in, is carried out prior to the drilling operation. In jetting-in, a steel conductor casing (150-300 ft long, 3 ft in diameter, with wall thickness of 1 in.) is attached to the drill string by means of a running tool (see figure 3). The assembly is lowered into the sea and due to the self-weight, it penetrates 30-75 ft into the sandy seafloor. Water is then forced through the drill string and its jetting out of the drill bit creates the hole. Throughout this process, the drill string and the conductor casing do not rotate at all. Once the casing is in place, the running tool is disconnected from it, and the drill string hoisted to the surface for removing the running tool. This operation typically takes three to eight hours at 500-800 ft deep water. Finally, the drill string is reconnected and inserted back into the conductor casing for further drilling.

As the offshore oil rig is expensive to lease and operate, a need exists for a new running tool that allows continued drilling after completing the jetting-in operation, and eliminates the necessity for pulling out the drill string to remove the running tool. Only after completing the drilling, the running tool will be raised back to the surface along with the drill string, so that the conductor casing is open for the insertion of further tubing. The structural requirements for the new running tool are:

1. While lowering the drill string–conductor casing assembly in the water (before hitting the seabed), the running tool must transfer the 60,000-120,000 lb weight of the casing to the drill string (see figure 4).
2. To facilitate the jetting-in operation (penetration into the soil), an additional 30,000-50,000 lb weight is applied to the conductor casing by relaxing the lifting force on the drill string. The force transmission path in this case is shown in figure 5.

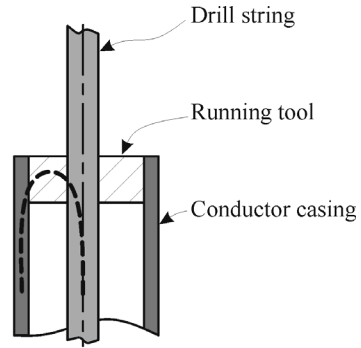


**Figure 3. Offshore drilling (the drill string and conductor casing are exaggerated to show details)**



----- Force transmission path

**Figure 4. The force transmission path for the transfer of the weight of the conductor casing to the drill string during lowering through the water**



----- Force transmission path

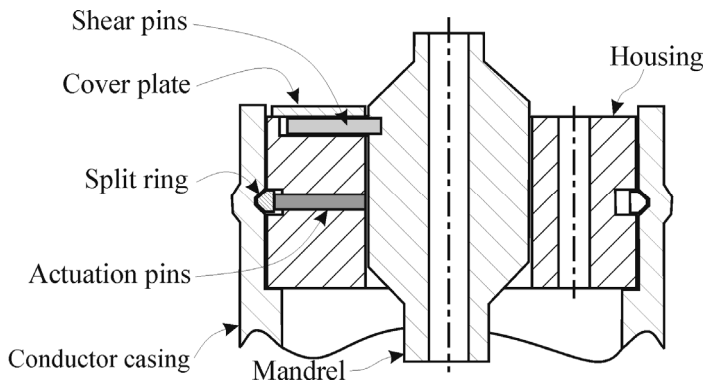
**Figure 5. The force transmission path for the transfer of the drill string weight to the conductor casing during soil penetration**

#### 4.2 Parameter identification #1

The task is to design a running tool that can handle the structural requirements of the jetting-in operation, and disengage the drill string at the start of drilling. The rotary motion, which marks the start of the drilling operation, can be used to disengage the drill string from the running tool. This insight defines our first parameter: “use the rotary motion to disengage the drill string from the running tool.”

#### 4.3 Creative synthesis #1

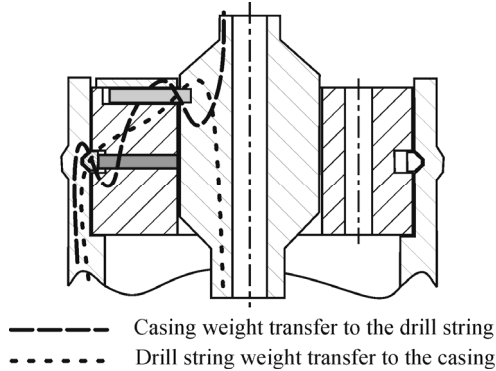
In the initial configuration (see figure 6), the mandrel becomes a part of the drill string. When the mandrel is inserted into the running tool, it forces the three actuating pins radially out. The pins expand a split ring, which in turn engages a corresponding groove in the conductor casing. A setscrew in the housing (not shown in figure 6) prevents the split ring from rotating and potentially binding in case an actuator pin is stuck accidentally in the split ring. Three shear pins are assembled in the mandrel. When the mandrel is inserted into the running tool, they rest in three cavities, and a cover plate is bolted to the running tool from above. The shear pins should withstand the axial loads but break and release the drill string when a predetermined torque is applied to the drill string.



**Figure 6. The initial configuration of the running tool**

#### 4.4 Evaluation #1

We now visualize the two key force transmission paths as shown in figure 7. The weight of the conductor casing travels through the split ring, the running tool housing, the cover plate (through the bolts), the shear pins, and finally, to the mandrel and up the drill string. This force path is very indirect. The second transmission path, wherein the weight of the drill string is applied to the casing, can be traced in a similar manner. Note that while both transmission paths pass through the shear pin, the casing weight force transmission path is more critical as the casing weight is much larger compared to the drill string weight.



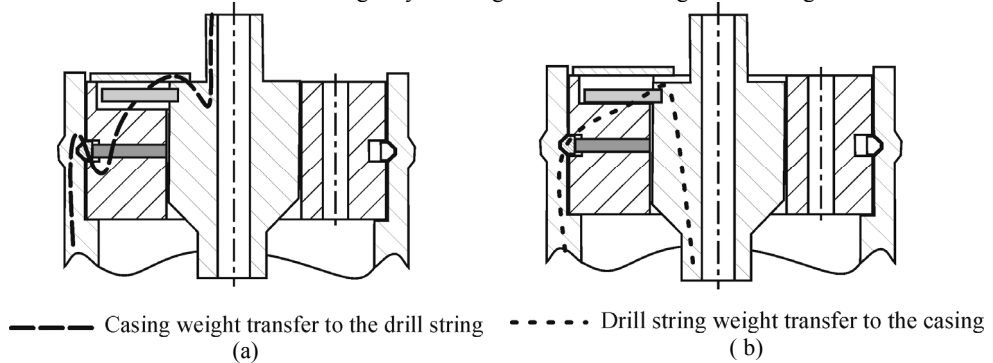
**Figure 7. Load paths in the running tool**

#### 4.5 Parameter identification #2

Recognizing that the large load makes the design of the shear pins difficult, the new parameter for the next design cycle can be defined as “provide a direct load path for transferring the weight of the casing to the drill string, avoiding the shear pins, by furnishing a load transfer interface between the running tool and mandrel.”

#### 4.6 Creative synthesis #2

The modified configuration is shown in figure 8. Here the mandrel is modified to have a flat shoulder and the cover plates are extended inward so they transfer the casing weight directly to the mandrel. Due to the clearance between the shear pins and their cavities, the shear pins are spared from the large force transmission due to the weight of the casing (figure 8a). When the mandrel moves down relative to the casing (figure 8b), the shear pins transmit the weight of the drill string to the casing. Thus, their function is now limited to transferring only the weight of the drill string to the casing.



**Figure 8. Load paths in the modified configuration**

#### 4.7 Evaluation #2

The load experienced by the shear pins is significantly smaller, making the structural design/sizing task easier to handle. The key component in this design are the shear pins which must safely transmit 50,000 lb of force in one direction, and fail under the application of 4,000 ft-lb torque by the mandrel.

#### 4.8 Parameter identification #3

The task poses potentially conflicting design requirements on the shear pins: be strong enough to support a large load but weak enough to deliberately fail when a small torque is applied. Using our understanding of the principle of direct transmission path, we identify a new parameter: “use direct shear for safe load transfer and bending (an indirect load path) to facilitate failure.”

#### 4.9 Creative synthesis #3

The shear pin configuration of figure 9 uses a rectangular section with a stress concentration feature and includes several unique design characteristics:

- During the assembly process, orienting a rectangular cross-section is easy. A circular pin, on the other hand, would have been difficult to orient.
- Direct shear loading is used for the effective transfer of the weight of the drill string.
- When the torque is applied, the shear pins break easily due to the induced bending stresses (indirect transmission path) and the notch (mismatched stiffness). Additionally, the cavities in the housing are shaped in a way that they break one pin at a time.
- The notch is heat-treated to encourage brittle failure.

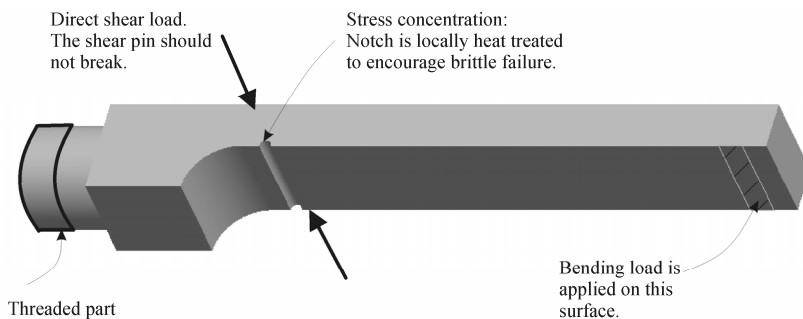


Figure 9. The shear pin

#### 4.10 Evaluation #3

When withdrawing the drill string, the mandrel can potentially reengage the actuating pins on its way up, and prevent the removal of the drill string and the running tool housing from the casing.

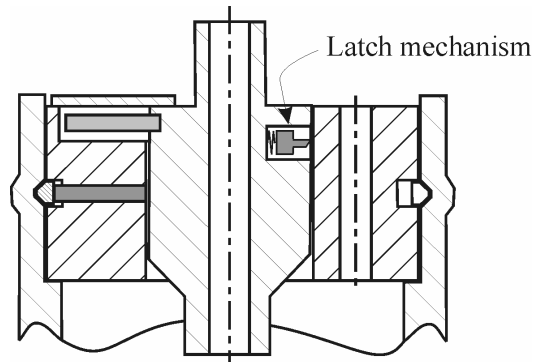
#### 4.11 Parameter identification #4

Because the mandrel might reengage the actuating pins when it enters the housing from below, we can define the new parameter as “prevent the mandrel from reaching the actuating pins during drill string withdrawal by contacting the running tool housing from below and extracting it.”

#### 4.12 Creative synthesis #4

This parameter can be embodied in the form of three latch mechanisms, as shown in figure 10. When the mandrel moves down beyond the running tool during the drilling process, the latches are forced out by the springs. When withdrawing the drill string, however, the latches support and drag the running tool housing while being subjected to direct shear.

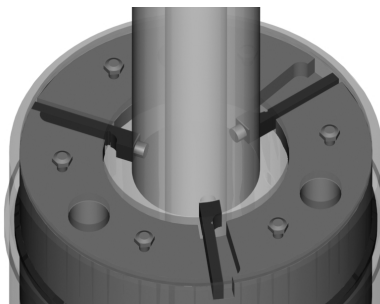




**Figure 10. Configuration with latch mechanism**

#### **4.13 Evaluation #4**

The design effectively eliminates the problem of undesirable reengagement. Several detailed issues, such as sizing the shear pins, retaining the broken pieces of the shear pins, sealing the latch mechanisms, and kinematic design for load transfer, remain and are addressed in the embodiment design. The overall layout at the end of the conceptual design is shown in figure 11.



**Figure 11. Schematic of the running tool with a set of three shear pins**

## **5. Conclusion**

Design principles represent a vast amount of knowledge in succinct qualitative statements. In spite of the importance of design principles, there is no general procedure for using them during the design process. This paper has presented parameter analysis as a systematic design methodology for incorporating design principles in general, and the principle of direct and short transmission path in particular. Other design principles that may be handled similarly include the principle of self-help, the principle of division of tasks, the principle of matched deformation, and many others. As parameter analysis follows the “natural way of thinking,” it is suitable for the incorporation of design principles during conceptual or embodiment design, and may be beneficial to both experienced and novice designers, helping them to avoid omissions of important considerations by organizing the thought process.

This paper has shown parameter analysis to be a rational tool for increasing the effectiveness of designers by guiding them in integrating the abstract knowledge of design principles in a meaningful way. Instead of blindly adhering to the principles, the designer who uses parameter analysis is in charge of identifying and prioritizing among the relevant principles, particularly in the parameter identification steps, making compromises as needed in the creative synthesis steps, and assessing the evolving designs for their conformance to the design principles in the evaluation steps.

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