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Morphological Analysis (MA) leading to Innovative Mechanical Design

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1 Introduction

In this paper we apply Morphological Analysis (MA) to a conceptual design where the designer is attempting to exhaustively search a manageably defined design space in order to select the most appropriate (innovative) design solution.

The morphological approach has not yet been fully developed or extensively applied. A common view is that MA is simply the “morphological box” as it is sometimes called. In our view morphological analysis is a methodology to be applied creatively, adapting and modifying it to meet the requirements of the problem on hand. The essence of the methodology is that the designer should be looking for new opportunities and for contradictions, and be prepared to modify a previously defined exhaustive morphological procedure as new information surfaces.

In our case study the initial search was to find all the ways to assemble the basic elements of down-hole water lifting piston pump. As we adaptively applied MA, we recognised that there were more sophisticated assemblies of the basic elements and we generated the down-hole pump patents of over 100 years as well as some configurations that were not found in the patent literature.

2 Background and Literature about Morphological Analysis

Many of the textbooks on engineering design process give a basic introduction to what earlier advocates of the morphological method proposed (Ullman, 2003; Otto and Wood, 2001; Cross, 2000; Dym and Little, 2000; Wright, 1998). These texts present it as a creative method for generating alternative solutions to a design problem. They illustrate the method by describing an example or two where a list of functional requirements (FRs), sub-problems or concept sub-modules are listed on one axis (say the vertical axis) of a matrix whilst variants satisfying each of these FRs, sub-problems or sub-modules are entered along the other axis. The designer then trials design solutions comprising various combinations, judiciously chosen, constructing them by taking one element from each row.

Some authors (Pahl and Bietz, 1996; Hubka and Eder, 2000; Dieter, 2000; Roozenburg an Eekels, 995) offer a broader view. French, (1999) has an entire chapter, Combinative Ideas, on this area. French gives a range of interesting examples demonstrating some broader applications of morphological method, unfortunately without mentioning the word morphology.

The word morphology derives from the Greek word morphé meaning “form”. Plato and Aristotle effectively employed morphological principles in their descriptions of the animal kingdom. Goethe, in the late eighteenth century, described the structural interrelationships between things as morphology. According to the Darwinian biological evolution theory, continued improvement of species results from advantageous genetic mutations. This theory suggests a model for the processes of technological design, where morphological examination of designs can identify superior mutations.

“Morphological analysis performs a systematic exhaustive categorization and evaluation of the possible alternative combinations of sub-capabilities which may be integrated to provide a given functional capability”, (Martin, 1994).

One of the best known examples of a morphological box is the Chemical (Mendaleev) Periodic Table. The orderliness of this table (increasing atomic number and shell completion) enabled the discovery of “missing elements” and facilitates the learning of the properties of the families of elements.

Zwicky (1969) is widely cited by design process authors in connection with morphological method. His goals were to expand the search space and to safeguard against overlooking good novel solutions to a design problem. Zwicky had a deeper view underlying his proposal of morphological analysis as a basis for discovery, invention and research. He proposed that all facts should be thoroughly investigated and properly appraised for the purpose of selecting the things among them that best satisfy our requirements. Zwicky states:

“the morphologist must never lose sight of the continuity of all things, all phenomena and all concepts and all mental outlooks… nothing should be discarded as unimportant… the morphologist will persevere where others have long since given up the effort”.

Zwicky also gives examples of different classes of morphological method. His first category is described as “Systematic Field Coverage” by which, as an example of the method, he generates all five possible regular polyhedra: tetrahedron, octahedron, icosahedron, cube and dodecahedron, finally demonstrating the impossibility of constructing regular polyhedra from regular polygons having more sides than the pentagon by demonstrating that the hexagon tiles a flat plane.

In Zwicky’s second category he introduces the morphological box (matrix) and in exemplifying this category gives a 10 X 10 matrix of energy transformations where a_{ij} represent energy transformations from one form to another (eg. elastic energy into kinetic energy). Under each energy conversion heading he then outlines historical information and examples of that particular type of energy conversion.

Zwicky also illustrated third, and final category, is entitled “The Method of Negation and Construction” which he employed in modifying Newton’s Universal Law of Gravitation where distances between galaxies are greater than about 100 million light years. At these distances, Zwicky’s investigations indicate that the attraction between mutual bodies is much smaller that the classical inverse square law predicts.

Zwicky gave a number of examples from his own morphological work on rocket propulsion systems for which he was awarded numerous patents.

3 Morphological Analysis and Combinatorial Explosion

It is well documented that morphological methods may lead to the problem of combinatorial explosion. Various techniques have been proposed to deal with this problem. In discussing this problem as it relates to the common method where the morphological matrix has FRs in the rows and solutions in the columns, some authors suggest evaluating the individual solutions, row by row, and then combining the optimum row ones to obtain the overall solution (Pahl and Beitz, 1996; Al-Salka and Cartmell, 1998). This will reduce the number of evaluations from a power relationship (m^n) to a multiplicative relationship ($m*n$) in a situation where the number of FRs is n and the number of solutions to each FR is m.

Mathematicians, in solving problems involving large matrices (before the advent of the computer) developed methods of partitioning the matrices, so that they could work on the individual partitions in a more manageable way. When setting up matrices to model engineering situations, the viability and value of partitioning is often readily apparent from the physical situation, as for example when applying finite element analysis to a stress analysis problem.

In designing/inventing an engineering system, the problem will most likely suggest some manner of breakdown into subsystems/sub-problems. Morphological method may then be applied to each of these. One must bear in mind that there are likely to be interactions between the sub-systems and that both the overall problem and the sub-problems are dynamic throughout the design process.

The morphological approach outlined by Zwicky has not yet been developed and extensively applied at the rigorous level that he believed in. His idea was not simply the “morphological box” as it is sometimes called. He saw it as a methodology, not merely a method. He intended it to be applied creatively and modified to suit the problem on hand. To sum up this point, the designer should be prepared to look for new opportunities and for contradictions, while pursuing a previously set exhaustive procedure.

4 The Need for Rapid Sketching and Recording Ideas during the Design Process

Several researchers such as Ullman have carried out protocol studies of engineering designers at work, doing design, in order to produce cognitive models of the design process. (Ullman et. al, 1988, 1995 and 1997).

Ullman and his co-workers were concerned that computer based systems should be developed to assist designers and design teams in their work. They observed that, as computers increased in capacity and speed, more powerful design software such as FEA packages and solid modelling packages were developed. However these packages, particularly the earlier ones, were time consuming and absorbed a great deal of the users’ energy in mastering their use. At the same time, they were rather specialised into particular areas such as detail drafting and various particular design analyses. Many of them did not easily allow the designer to work seamlessly between the processes involved. They also lacked facilities for recording the history of design process, the decisions made during the design process, and the relevant criteria. We will now discuss some of the goals of the 1995 paper by Ullman, which was directed toward the idea of an “Ideal Mechanical Engineering Design Support System” These goals are best related to Figure 1.

Ullman defines the term "architecture" as “the stick figure that can be easily manipulated and changed before the shape is refined. Shape implies the geometry that adds body and detail to the architecture. Often designers first develop the general architecture of the object being designed and then they add details about shape and fit." Ullman's diagram shows these entities in a central position. Form refers to both architecture and shape.

The short term memories (STM) of the designers act quickly as the architecture comes to mind whilst they attempt to meet functional requirements and constraints related to parts and sub-assemblies. The computer software should support the graphical documentation of this architecture in a speedy and non-burdensome way and allow recording of reasons behind the ideas and decisions. Function happens primarily at interfaces between components making up an assembly.

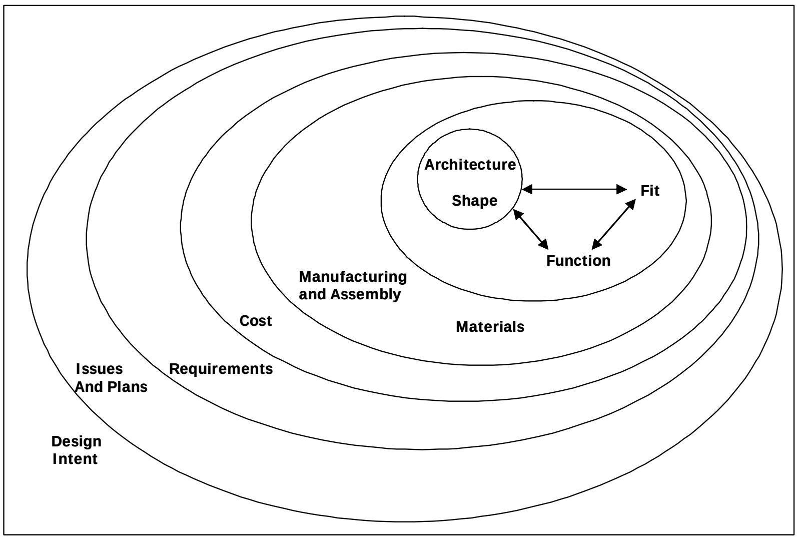


Figure 1: Ullman's diagram related to design decisions

As the design progresses (moving outwards in Figure 1), information related to manufacturing, assembly, materials and cost of the current concepts need to be to be readily accessed. The ideal computer software should support this access so that rapid evaluation along with documentation can take place.

Next, Ullman points out that as the design moves from conceptual to layout to detail, constraints and limitations come to light in addition to the initial functional requirements (FRs) that may have resulted from a QFD type process. Ullman refers to both initial FRs and evolving constraints as requirements and he recommends that the software integrate the management of these requirements into the development of parts and assemblies.

The term "issues and plans" includes ideas such as Integrated Product and Process Planning (IPPD), the successor to concurrent engineering. Again, the computer software should support issues and plans.

What does Ullman mean by Design Intent? He explains that the ideal engineering design support system should manage all the items inside Figure 1 in a database. In addition it should support detailed information about arguments for and against decisions made based on requirements as well as recording the decisions themselves. He points out that other authors have used terms like design history, rationale and corporate memory in a similar vein to his expression of "design intent".

Studies of human information processing have shown that over two thirds of the strategies used by design engineers whilst developing new products were searches through the design space. The artificial intelligence community has put much effort into the area of search strategies. Efficiency in capturing, archiving and querying the full range of design information is clearly an important goal for a design support system.

When the first author started to generate the morphology of down-hole piston pumps, he initially employed two techniques (Dartnall, 2003):

- The use of an Excel spread sheet and careful symbolic labelling of all combinations and permutations to represent the different pumps.
- The construction of solid models of each pump.

Both techniques were tedious. Visualisation from the first technique was so difficult that eventually images would have to be constructed in order to present the results for the benefit for communication to others. Construction of the solid models was time-consuming – taking times ranging from about 1 hour to one day for each model. He realised early that there were in excess of 60 models involving a large amount of tedious work. Clearly, some form of stick diagram is desirable, as indicated by Ullman.

However the designer needs to do a lot more than the tedious construction of solid models or even the more expedient construction of stick diagrams. The designer needs to be evaluating each idea, possibly each step of the construction to see how it affects various performance requirements, cost, design for manufacture (DFM), design for maintenance, design for assembly (DFA), efficiency, life cycle, reliability, how it supports the total concept. Manual sketching, in the past has allowed designers, as individuals or in groups, to discuss these issues over quick sketches.

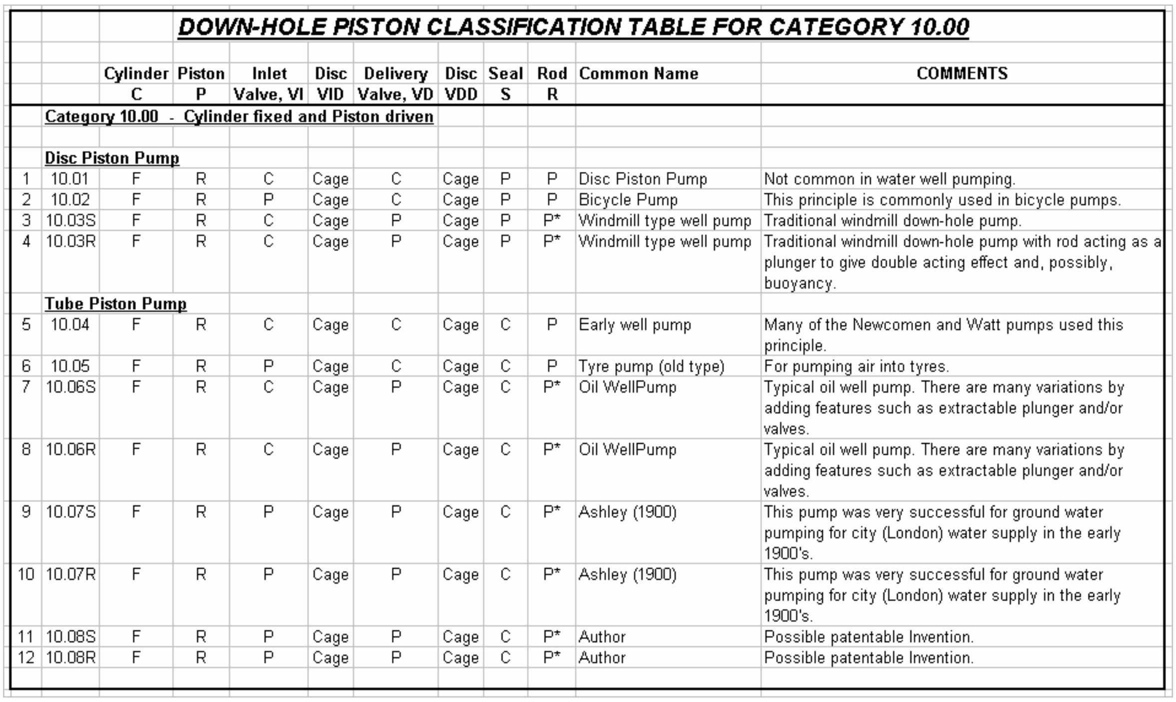
5 Morphology of Down-hole Piston Pumps – Case Study

We now show how, an initial morphological analysis was attempted by constructing a matrix (spread sheet of Table 1) having the basic piston pump elements in columns and the various conceptual pumps, systematically constructed in the rows. It was soon recognised that the pumps generated could be categorised into categories such as Disc-piston pump and Tube-piston pump. Many such categories were anticipated and these were added to the summarising Table 2 as they were recognised. Some of these were recognised later in the process.

Some of the solid models of the early conceptual pumps are shown in Figure 2. The constuction of these was time-consuming and led to the idea of rapid graphical generation of conceptual pumps from elements of the code of Figure 3.

The rapidly constructed computer sketches were constructed in Microsoft Word, after defining the graphical code of the basic elements such as valves, valve elements such as discs and cages, tubes, seals etc., that are common to all conceptual piston pumps. The various down-hole pump configurations were then built from these by copy and paste operations. In this way, the rapid computer sketching of conceptual pumps was not burdensome.

Table 1: Combinatorial generation of some early symbolic models of down-hole pump configurations (morphological analysis of the first category, 10.00).



DOWN-HOLE PISTON CLASSIFICATION TABLE FOR CATEGORY 10.00

		Cylinder C	Piston P	Inlet Valve, VI	Disc VID	Delivery Valve, VD	Disc VDD	Seal S	Rod R	Common Name	COMMENTS
	Category 10.00 - Cylinder fixed and Piston driven										
	Disc Piston Pump										
1	10.01	F	R	C	Cage	C	Cage	P	P	Disc Piston Pump	Not common in water well pumping.
2	10.02	F	R	P	Cage	C	Cage	P	P	Bicycle Pump	This principle is commonly used in bicycle pumps.
3	10.03S	F	R	C	Cage	P	Cage	P	P*	Windmill type well pump	Traditional windmill down-hole pump.
4	10.03R	F	R	C	Cage	P	Cage	P	P*	Windmill type well pump	Traditional windmill down-hole pump with rod acting as a plunger to give double acting effect and, possibly, buoyancy.
	Tube Piston Pump										
5	10.04	F	R	C	Cage	C	Cage	C	P	Early well pump	Many of the Newcomen and Watt pumps used this principle.
6	10.05	F	R	P	Cage	C	Cage	C	P	Tyre pump (old type)	For pumping air into tyres.
7	10.06S	F	R	C	Cage	P	Cage	C	P*	Oil WellPump	Typical oil well pump. There are many variations by adding features such as extractable plunger and/or valves.
8	10.06R	F	R	C	Cage	P	Cage	C	P*	Oil WellPump	Typical oil well pump. There are many variations by adding features such as extractable plunger and/or valves.
9	10.07S	F	R	P	Cage	P	Cage	C	P*	Ashley (1900)	This pump was very successful for ground water pumping for city (London) water supply in the early 1900's.
10	10.07R	F	R	P	Cage	P	Cage	C	P*	Ashley (1900)	This pump was very successful for ground water pumping for city (London) water supply in the early 1900's.
11	10.08S	F	R	P	Cage	P	Cage	C	P*	Author	Possible patentable Invention.
12	10.08R	F	R	P	Cage	P	Cage	C	P*	Author	Possible patentable Invention.

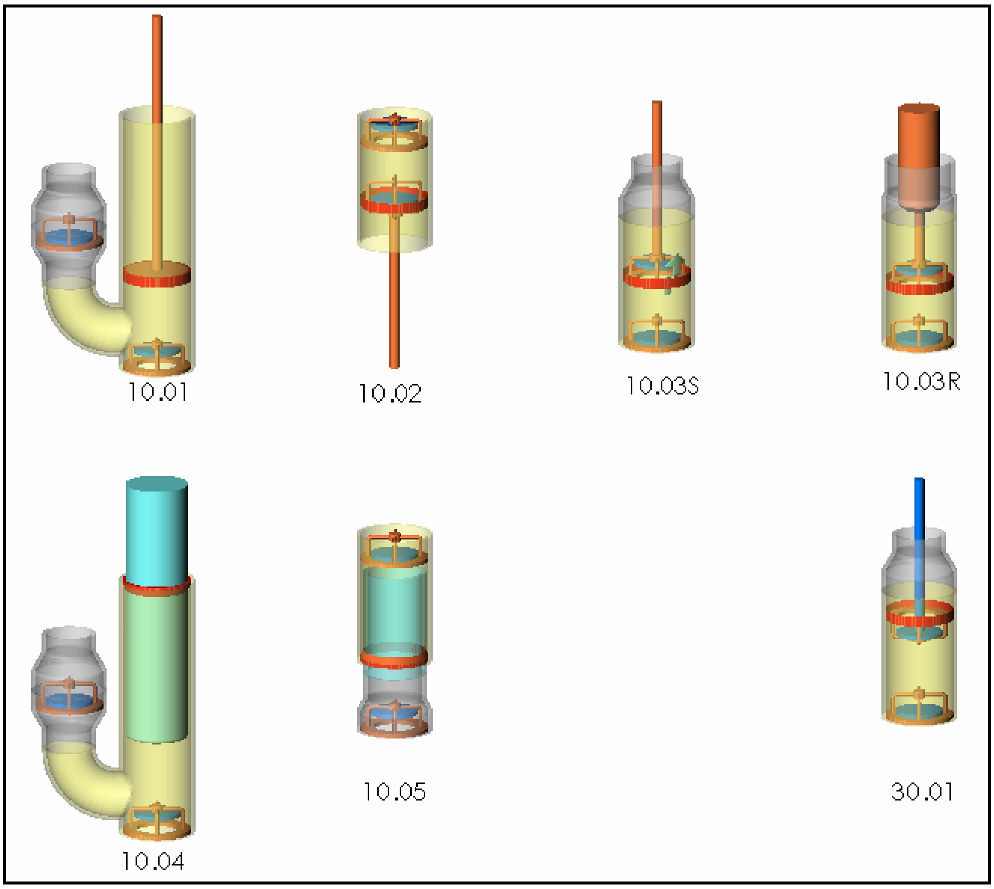


Figure 2: Some early solid models constructed for generation of down-hole pump configurations

By colour coding and employing conventions such as drawing only half of any symmetrical (completely round) pump, the process was visually efficient. The entire pump was drawn if it contained any non-symmetrical feature. Symmetry is both a DFM/DFA issue and a functional issue in the down-hole pump design. From the DFM/DFA point of view, symmetry implies faster and less expensive machining operations such as turning and drawing as well as rapid, screwed assembly. From a functional view, round, symmetrical elements, such as tubes and rods can be concentrically assembled and are helpful in minimising the diameter. A minimum diameter design to fit inside a minimum diameter well is highly desirable. Screwed assembly also has the advantage of being readily disassembled for maintenance.

Another evaluating criterion of the designs is the problem of abrasive particles being captured in the seals and wearing the mating walls. This problem needed to be thought through with every pump configuration. No “dirt pockets” are permitted, especially above seals, as the dirt is sure to cause serious wear.

A further desirable feature of a pump design is to minimise leakage from the seals and valves, not only during operation but also during periodic non-pumping periods such as when there is a lull in the wind to a wind-pump. This often leads to the leak-back of the entire delivery column during a lull. In order to achieve minimal long term leak-back, valve and seal design and positioning are very important. The designer will have many of these sorts of problems to check out as he/she works through the different configurations of a design.

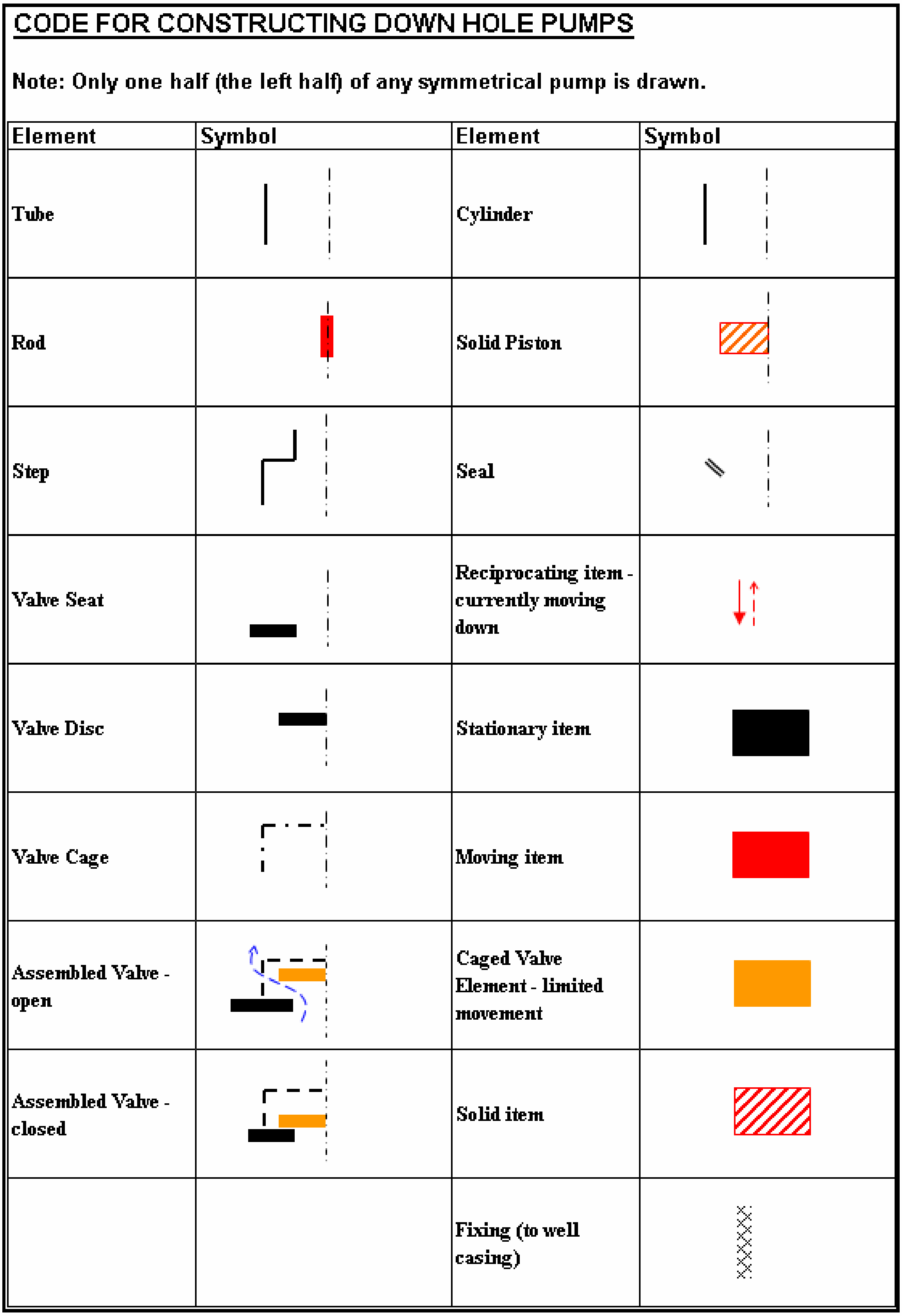
The first five of the pumps generated from the graphical code are given in Figure 4. In the first pump, water is delivered via an eccentric pipe containing the delivery valve. This pump is drawn in full, whereas the other four pumps are comprised of concentric circular elements and therefore only their left half is drawn. The first pump, although once widely used in the Watt era, is not suitable for modern small diameter tube wells.

Some comments on the remaining pumps of Figure 4 are now given. They demonstrate how evaluation of each concept may take place.

Pumps no 2 and 3 of Figure 4 are widely used in conventional wind-pumps. These devices have had a long history of premature wear when used to pump water containing abrasive sediments as these sediments tend to become captured between the lip seal and the cylinder – i.e. a "dirt pocket" effect. In addition, friction tends to axially compress the lip of their seal especially during high pressure surges that occur due to water column inertia at the beginning of a pumping stroke. It is common knowledge that excessive wear is found at the bottom of wind-pump cylinders where inertial pressure pulses have their effect.

Pumps no 4 and 5 of Figure 4 have inverted seals, external to the water flow in order to avoid both the dirt pocket effects and the axial lip compression effects present in the above two pumps. However they are single volume even though pump 5 is double acting. In addition, because a tube containing the delivered water is reciprocated rather that a rod they have further complications at their interface with other sub-modules (such as the delivery pipe) of the complete pumping system.

As generation of further conceptual pumps took place, the thought occurred to the author to investigate the idea of having two moving valves, rather that one fixed and one moving. This resulted in the configuration 12 of Figure 5. It had certain advantages such as smooth flow, as outlined in the diagram text. However the advantages were obtained at the expense of the extra complexity of having to drive each piston valve separately.

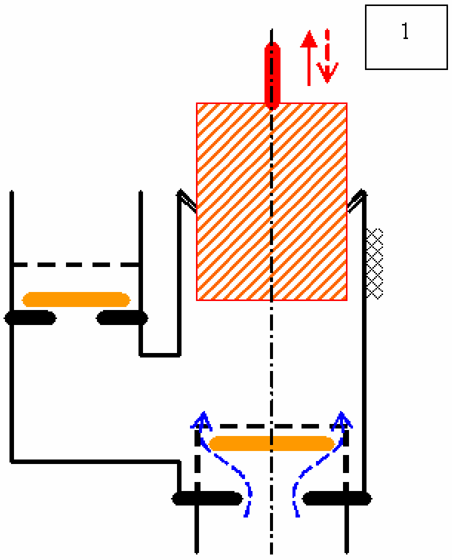


CODE FOR CONSTRUCTING DOWN HOLE PUMPS

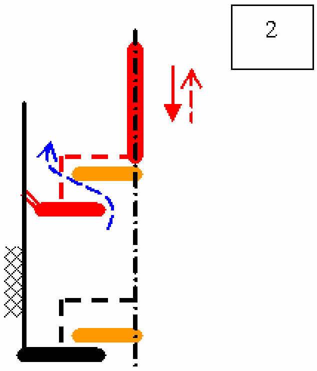
Note: Only one half (the left half) of any symmetrical pump is drawn.

Element	Symbol	Element	Symbol
Tube		Cylinder	
Rod		Solid Piston	
Step		Seal	
Valve Seat		Reciprocating item - currently moving down	
Valve Disc		Stationary item	
Valve Cage		Moving item	
Assembled Valve - open		Caged Valve Element - limited movement	
Assembled Valve - closed		Solid item	
		Fixing (to well casing)	

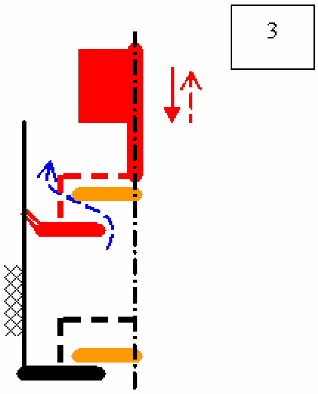
Figure 3: Code for rapid graphical generation of conceptual down-hole pumps



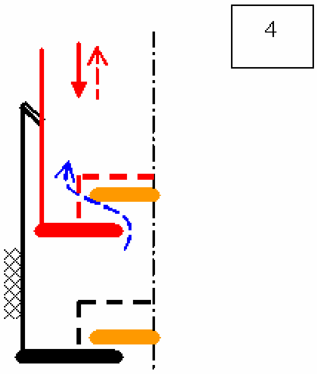
The plunger pump. This is one of the oldest down well configurations dating back to the James Watt era. The rod was guided and its weight assisted the pumping which occurred on the down stroke. Clearly unsuitable for pumping tube wells. Inertia of the rod limits piston speed.



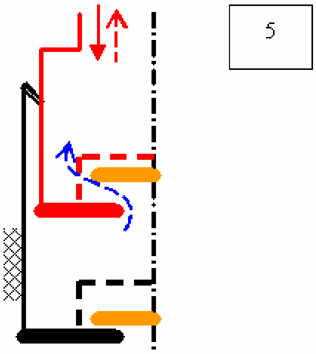
Standard wind - pump having a thin rod. This is single acting pumping on the up stroke and charging its cylinder at the same time.



Standard wind - pump with stepped rod. This step has a plunger effect. Pumping occurs on both strokes and charging the cylinder on the up stroke.



Single acting tube piston pump. Pumping occurs on the up stroke and charging its cylinder at the same time as for the standard wind pump.



Double acting (single volume) tube piston pump. Pumping occurs on both strokes. Charging of its cylinder occurs on the up stroke as for the standard wind pump.

Figure 4: Some of the early conceptual pumps generated by the rapid graphical technique. Note the numbers do not match the categories of Table 1. They are respectively 10.01, 10.03S, 10.03R, 10.08S and 10.08R.

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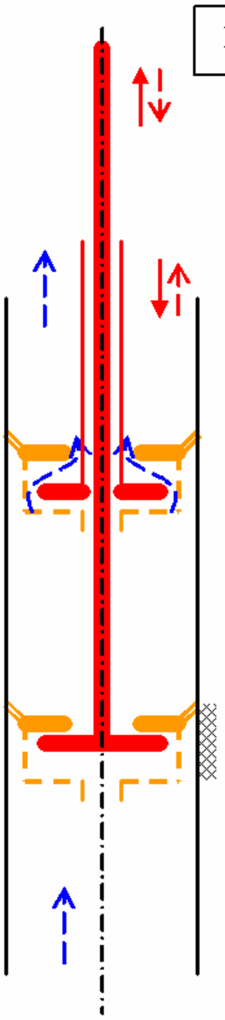
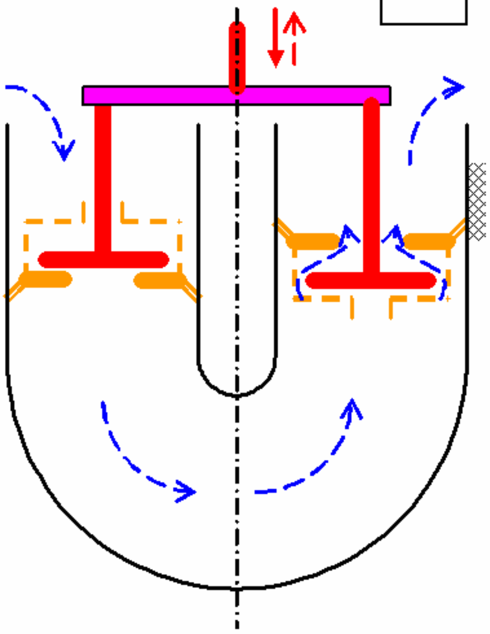


This tube well pump was produced as early as 1880's. It was known as the "concertina pump". The Pomona Pump Company produced a version in which the pistons were driven by two Whitworth quick return mechanisms so that their upward pumping movement overlapped (the quick return was on the down stroke). Very smooth flow was obtained.

14

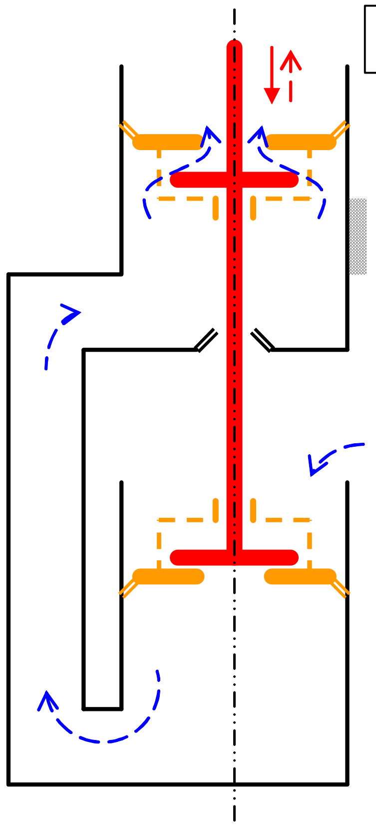


This is the author's "U-tube" pump. It was devised as a conceptual tool to support the thinking process. It may have some practical use! It arose in answer to the question: "How does one gang two piston valves together in such a way that one pumps on the down-stroke and the other on the up stroke?"

Figure 5: Two innovative concepts, both involving two moving piston valves, one having independent piston valve movement and one having the piston valves ganged together.

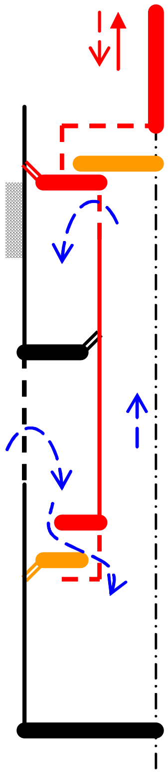
The next thought was to see if the above situation could be simplified by driving two piston valves with one reciprocating rod. Figure 14 illustrates that this could be done by forming the cylinder into a "U" tube. This configuration, of course is, is not suitable for fitting down tube wells. Can this conceptual design be re-configured so that it is essentially constructed from concentric circular elements?

Pump 14 can be rearranged by placing one leg of the U tube above the other, as shown in pump 16 of Figure 6. Unfortunately, we still have a space wasting eccentricity, so we transform the rod joining the two piston valves into a tube. Now we arrive at pump 17 in which we have the flow path of pump 16 in a pump made up from essentially circular elements.



16

This double acting tube well pump was "invented" by the author. It is a conceptual model Its layout is similar to the Deming pump of the early 1900’s, one difference being that a piston valve replaces the lower piston of the Deming pump. Another is that the intake is through the open top of the bottom cylinder. The bottom intake valve of the Deming pump is deleted. The author's next pump is a nested transformation, which follows from the circuit of this pump



17

This is one of the author's configurations. It is a double acting (say, 1.75 acting) rod driven pump. A potential advantage with respect to maintenance is that both valves and the seal are on the rod and could be extracted from the well with the rod without removing the cylinder and its casing. Slim, elegantly simple

Figure 6: Pump 16 is an intermediate transformation from the conceptual pump 14 of figure 5, leading the practical double acting pump 17

Many configurations were generated and it was important to evaluate the configurations in conjunction with other modules of the pumping system.

As superior deigns emerged it was useful to construct solid models of these in order to evaluate them more thoroughly. An example is shown in Figure 7.

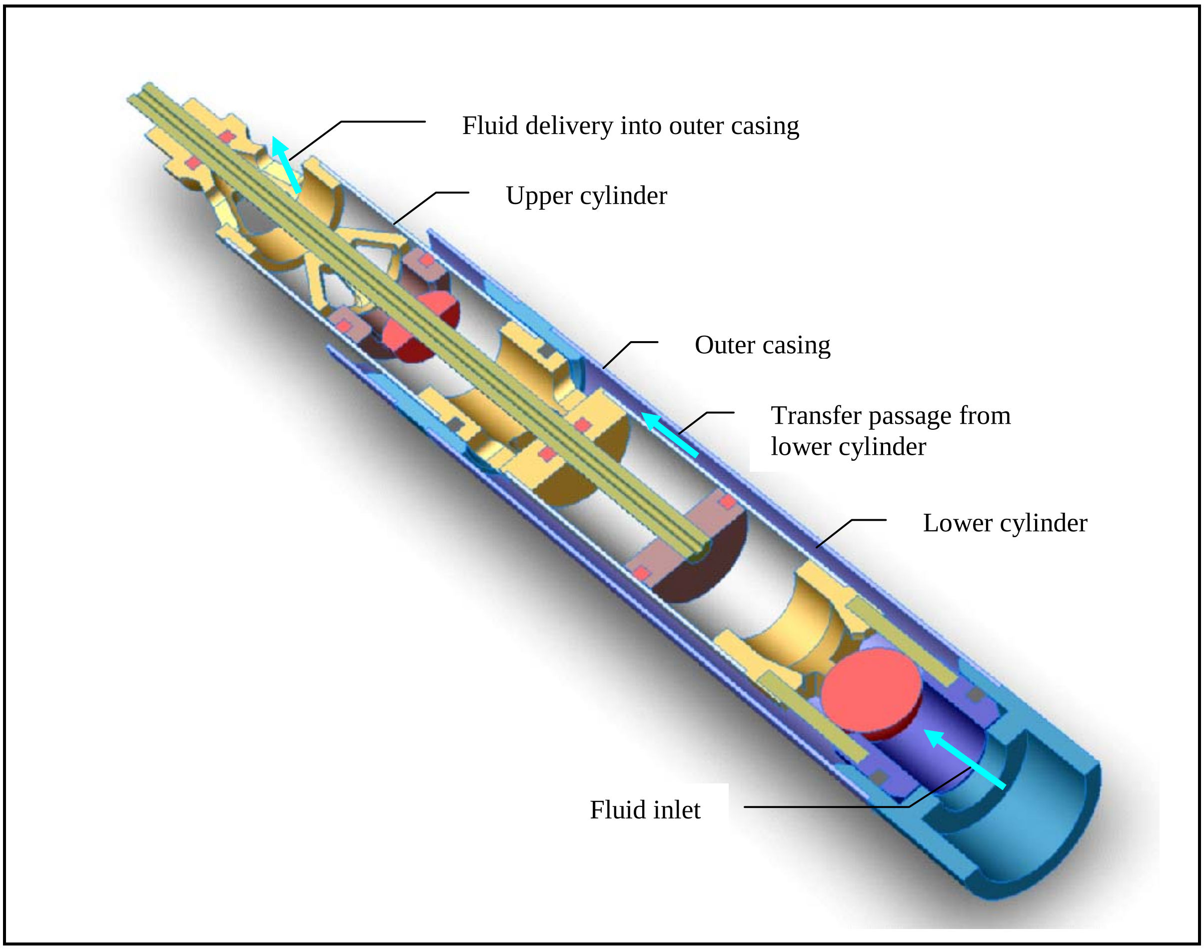


Figure 7: The conceptual solid model of a pump that is essentially an inversion of pump 17. The flow between the bottom and the top stages is via an external annular passage. Another difference is that water enters through a bottom valve rather that a side port.

6 What are the benefits of the kind of Morphological Analysis of this case study?

- The procedure demonstrated in our case study has revealed the following:
- In order search for improvements in a device such as the down-hole wind pump it is highly desirable to be able to rapidly construct the many conceptual designs that are possible.
- The potential techniques to aid the search include matrix based analytical techniques and various graphical techniques. Rapid graphical techniques greatly reduce the time wasted on meaningless and non-functional combinations that will nearly always be present when a complete combinatorial analysis is carried out.
- Rapid graphical techniques enable immediate evaluation of the generated conceptual designs to be made.
- Rapid graphical techniques along side the appropriate analytical matrix enable the researcher to see where new opportunities are.

- This case study supports Zwicky's claim about the power of morphological method in that it rapidly generated numerous conceptual designs. An indication of this power is that the conceptual designs that it generated were the patents of the past hundred or so years in this area.

- Software designed and constructed on the basis of the techniques outlined in this case study would be useful.

7 Conclusions

By way of a case study, this paper has demonstrated the use of morphological analysis in innovative mechanical design. It has demonstrated that there is more to morphological analysis than the commonly described "morphological box". Designers need rapid sketching facilities to assist them as they progress from one idea to another, making evaluations at each stage. These sketches need to reveal sufficient information to assist the designers in their assessment and decision making processes without being burdensome. The process needs to facilitate the type of thinking that will enable the designer to see new combinations of elements and new categories of the morphological analysis. The case study demonstrated some foundations (efficient combination of tabular and graphical procedures) from which useful software could be produced to assist the designer in more effectively applying morphological analysis.

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