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STRUCTURED CONCEPT DEVELOPMENT WITH PARAMETER ANALYSIS

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ABSTRACT

The popular systematic design process model prescribes functional decomposition and morphology as the main method for accomplishing the conceptual design phase. This approach exhibits some weaknesses, which are discussed and demonstrated with an example from a design textbook. It is shown that the method of functional decomposition and morphology requires the difficult task of creating a function structure, generates product concepts in an inefficient breadth-first manner that may also lack quantification, and most of all, does not offer a step by step mechanism for *developing* the concept, as opposed to just *generating* it. An alternative methodology, called parameter analysis, is proposed. It presents a more natural and efficient way of not only generating initial concepts, but also developing the concepts in a structured manner all the way to a viable conceptual design. The same example is used to show how parameter analysis focuses the designer's efforts on the most critical aspects of the evolving design and combines repeated cycles of conceptual level reasoning, configuration development with quantitative thinking, and critical but constructive evaluation.

Keywords: Parameter analysis, systematic design, function analysis, functional decomposition, morphology

1 INTRODUCTION

Systematic design is a rational model of the engineering design process that originated in Germany [1-3], with many British [4-6] and American [7-9] adaptations in engineering design textbooks. The model prescribes a sequence of major stages for the design process (clarifying the task, drawing the specifications, conceptual design, embodiment design, etc.), and offers various tools for each stage. Many researchers and practitioners use this prescriptive model, which has also been adopted in software engineering as the "waterfall" or linear sequential model [10] and in systems engineering as the stage-gate model [11]. Over the last few years there has been considerable criticism of this design process model [12]. Most critiques claim that the method is not used by expert designers, fails to capture the dynamics of the design process, and may adversely affect innovation. Some alternative models have been proposed, such as the co-evolutionary model, in which the requirements and solution evolve simultaneously [13,14], and systems engineering's spiral model, which calls for revisiting the same stages over and over again [10].

Of particular interest to the current paper is what systematic design offers as the method for the conceptual design stage: functional decomposition + morphology. Under this scheme, the main function of the artifact is decomposed into finer and finer subfunctions, constituting a "function structure", solution principles (we shall call them "subconcepts") are sought for each subfunction, and finally, the subconcepts are combinatorially assembled to form multiple overall design concepts. Searching for solution principles for the subfunctions is done by various creativity methods (e.g., brainstorming and TRIZ), internal (for example, analogical thinking) and external (expert consultation, patents, etc.) searches. The listing of subfunctions and their corresponding subconcepts is done with a morphological chart or matrix. This method is quite popular in university design classes due to its structured character and ease of use. A generic systematic design process model is shown in Figure 1.

There are several weaknesses in the functional decomposition + morphology method: the development of the function structure is difficult, the breadth-first nature of the reasoning process is inefficient, and the concepts developed lack quantification in most cases. However, there is an even bigger problem with the method, that of the absence of a step by step structured design process to lead the designer through developing the overall concepts into viable conceptual designs that are suitable for a selection process such as Pugh's [4].

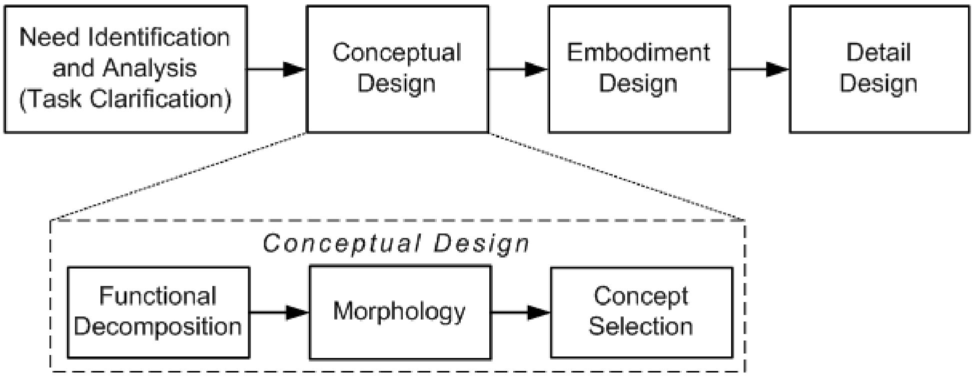


Figure 1. A model of systematic design with the conceptual design stage expanded to its constituent steps.

It might be argued that some of these weaknesses stem from the blurry border between conceptual design and the next stage, embodiment design. It seems that in most cases, conceptual design encompasses only the *generation* of abstract product concepts, while most concept *development* is left for the embodiment design stage. But for concepts to be evaluated, they need to be developed and proven viable first, and a process for doing so is much needed, whether it is labeled conceptual or embodiment design.

Pahl *et al.* [3], in section 6.6 of their book, demonstrate the conceptual design stage with several examples that emphasize the generation of function structures, the search for solution principles, and the combination of principles to form overall product concepts ("solution variants"). However, close examination of their examples (the one-handed mixing tap and impulse-loading test rig) shows a gap between the crude and abstract sketches in the morphological chart and the subsequent highly detailed solution layouts. Admittedly, Pahl *et al.* say that concept variants must be firmed up – given concrete qualitative and rough quantitative definition – before they can be evaluated, so the detailed drawings may refer to a much later stage in the design process, probably after embodiment design. The coverage of embodiment design in [3] accounts for about one-third of the book, and lists many rules (e.g., clarity, simplicity), principles (for example, short and direct force transmission path, self-help) and guidelines (design to allow for expansion, design for assembly, etc.). However, there is no clear process for carrying out this stage of design, except for mentioning that the methods should be similar to those used during conceptual design.

Other textbooks that teach systematic design follow a similar approach. Ullman [9] warns against the danger inherent in the morphological approach, of producing "Rube Goldberg" type of designs, whereby each function is independently realized in a separate piece of hardware. However, the basic methodology is still the functional decomposition + morphology for generating abstract concepts, which are then evaluated against each other, and the selected concepts are developed further in the embodiment design stage (called "product generation" in [9]) in terms of form, materials, manufacturing and assembly. Otto and Wood [7] and Ulrich and Eppinger [8] go from concept generation directly to concept selection, leaving the development of the concept to later stages that deal with product architecture, industrial design, design for manufacturing, etc. Like other authors, and indeed as also originally intended by Pugh [4], both books mention that concept selection should be carried out multiple times during the product development process, and used not just for screening but also for improving the design. Yet, the selection itself is demonstrated immediately after the concept generation stage, dealing with concepts whose development process is not explicitly shown.

We propose here another methodology for generating and *developing* concepts that follows more closely the natural way of thinking by designers. It replaces the formal functional decomposition + morphology method with a more intuitive stage of identifying and assessing the core technologies at the heart of the design (we call it "technology identification"), and adds a prescriptive design model of concept development ("parameter analysis") that takes place *before* the concept selection stage.

The structure of the paper is as follows: We first elaborate on some shortcomings of the functional decomposition + morphology model. Next we describe an example from the literature that is typical of how conceptual design is presented in design textbooks. The introduction of our technology identification + parameter analysis methodology follows, and the previous example is reworked in terms of the proposed scheme. Finally, a discussion shows the benefits of the new concept development methodology.

2 FOUR WEAKNESSES OF FUNCTIONAL DECOMPOSITION + MORPHOLOGY

2.1. Developing the function structure

This is a relatively difficult and time consuming task. Designers are often reluctant to make the required effort here instead of proceeding quickly to synthesizing a solution. The ability of designers to think in abstract terms and carry out a solution-independent functional decomposition is questionable. Moreover, in real life, some functions can only be discovered in the context of a particular solution. Such functions cannot be identified during the initial functional decomposition activity, but should be considered by the designer later in the process. In spite of many attempts to formalize the functional decomposition process [15], it seems that different designers will almost always come up with different results; something that is completely reasonable in design in general, but surprising when it comes to a rigorous analysis method that is independent of any particular solution.

2.2 Breadth-first reasoning

It has long been known that humans cannot consider and process more than a few items of information simultaneously. The systematic design method treats all the intended product functions equally, listing them in the same chart and seeking solution principles for each of them. This may distract the designer from concentrating on the most important functions first, which may be much more efficient.

2.3 Lack of quantification

Ultimately, the systematic design method calls for comparing the conceptual designs against each other using a formal concept selection process, which consists of assigning rough grades for the concepts against various criteria. However, the evaluated concepts are often just sketches whose performance cannot be readily rated, and sometimes they cannot even be proven viable. This problem may stem from the unclear boundary between the conceptual and embodiment design stages. Most advocates of systematic design include only concept generation by functional decomposition + morphology in conceptual design, resulting in just sketches and hardly any quantifying data. The process model then calls for selecting the best candidates among these concept sketches, and carrying those selected into embodiment design.

2.4 Getting from the subconcepts combination to the final concept

Perhaps the main weakness in systematic design is that there is no process for converting the collection of abstract subconcepts derived by the morphology into a well-developed, viable conceptual design that can be evaluated against the design requirements and other concepts. In most cases, it is quite easy to show that the final product concept contains a certain combination of subconcepts from the morphology, but the reverse is not true: given a subconcepts combination, how do you generate a good overall conceptual design? This is certainly not a “one step” process, and the nature of design as a gradual development through repeated refinements and additions of attributes has long been recognized.

3 BILGE PUMP EXAMPLE FROM THE LITERATURE

The following example is taken from a design textbook [7] and used here to demonstrate the major points of this paper. We do not intend to criticize the quality of the design example, nor do we pretend to be familiar with all its aspects. We only use the information available in the book.

Figure 2 is the function structure developed for a device to remove water from the bilges of unattended boats by using natural energy sources. The design requirements included a minimum of 8 L/hr of water removal capacity, size of less than 1 m^3, and cost of less than $50. Next, the subfunctions of Figure 2 were entered as the first column in a morphological chart, and solution principles for each subfunction were sought and entered too. A portion of this chart is shown in Figure 3. Several combinations of overall product concepts are formed by selecting subconcepts in each row of the chart. One such combination consists of the marked items in Figure 3, leading to the product concept

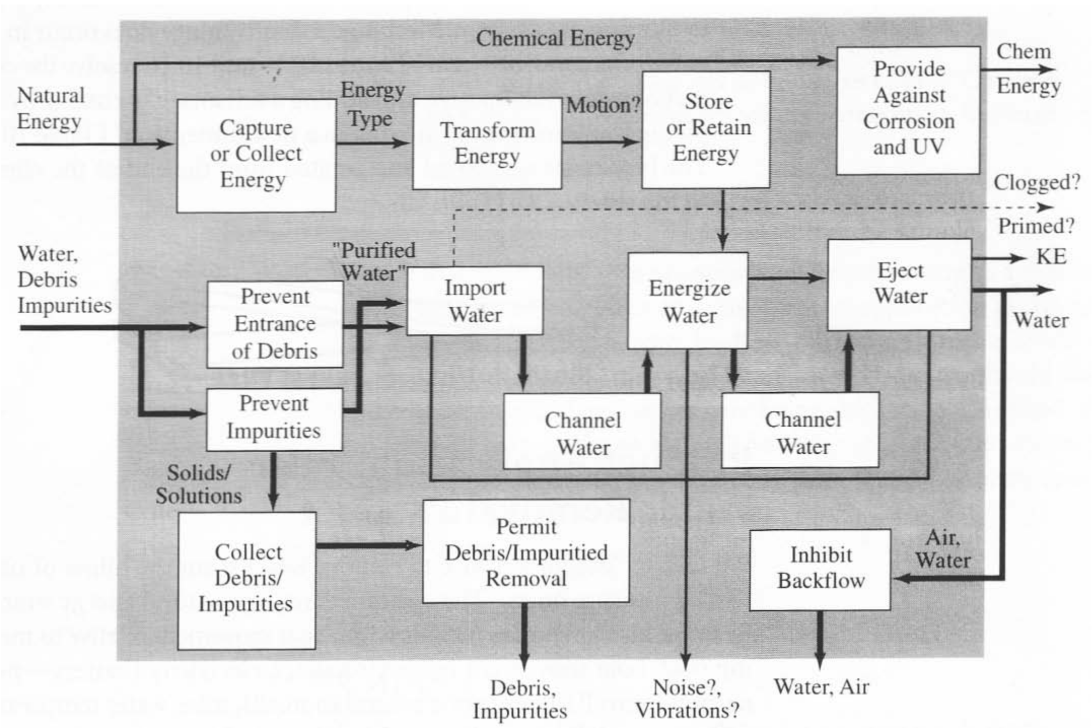
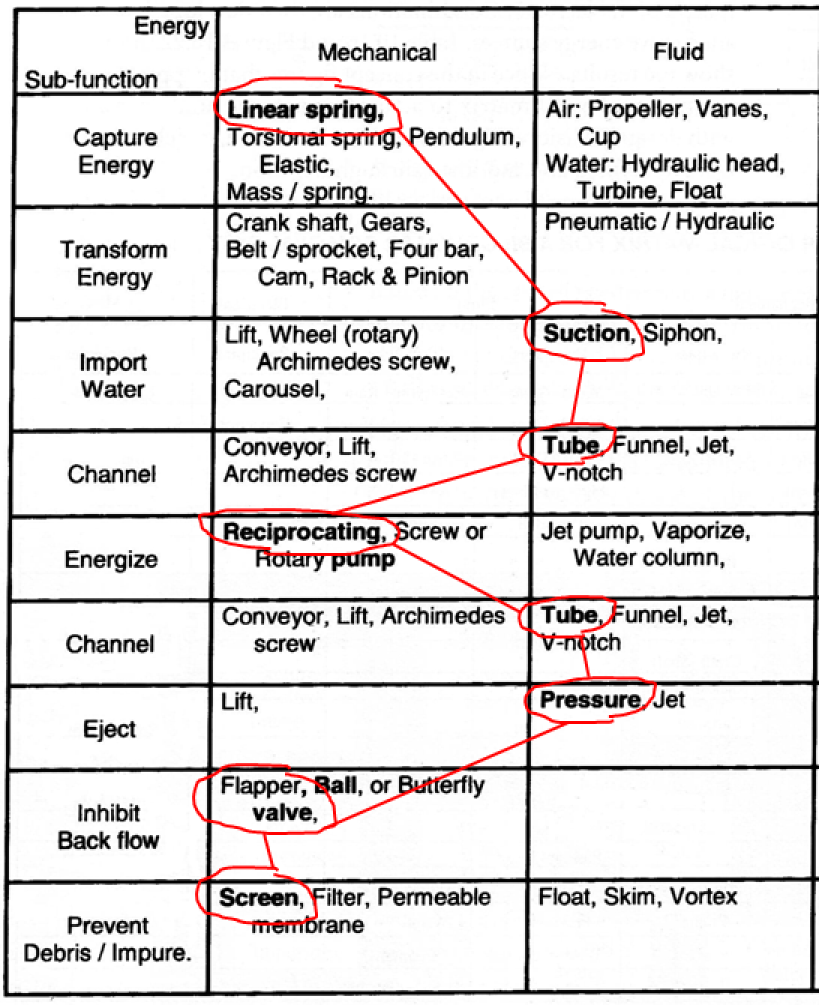


Figure 2. The function structure for the bilge pump [7]



Energy / Sub-function	Mechanical	Fluid
Capture Energy	**Linear spring,** Torsional spring, Pendulum, Elastic, Mass / spring.	Air: Propeller, Vanes, Cup Water: Hydraulic head, Turbine, Float
Transform Energy	Crank shaft, Gears, Belt / sprocket, Four bar, Cam, Rack & Pinion	Pneumatic / Hydraulic
Import Water	Lift, Wheel (rotary) Archimedes screw, Carousel,	**Suction**, Siphon,
Channel	Conveyor, Lift, Archimedes screw	**Tube**, Funnel, Jet, V-notch
Energize	**Reciprocating,** Screw or Rotary **pump**	Jet pump, Vaporize, Water column,
Channel	Conveyor, Lift, Archimedes screw	**Tube**, Funnel, Jet, V-notch
Eject	Lift,	**Pressure**, Jet
Inhibit Back flow	Flapper, **Ball**, or Butterfly **valve,**	
Prevent Debris / Impure.	**Screen**, Filter, Permeable membrane	Float, Skim, Vortex

Figure 3. A portion of the morphological chart for the bilge pump [7]. We added the markings of one combination of subconcepts

of Figure 4. It includes using the boat movement relative to a mooring post as the energy source, capturing this energy by storing it in a linear spring, which drives a reciprocating pump. The pump produces suction and pressure to move the water through a screen filter, tubes and flapper valves. Other combinations led in the original example to several other concepts that were shown as sketches similar to the one in Figure 4.

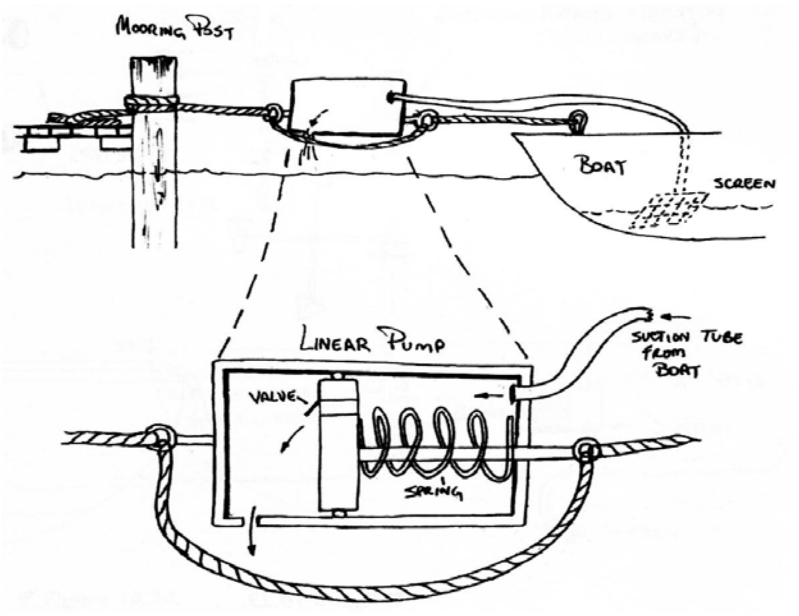


Figure 4. One concept for the bilge pump that uses wave energy [7]

Let us examine this example in depth. We can see in Figure 2 that the function structure is not at all trivial, and that it is quite complex for a relatively simple design task. It includes five subfunctions (those with "water" as the noun) that together describe what engineers call "a pump". It also includes subfunctions that may not be essential, such as "transform energy", as becomes clear from examination of Figures 3 and 4. On the other hand, it is unclear why the subfunction "permit debris/impurities removal" was generated and not "remove debris/impurities". It is also interesting to note that the function structure of Figure 2 led, in the case of the design of Figure 4, to actually designing a reciprocating pump from scratch, while another concept generated in the original example [7] and not shown here used a rotary pump as an off-the-shelf item.

Figure 3, which is just a portion of the complete morphological chart, raises other issues. The chart contains a wealth of information, which might be difficult to process simultaneously in the designer's mind. All the subfunctions are listed as equal entities, so the designer needs to think about major issues, such as how to capture the mechanical energy (e.g., boat motion on the waves) and what type of pump to use, together with marginal concerns, such as moving the water from one location to another ("channel" subfunction) and filtering the water flowing into the pump. Moreover, some solution principles, or subconcepts, seem superficially forced: a pump is the obvious solution to this design problem, yet the chart lists subfunctions of the pumping action ("import water", "channel", "energize", "channel" again and "eject"), which are not straightforward. It may also lead to combinations of subconcepts, such as using a pump to "energize" the water together with two Archimedes screws to "channel" the water, which seem illogical. In fact, an Archimedes screw is a pump by itself, so there might not be a need for the "energize" subfunction at all.

As with most textbook examples of conceptual design by functional decomposition + morphology, the concept generated in Figure 4 lacks quantification at this stage, but is nevertheless considered ready for a formal selection process. Admittedly, the original example [7] has some analysis associated with it, but this was done later, under the title of "concept embodiment".

While this example is quite simple, we should also question the ability of a designer to generate a design such as shown in Figure 4 "in a single pass". Suppose the designer generated the marked combination on the morphological chart of Figure 3. Was the sketch of Figure 4 a direct result of the verbal description of the subconcepts combination, or was there an iterative effort that culminated in

Figure 4? We believe the latter is the case, but nowhere in systematic design textbooks there is a formal process for developing the subconcepts combination into a concrete embodiment.

4 A MODIFIED CONCEPTUAL DESIGN PROCESS MODEL

We propose the model shown in Figure 5 for the conceptual design stage. It consists of two new blocks compared to the process model of Figure 1, with the parameter analysis block further elaborated by explicitly showing its three repeated steps, as explained below.

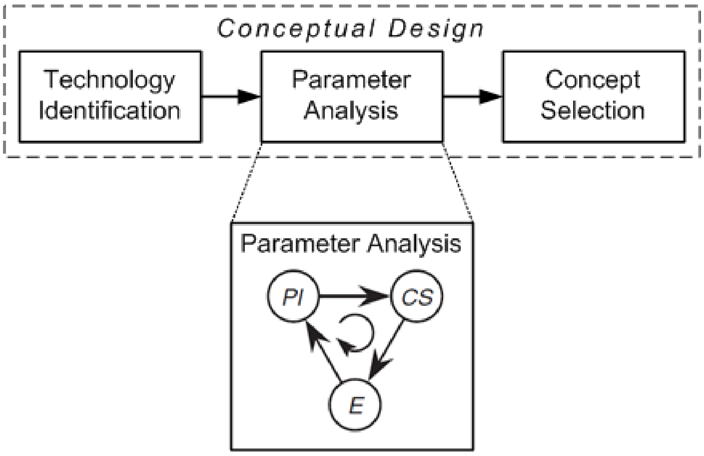


Figure 5. Process model for conceptual design by technology identification and parameter analysis (PI = parameter identification, CS = creative synthesis, E = evaluation)

Parameter analysis [16-18] is a structured methodology for conceiving innovative ideas and developing them into workable designs. It is preceded by a stage called “technology identification”, which 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. Often, several such core technologies, or physical principles, can be used in a particular design. Technology identification plays a similar role to functional decomposition + morphology, except that it focuses on the working principles for the most important function of the designed artifact, and ignores the less significant aspects. A cursory listing of each candidate technology’s pros and cons is usually all that is required at this stage to allow the designer to pick the one that seems most likely to result in a successful design.

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, that facilitate the back and forth movement between concept space and configuration space (Figure 6).

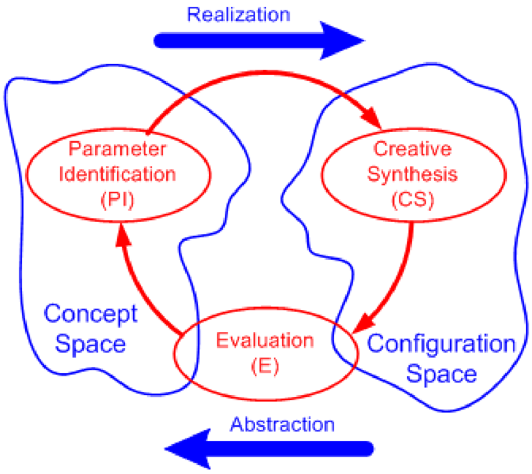


Figure 6. Parameter analysis process model with concept and configuration spaces

Parameter identification consists primarily of the recognition of the most dominant issues at any given moment during the design process. The "parameter" 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 parameter analysis is *creative synthesis*. This part of the process includes the generation of a representation 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.

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.

Parameter analysis shifts the burden of truly innovative activity from creative synthesis to parameter identification, the creation of new conceptual relationships or simplified problem statements, which lead to desirable configurational results. Thus, the task of creative synthesis is only to generate configurations that, through evaluation, will enlighten the creative identification of the next interesting conceptual approach. Each new configuration does not have to be a good solution, only one that will further direct the discovery process. More explanations about parameter analysis and detailed application examples can be found in [16].

5 APPLYING PARAMETER ANALYSIS TO THE BILGE PUMP EXAMPLE

To demonstrate the generation and development of concepts with parameter analysis, we hypothesize the design process elaborated in Figures 7 and 8. It begins with a technology identification step (Figure 7) wherein the main problem is identified (capturing natural energy) and some energy sources are evaluated. The boat's motion relative to its mooring post is selected as the most promising starting point. The chosen technology serves as the initial parameter, or concept, in the parameter analysis process of Figure 8.

6 DISCUSSION

Technology identification is used instead of functional decomposition + morphology to generate concepts. However, these are not overall product concepts but rather, concepts for the core operating principle only. This ensures that the designer is focused on the main issues of the design, and is not distracted by minor aspects that are left to be handled later. In the bilge pump example, the designer assumed that the actual pumping action of water was a straightforward issue, because he or she was acquainted with many such devices. The challenging aspect of the design was determined to be the selection of a natural energy source and capturing that energy. A quick survey of the options with some evaluation of their potential was carried out, and the most promising concept chosen. Sometimes, deeper investigation is needed to come up with the suitable technologies or for evaluating their pros and cons, but this usually should not go beyond what is necessary for identifying the preferred core concepts. If more than one alternative conceptual design is to be developed, or should parameter analysis fail to produce an acceptable design, other options from the technology identification step would be chosen as starting points for new concept development.

The gap demonstrated earlier between the concept of Figure 3 and the conceptual design of Figure 4 was closed by the structured parameter analysis process as demonstrated in Figure 8. This is obviously a hypothetical outline of one thought process that could take place, and not a factual description of what really transpired. However, it demonstrates an effective methodology for concept development that starts with an initial idea regarding the core technology of the design, and proceeds by repeatedly

Technology Identification:

The actual pumping of water out of the bilges of boats is an easy problem. The difficult task is to capture the required energy from a natural source. We can use:

** Solar energy (photovoltaic array)*
** Wave energy*
** Wind energy*
** Energy from falling rain*

Solar energy isn't available all the time, so we'll need to charge batteries, which will drive an electric motor to power the pump. Also, the solar panels may need to be aligned with the sun. The cost of all the equipment may be prohibitive. Wave energy can be captured directly from the waves, with a float-like device, or using the boat's motion due to waves to energize a mass. The boat will move horizontally and vertically. It's not trivial to capture this energy, but it may work. Wind energy is relatively easy to capture, but may require a large turbine to produce enough power. The size of the energy-capturing device may be problematic. Falling rain drops have kinetic energy when they hit the boat, but it doesn't feel like there will be enough energy to produce the required pumping power. Besides, how do we capture this energy?

The most likely candidate to result in a viable design seems to be wave energy. Let's try this first, using the boat's motion relative to the mooring post. If this fails, we can try the boat's vertical motion or the wind energy option.

Figure 7. A hypothetical technology identification step for the bilge pump

identifying important conceptual-level issues, implementing them in an evolving configuration, and evaluating the design for proper functioning and against the requirements. As opposed to the breadth-first nature of morphology, parameter analysis is clearly a depth-first process, handling at any given time just one or a few issues that are judged to be the most important. In the bilge pump example this naturally led to establishing the working principle for capturing wave energy first, followed by producing pumping action, controlling the flow direction, and finally filtering and installation issues.

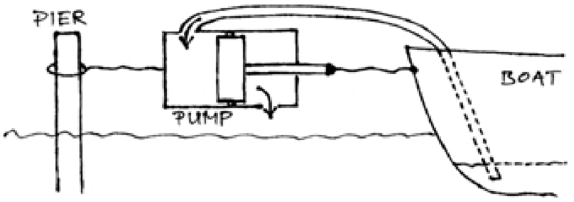
When compared with functional decomposition + morphology, it can be seen that parameter analysis seeks conceptual solutions in the relevant context of the evolving design, and does not involve proposing a plurality of working principles that might not make sense when implemented together. Instead of functional and conceptual reasoning only at the beginning, parameter analysis prescribes evolutionary implementation of concepts as configurations, together with rough, back-of-the-envelope calculations, to the extent that allows evaluating the design along its development. Quantitative information about the design is a must to also prove its viability and to compare alternative conceptual designs in a formal selection process.

7 CONCLUSION

Weaknesses of the functional decomposition + morphology method of conceptual design were explained and demonstrated with a representative textbook example. The biggest shortcoming was shown to be the lack of structured development process for the conceptual design, after generating the product concept by morphology. An alternative was introduced as technology identification + parameter analysis, which is a very different process by nature. It is more focused on the main issues and explores them depth-first. It combines analysis, synthesis and evaluation into repeatedly applied cycles within which the designer's thought process alternates between concept space and configuration space. This method is very useful in teaching engineering design and becomes a second nature for practitioners.

PI: Use the boat's horizontal motion on the waves relative to the pier to move a piston in a cylinder to generate pumping action.

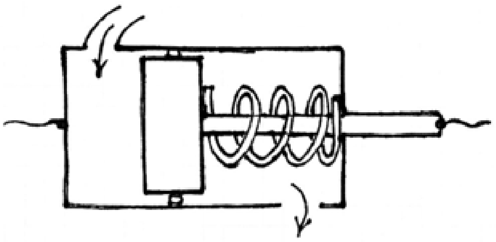
CS: A piston-in-cylinder type of reciprocating pump is attached by ropes between the pier and the boat. When the boat moves away from the pier, the piston creates suction on one side and pressure on the other side, so the bilge water can be removed from the boat.



E: What happens when the boat moves towards the pier? The ropes can't transmit compression, and the piston needs to move back and forth inside the cylinder.

PI: A spring can be used for a restoring force.

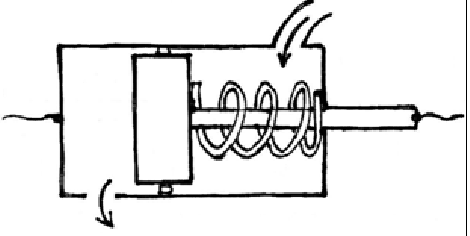
CS: A spring is added, so that it's compressed when the boat moves away from the pier, and released on the way back.



E: The boat movement away from the pier may be too slow to produce enough suction due to the spring's resistance. In other words, only some of the boat's energy will be used for pumping the water, as some energy will be stored in the spring.

PI: Capture all the boat's motion as elastic energy, and use it for pumping water when the spring is released.

CS: The suction and ejection sides of the pump are reversed. When the boat moves away from the pier, the spring is compressed. When the boat moves towards the pier, all the spring's energy is used for pumping water from the boat and ejecting it.



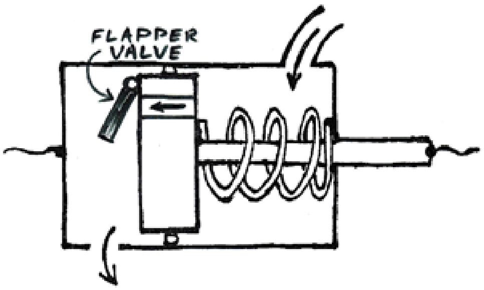
If we set the stroke of the piston to 50 mm, and its diameter to 30 mm, then the volume displaced per stroke is ~35 cm^3. The required throughput is about 8 L/hr ≈ 2 cm^3/s. The pump will actually move water only when the spring returns the piston, so let's assume this happens during 1/4 of the time. This means that we need a complete stroke of the piston every 4 to 5 seconds.

E: The dimensions of the pump seem small enough, but the water entering the pump needs to be transferred to the other side of the piston so it can be ejected.

PI: Add a one-way valve in the piston to allow passage of water when the piston moves to the right.

Figure 8. A hypothetical parameter analysis process for the bilge pump concept development (continued on next page)

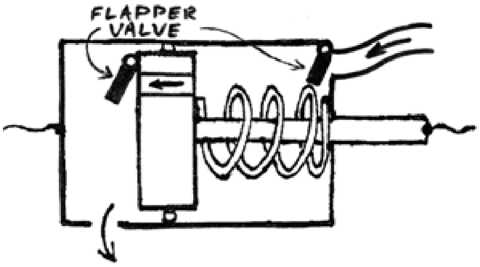
CS: A flapper valve is added:



E: When the piston moves to the right, there may be a back-flow of water from the pump to the boat.

PI: Add a one-way valve to the pump's inlet.

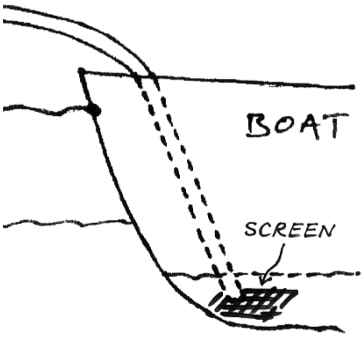
CS: Another flapper valve is added:



E: Debris/impurities may be pumped and clog the pump or interfere with the operation of the valves.

PI: Filter the water at the hose inlet.

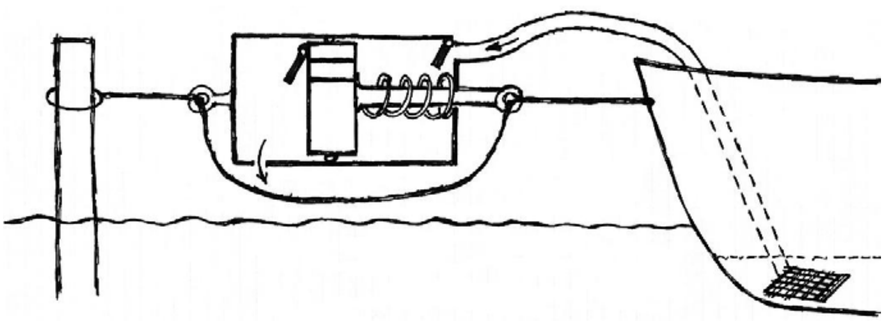
CS: A screen is added:



E: Cutting the rope between the boat and pier to install the pump is difficult and inconvenient.

PI: The rope doesn't have to be cut. The pump can be connected to 2 points on the rope with a slack between them.

CS: Suitable anchoring hooks are added.



E: This concept seems to work.

Figure 8. (continued)

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