INNOVATIVE MECHANICAL DESIGN
WITH A CASE STUDY OF PUMPING SYSTEMS
FOR LOW YIELD TUBE WELLS

By

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A thesis submitted in fulfilment of the requirements for the degree of

Master of Engineering

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Finally, I would like to dedicate this dissertation to my wife, Eleanor, my children, Alexander and Stephanie and my friends who have supported my project. Their profound and unconditional faith has made this work worthwhile and rewarding.
Innovative Mechanical Design with a Case Study of Pumping Systems for Low Yield Tube Wells

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<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
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<tbody>
<tr>
<td>AI</td>
<td>Artificial intelligence</td>
</tr>
<tr>
<td>ASE</td>
<td>Analysis, synthesis, evaluation.</td>
</tr>
<tr>
<td>BFGS method</td>
<td>Nonlinear optimization method of Broyden, Fletcher, Goldfarb and Shannon.</td>
</tr>
<tr>
<td>CAD</td>
<td>Computer aided design (sometimes drafting).</td>
</tr>
<tr>
<td>CAD-CAM</td>
<td>Computer aided design and manufacture</td>
</tr>
<tr>
<td>CAE</td>
<td>Computer aided engineering</td>
</tr>
<tr>
<td>CFD</td>
<td>Computational fluid dynamics</td>
</tr>
<tr>
<td>CBR</td>
<td>Case based reasoning.</td>
</tr>
<tr>
<td>CW</td>
<td>Closed world condition</td>
</tr>
<tr>
<td>DAC</td>
<td>Double acting cable.</td>
</tr>
<tr>
<td>DFA</td>
<td>Design for assembly.</td>
</tr>
<tr>
<td>DFM</td>
<td>Design for manufacture.</td>
</tr>
<tr>
<td>DFX</td>
<td>Design for X.</td>
</tr>
<tr>
<td>DH-UniPump</td>
<td>Down-hole UniPump.</td>
</tr>
<tr>
<td>DP</td>
<td>Design parameter.</td>
</tr>
<tr>
<td>EDP</td>
<td>Engineering design process.</td>
</tr>
<tr>
<td>FEA</td>
<td>Finite element analysis.</td>
</tr>
<tr>
<td>FR</td>
<td>Functional requirement.</td>
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<tr>
<td>GA</td>
<td>Genetic algorithm.</td>
</tr>
<tr>
<td>IPPD</td>
<td>Integrated product and process planning.</td>
</tr>
<tr>
<td>KBES</td>
<td>Knowledge based expert system.</td>
</tr>
<tr>
<td>KBS</td>
<td>Knowledge based system.</td>
</tr>
<tr>
<td>LSRM</td>
<td>Long stroke reciprocating mechanism.</td>
</tr>
<tr>
<td>LSWHR</td>
<td>Long stroke well head reciprocator.</td>
</tr>
<tr>
<td>LTM</td>
<td>Long term memory.</td>
</tr>
<tr>
<td>MS</td>
<td>Machine system.</td>
</tr>
<tr>
<td>OEM</td>
<td>Original equipment manufacturer.</td>
</tr>
<tr>
<td>PDS</td>
<td>Product design specification.</td>
</tr>
<tr>
<td>PDM</td>
<td>Product data management</td>
</tr>
<tr>
<td>PE</td>
<td>Polyethylene.</td>
</tr>
<tr>
<td>PMDC motor</td>
<td>Permanent magnet direct current motor.</td>
</tr>
<tr>
<td>PVC</td>
<td>Polyvinylchloride.</td>
</tr>
<tr>
<td>QC</td>
<td>Qualitative change in problem characteristic</td>
</tr>
<tr>
<td>QFD</td>
<td>Quality functional deployment.</td>
</tr>
<tr>
<td>SIT</td>
<td>Structured inventive thinking.</td>
</tr>
<tr>
<td>STM</td>
<td>Short term memory.</td>
</tr>
<tr>
<td>TREND-MORPH-PDS</td>
<td>This is the engineering design methodology developed and investigated in this thesis.</td>
</tr>
<tr>
<td>Acronym</td>
<td>Description</td>
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<tr>
<td>TRIZ</td>
<td>Teoria Resheniya Izobretatelskikh Zadatch, which translates approximately into English as: Theory of Inventive Problem Solving.</td>
</tr>
<tr>
<td>TS</td>
<td>Technical system.</td>
</tr>
<tr>
<td>UDE</td>
<td>Undesirable effect.</td>
</tr>
<tr>
<td>UNDP</td>
<td>United Nations Development Program.</td>
</tr>
<tr>
<td>UniPump</td>
<td>The proposed commercial registered name for the pumping system of this case study.</td>
</tr>
<tr>
<td>VLOM</td>
<td>Village level operation and maintenance.</td>
</tr>
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Innovative Mechanical Design with a case study of
Pumping Systems for Low Yield Tube Wells.

John Dartnall, 2003

This thesis focuses on combinatorial methods of invention/innovation/design emphasizing the manipulation of form (as distinct from the manipulation of function alone) that help the designer to generate a wide range of good design alternatives. It is based on my case study of a morphological analysis of a ground water pumping system suitable for low volume flow pumping.

The first premise of this approach is that the elements and functions of mature technologies such as mechanical machines are well documented and understood. Thus, innovations are more likely to involve new combinations of existing forms than the introduction of new machine elements.

The second premise is that valuable information is available about most elements and the more popular sub-systems and machines. That information has evolved, sometimes over time spans ranging to hundreds of years, but it has not usually been systematically documented and categorised, thus leaving opportunities to investigate these areas and discover good design possibilities. Further, some valuable information is available only anecdotally or is tightly held by the managements of the companies that have manufactured the device(s) or own the intellectual rights.

In recent years a proposed "design science" has been the subject of much research and many models have been proposed of processes for designers to follow. These typically model the design process in stages, including: clarifying the problem, conceptualising, embodiment selection and detailing.

It is widely recognized that industrial invention/innovation/design processes are non-linear, and so complex that, despite extensive research, design science and models are still at an immature stage.
The literature confirms that industry is often driven by cost/time constraints and short term thinking, rather than using “design science” methods.

My methodology (abbreviated as TREND-MORPH-PDS) is an original contribution to design science. It outlines three stages to be followed by the designer:

1. Start with a general goal(s). Break this down into sub-areas/systems, including: socio-economic, near physical environment, power source, prime mover, gearing/matching, transmission, working sub-system and control system. Research and document historical trends in each of these areas and their possible influences on the design.

2. Apply morphological analysis to each sub-system, using rapid graphical techniques. Move to detail design for specific alternatives as satisficing sub-systems are identified.

3. At all times during these stages, take advantage of design knowledge/tools that are currently available, looking for ideas and opportunities. Work constantly on constructing the Product Design Specification (PDS). The conceptual design is complete when the PDS is finalized. Detail design, which would follow from the PDS is not treated in this thesis.

The methods and ideas put forward in this thesis and its case study are an original contribution to design science. They also identify issues and differences between design science models and the design processes seen in industry.

Several patentable inventions have resulted from my application of the methodology, and the dissertation is a significant contribution to the knowledge domains of mechanical machine design and the technology of ground water pumping.
CHAPTER 1

INTRODUCTION TO THE THESIS

1.1 INTRODUCTION

This chapter introduces and gives an overview of my thesis which describes a new innovative engineering design methodology that I have called *TREND-MORPH-PDS*, which is especially applicable to mechanical design.

Designers work in a wide variety of design environments requiring different methods. Some of these may be characterised as routine and some innovative. Some times the organization through which the designer works is small and sometimes it is a large corporation, sometimes the work involves a one-off project and sometimes the design involves a long term approach for a volume produced product. The product may be simple or it may be complex. These are some of the more typical engineering design environments.

The design environment envisaged throughout this thesis is where there is considered to be a need to improve, by innovation, the competitive advantage of a complex, volume produced engineering machine (possibly involving a range of sizes) requiring applications engineering in order to meet the needs of varying field conditions.

In Chapter 2 I describe the motivational background that led me on to the main task of the thesis. This task was to discover and test an effective innovative design procedure that would help an engineering designer to design an improved system, like the ground-water pump, which is the subject of my case study.

In Chapter 3, I outline and comment on “design science” and on the main engineering design paradigms.

Chapters 4, 5 and 6 describe my own methodology, dealing with the benefits of researching the historical design *TRENDS* in Chapter 4, *MORPH* (ology) of design in Chapter 5 and the evolution of an appropriate Product Design Specification (*PDS*) in Chapter 6. Chapter 7 shows how this methodology has helped with my case study.
The relevance, validity and limitations of the methodology are discussed in the Conclusions of Chapter 8.

1.2 ORIGINS AND MOTIVATION

Because of the confusing complexity and challenges of design cases such as my case study, I will commence this thesis by giving the historical background and motivational aspects that caused me to pursue the case study.

Chapter 2 describes in detail how, in 1974, I was excited by the technical challenge to apply renewable energies, particularly solar energy, to appropriate applications. One such application was remote area ground-water pumping, where the cost of fuel and other forms of energy are often high, and the management of the systems is difficult. Initially, solar thermal systems, employing two phase cycles looked promising. I undertook numerous investigations, looking carefully at the overall efficiency of various systems and building my own experimental systems. The complexity of the systems and design issues became apparent: eventually my enthusiasm moved to the engineering design area. In the meantime I recognised that photovoltaic systems would become commercially more likely to succeed than photo-thermal systems because of their greater efficiency, compactness and likelihood of lower maintenance costs and greater reliability.

1.2.1 About Heliseal

In 1986 I founded a technology company. Originally Dartnall Engineering and Innovation Pty Ltd, it is now Heliseal Pty Ltd. Heliseal manufactured and sold a trial batch of about 150 innovative photovoltaic ground water pumps. A report on this is given on my web-site under "Power point UniPump 1" and "Power point UniPump 2" at: http://www.eng.uts.edu.au/~johnd/

Using the company as a vehicle, I developed and patented several inventions related to fluid pumping and linear actuation.

More recently, Heliseal approached a Western Australian company, W D Moore Pty Ltd, a long-established wind pump manufacturer. Moore has agreed to produce Heliseal designs for adaptation to W D Moore’s wind pumps and to commercialize UniPump
systems, powered by solar, internal combustion engine and human power. (Human powered hand pumps are important for village water supplies in developing countries). The website for W D Moore Pty Ltd is:


The engineering design discipline has been crucial to the success of projects like those undertaken by Heliseal. During development cycles, I have routinely examined the significant research completed in the areas of systems engineering, design science, design methodology and design methods.

1.3 THE ENGINEERING DESIGN PROCESS

My thesis examines design processes in engineering, with particular emphasis on mechanical systems design. In my analysis of the design process, I have continually tested theoretical ideas against the experience gained through my case study, in which I have described and analysed the design, development and testing of the UniPump ‘family’ of reciprocating ground water pumps. The central criterion for these pumps is that they should be suitable for operation in small diameter tube wells (bore holes) and be able to accept a wide range of power inputs, including: solar; wind; IC engine; grid electric; and even human or animal power.

The case study is well-researched and well-documented, and the analysis and conclusions in the thesis draw on years of exhaustive trials and experimentation. Some of this work casts doubt on the idea that engineering designers will eventually arrive at universal procedures and methodologies.

Examination of existing literature on engineering design processes (EDP) reveals many individual methodological approaches to the process of design. These procedures and methodologies are usually presented with block diagrams. Most of them contain the following elements:

- Establish and **clarify the need** for the product to be designed.
- Set up a list of functionally independent **functional requirements** (FRs).
- **Search for conceptual designs** that meet the functional requirements.
• Set up **evaluation criteria** and use them to choose the most promising of the above conceptual designs.

• Now produce **detail designs** of the most promising conceptual designs.

• **Evaluate the detail designs** and select the most appropriate.

• **Document details and processes for development, manufacture and commercialization.**

• In each of the above stages **looping back to previous stages** is understood to be a normal part of the procedure, since later steps shed light on the possibilities and limitations of earlier ones.

During a design project, engineers and others involved with them in the design process, constantly face problems that require intelligent balance, or even compromise, between conflicting requirements. The situations may sometimes be resolved by "**trade-offs**" between the conflicting requirements. Sometimes problems are not properly defined or understood, and therefore further or even fundamental research is needed to establish the relevant technical, scientific or engineering principles. Marketing, manufacturing, maintenance, environmental and other issues influence the definition of the problem during the design process. On some occasions, the situation is fairly well understood and refinements and trade-offs have already taken place over a period of time, so that it seems that "**A Law of Diminishing Returns**" applies. In these situations a **breakthrough or an invention** may provide the basis for improvement in design.

The truth is that design problems, particularly those requiring invention or innovation, are particularly complex and are characteristically ill-defined and ill-structured. The processes available to deal with such situations are not yet well understood. This has resulted in many methodologies and methods for tackling such problems.

### 1.3.1 Barriers to Success

The presence of human beings and socio-economic systems adds further complexity. Accepting that part or all of a project requires a new start is rarely easy for those involved. Most experienced engineers would agree that the reluctance to change increases with the investment to date and the number of stages or sub-systems completed. The diversity of established approaches reflects the range of the types of problem. It has become clear to me that no single approach is likely to deal with all
aspects of the design process. While marketing, manufacturing, maintenance, environmental and other issues may influence the definition and resolution of the problem during the design process, delivering a truly new solution may require a breakthrough or an invention.

My main case study is in the specialized area of mechanical (additionally, electromechanical) machine systems design, where the product requires flexibility and applications engineering, so that it can be adapted to varying working environments. In order to meet the market requirements effectively, this flexibility may include a requirement for the design to be developed into a range of marketable sizes.

The case study highlights most of the difficulties mentioned above: the need for careful/fundamental research; the need for the engineering designer to understand the marketing, manufacturing and commercial issues; and the need to search for breakthrough(s) and/or invention(s) in order to go beyond the current situation. It also acknowledges that, regardless of the skill sets and creativity of the people involved, there are going to be multiple solutions with different emphases and cost-benefits. All of these solutions may satisfy the same established need.

1.3.2 “Design Science” and the Main Paradigms of Design Methodology

The pioneering work that will one day lead to a Design Science is discussed in Chapter 3. The various paradigms and diagrams representing methodologies are discussed there. To give an idea of the scope of this work, I will list them here, with brief comments on each of them:

- Case based reasoning (CBR) – typical mechanical and civil engineering approach, in which a similar previous case(s) is recalled and used as the basis for a new case.
- Cognitive – analysing the design methods and procedures of human designers.
- Creative – includes a list-making process such as brainstorming, morphological approach, synectics, TRIZ, SIT and others.
• Algorithmic – typical computer based computational approaches including FEA, SIMPLEX method, genetic algorithm based (GA) methods.

• Artificial intelligence (AI) – computer based designer assistance or complete computer design, including expert systems, knowledge based systems (KBS), CBR and design history recording modules.

• Social – construction of shared meaning.

With all these methodologies, there is a tendency to require significant definition of the design problem at the start of the design process. This is probably due to the fact that the design engineer is typically an employee, or that many engineering product designs are justifiably incremental in character, rather than radical.

My finding is that the most difficult thing to deal with in engineering design of a system of significant complexity, where no clearly superior design has emerged, and where there are multiple stakeholders, in a technologically changing world, is to clearly define the design problem. This is because the required knowledge about the stakeholder requirements/wishes, the product area and the design process is rarely available before the design effort starts. This is clearly so in cases where there is room for a high level of innovation. The design process must therefore incorporate a learning component. This may often require around sixty percent of the designer’s time (Ullman, B2-2003). This is valuable knowledge and should be documented efficiently, along with key decisions and reasons behind them.

1.4 "TREND-MORPH-PDS" METHODOLOGY

Chapters 4, 5 and 6 cover my methodology, which for convenience of reference, I have named TREND-MORPH-PDS methodology. This is because I see the methodology as having three phases.

• TREND - represents the first phase where, after setting a general goal, the designer carves the general problem up into a small number of sub-areas/systems, each requiring trend analysis to find how each trend may contribute to the design. This phase is discussed in Chapter 4.

• MORPH – represents the second phase in which the designer applies thorough morphological analysis to each of the machine sub-categories of the TREND
analysis. This may be done opportunistically, choosing the most promising ones first. This phase is discussed in Chapter 5.

- PDS – represents the construction of the Product Design Specification (PDS). This is considered be a very important objective of the design process (Pugh, B1-1990, 1996). This phase is discussed in Chapter 6.

My recommendation is that, while following any design methodology, particularly TREND-MORPH-PDS, the designer should not become too pedantic about procedure. The designer will do well to read widely about Design Science and the many paradigms and methodologies that are available, keeping an open mind and always looking for new opportunities.

1.5 CONCLUSION

My UniPump project illustrated the need for methodologies such as TREND-MORPH-PDS to guide the designer. Chapter 7 details the methodology’s application as it aided my progress from my earlier, narrow focus on solar pump design to the broader and more systematic thinking (Zwicky (B1-1969) would say the “morphological approach”) that produced the concept of UniPump and the various spin-off concepts.

In Chapter 8, the final chapter of this thesis, I will sum up my work in the area of ground water pumping technology, my contributions to the area of mechanical machine technology, and my innovative design methodology. The main focus of this thesis is on innovative design methodology. In this final chapter I summarise the work performed on TREND-MORPH-PDS, its relevance, benefits, limitations and further possible research to be done in the engineering design area.
CHAPTER 2

MOTIVATION AND BACKGROUND

2.1 INTRODUCTION

The OPEC oil embargo of 1973-4, which encouraged a resurgence of interest in solar energy, coincided with my gaining my professional qualification (BE equivalent) in mechanical engineering at the Western Australian Institute of Technology (now Curtin University of Technology).

This precipitated in me a life-long interest in ground water pumps for remote and low infrastructure areas of the world, areas where conventional energy sources are usually limited.

As I mentioned in the previous chapter, in 1986 I founded a technology company (Dartnall Engineering and Innovation Pty Ltd now called Heliseal Pty Ltd). This company has successfully manufactured and sold about 150 innovative photovoltaic ground water pumps. Through the company I have developed and patented several inventions related to fluid pumping and linear actuation. Heliseal formed a long term association with a 130 year old Western Australian company (W D Moore Pty Ltd) that has been manufacturing wind pumps since the 1890’s and has now formalised an agreement to adapt my pump design for wind-driven pumping and to produce it. My pump can also be used with energy sources such as solar, internal combustion engine and human power (hand pumps for villages of developing countries).

Over time, I became increasingly aware of the fact that working to a good engineering design process is crucial to the success of projects such as mine. This caused me to turn my attention to the significant research that has been carried out in the areas of systems engineering, design science, design methodology and design methods in recent years. Design, particularly innovative design, involves more than engineering science and practice, economics, and social science. Engineering design involves planning for future human activity. It results in the creation much of our material world and thus interacts with our way of living, and the physical environment in which we live. It can
significantly influence our quality of life, the time we spend working, our compatibility with the environment, our materials and energy consumption and many other important things. Good design must address complexity and this presents a motivating challenge.

2.2 THE CHALLENGE, THE MARKET AND THE INITIAL DESIGN FOCUS

As I mentioned above, my interest in groundwater pumping goes back to the years of the OPEC oil embargo, 1973-4, when there was a resurgence of interest in using solar energy. In 1974 my major final year design project was for a thermal solar water pump. I was motivated by the prospect that solar energy could reduce our dependence on oil.

During that project and in subsequent years, I became aware of the need to design for issues such as: best efficiency; reliability; ease of maintenance; cost; distribution; and many others. I realized that solar pumps would not become competitive in the market unless they could demonstrate improvements over existing technologies such as wind pumps and electric submersible pumps. Later my company focussed its attention on a market that I labelled "the market for low yield ground water pumping systems". I considered that my company should not invest in the design and development of surface water pumping systems, because the technical challenge to provide pumps for this market was much less than that of pumping from tube wells. The surface pump market was mature and highly competitive, with less opportunity for inventive/innovative improvement. I saw as much more significant, the challenge of recovering water from small diameter wells, while minimizing capital and operating cost, distribution cost and environmental impact.

The market which then attracted my attention continues to present an extremely complex situation, both technically and commercially. The local environment differs from well to well, raising the question as to how to gain the benefits from volume production of a standard system, and at the same time optimize the system for local requirements. Some bore-hole locations have reliable wind energy and low solar insolation, others have adequate sunshine but unreliable wind energy, and others have neither wind nor sun. In many locations, the cost of providing grid power is prohibitive. Most locations have some degree of difficulty or high cost associated with providing
hydrocarbon fuel for an engine driven pump. Because of their remoteness, distribution and servicing of products in these locations is difficult. The depth and quality of water in the low yield bore-holes are also variable: in many locations they impose severe constraints on pump design.

I became aware of various markets for bore-hole (tube well) pumps around the world such as Australian and American stock-watering bores (Fraenkel, B2-1993; Allen and Davidson, AWRC Conference, B2-1982). These are traditionally pumped at flow rates in the range 0.1 to 2 litres per second (usually less than 1 litre per second). The depth of the pumped water in a typical bore-hole may be anywhere between 5 metres and 100 metres (rarely deeper). I hypothesized that these flow rate limitations for stock watering wells related to two things: the natural water inflow rate in typical wells, and the amount of water required to meet the demands of the maximum stock level which could be allocated to a particular well. Excessive live-stock concentrations damage the environment surrounding the wells. Animals only feed within a limited radius of their water source, so they tend to over-graze within this radius, causing local environmental damage. Discussions with various station managers and farmers confirmed my ideas and supported my concentration on the flow range referred to above.

There are many other interesting markets, such as those for the approximately two-hectare farmlets that are typical of many developing countries. Grid electric power is not available in these situations (Hulscher and Fraenkel, B2-1994; Carruthers and Rodriguez, B2-1992). Other markets include tube well pumps for village water supply (Arlosoroff et. al. B2-1987). Because of the potential health improvement associated with sealed tube well hand pumps, this market has received significant attention from The World Health Authority. A web-search on “UNDP hand pump” reveals many web-sites that detail international hand pump projects. One excellent site is:

http://www.lifewater.ca/ndexkard.htm

Yet another market is in the many thousands of islands and estuaries around the world that require low volume flow rates of pumping from fragile underlying fresh water lenses. High volume or over-pumping of these fresh water lenses causes salinity damage to the lenses by drawing up the salt water table below them. A search under "island fresh water lens" gives many articles relating to this problem such as:
2.3 MY EARLY FOCUS ON TWO DESIGN ISSUES: EFFICIENCY AND RELIABILITY IN THERMAL SOLAR PUMPS

From the 1950's until the late 1970's there were many researchers working on conversion of solar energy to mechanical energy (particularly related to devices such as pumps). A comprehensive review of these devices (Spencer, B2-1989a,b&c) concluded that "since 1980 the great optimism surrounding solar powered devices, particularly pumps, has been whittled away as the magnitude of the technical task became better appreciated. With fuelled systems, a constant and controllable heat source is available and taken for granted. With solar energy, there are diurnal and seasonal variations, which are predictable, then there are essentially random variations due to cloud cover. These must be added to all the normal problems encountered in power conversion systems." The review also noted the need for extra attention to reliability and maintenance of plant because it is usually situated in remote locations, often with little or poor technical infrastructure.

For me, the above problems became challenges to search for possible solutions to these problems. I worked to improve my understanding of the problems, and I experimented with ways of working within the related constraints or of overcoming them.

Starting with feasible options such as those implied in Fig 2.1, in 1975 I decided to design and build an experimental pump. This work is detailed in the drawings and photographs in Appendix A7.2. The pump used a double glazed flat plate solar collector. Double glazing was chosen to allow efficient operation at higher temperature. A flat plate design was chosen for simplicity. The working fluid was ammonia, selected for its superior thermal properties and its availability in remote agricultural areas and in developing countries. The ammonia was to drive a liquid piston in the collector's heat transfer tubes. In one of the prototypes built, tubular diaphragms separated the ammonia from a hydraulic fluid. This integrated design was chosen to reduce thermal mass and complexity. The liquid piston actuated a hydraulic-over-mechanical drive to a
conventional down-hole bucket pump (as used in wind pumps). The pumped water was
to be used as a coolant in the simple tubular condenser required for the working fluid. A
small injector actuated by the reciprocating drive injected the liquid ammonia into the
collector, where it was expanded by the high temperature heat supplied by the collector.

Figure 2.1: Feasible options for solar powered pumping systems, adapted from
Fraenkel, (B2-1986)

Figure 2.2: Model of my 1975 thermal solar pump
The reasoning behind the liquid piston was that this would enable boiling and expansion
of the thermodynamic fluid to take place directly at the riser tubes in the solar collector,
thus minimising heat energy loss. A liquid piston could readily be manifold into many collector tubes and harness the expansive motion available. For its time, this integrated concept was very innovative.

2.4 COMPLEXITY AND MORPHOLOGY

My system was essentially a compact (integrated) version of one chosen from the left side of Figure 2.1 and modelled as shown in Figure 2.2. The analysis that resulted in my concept was essentially an example of the morphological approach applied to a complex situation. I will show later just how much more complex the situation really is.

I can summarize the reasons for this system configuration as follows:

1. The collector was to be a flat plate type because the farming environment requires robustness and simple construction that only a flat plate can offer.

2. The collector was to be a double glazed, and possibly of honeycomb construction or even of evacuated tube construction (Duffie and Beckman, B2-1974), so as to operate at a high enough temperature for the trade-off between collector efficiency and thermodynamic cycle efficiency to be acceptable.

3. The collector was to be integrated, in the sense that boiling of a two phase organic fluid (refrigerant 12 or ammonia) was to take place directly over (possibly with membrane separation) a hydraulic transmission fluid. This is known as a liquid piston arrangement. I reasoned that losses due to re-condensation of the thermodynamic fluid would be minimised by having the expansion (conversion to useful work) take place in the collector. Further, this integration would support the very desirable "design for manufacture and assembly" (DFM/DFA) and "design for maintainability" approaches to design. It would also result in a compact modular system that could satisfy stringent requirements for hermetic sealing. A small liquid injector would be fitted to the collector at its top point, with manifold distribution to the evaporator tubes, which would in fact be the collector tubes.

4. The hydraulic transmission would be kept short and would require insulation to minimise heat energy loss. It would drive a hydraulic cylinder, which would be part of a
mechanism whose mechanical advantage would vary to compensate for the "Rankine Cycle" pressure fall beyond "cut-off point".

5. The mechanism in 4 would reciprocate a down-hole rod driven "wind-pump".

6. The cool, pumped water would recondense the thermodynamic fluid on its way to its destination.

At the point of designing and constructing my system I became aware of the problems mentioned by Spencer (B2-1989a). My concerns were reinforced by Spencer's work. I developed a keen interest in the critical issue of overall system efficiency of systems of this type, which was very low. The reason for the low system efficiencies can be understood from the typical energy conversion efficiencies in Table 2.1, below. Since the elements of the table apply serially the one percent bottom line efficiency is (very roughly, ignoring solar fluctuation) the product of the individual efficiencies.

| Daily average collector efficiency (peak fluid temperature of 100 °C) | 20 % |
| Thermodynamic cycle ideal efficiency (daily average) | 15 % |
| Ratio of real cycle to ideal cycle efficiency (daily average) | 70 % |
| Transmission efficiency (daily average) | 70 % |
| Down-hole pump efficiency (daily average) | 80 % |
| Daily average over all system efficiency - approximately equal to the product of the component efficiencies above. | ≈ 1 % |

**Table 2.1: Typical component and overall efficiencies of solar thermal pumps**

In his comprehensive review, Spencer gave measured instantaneous overall system efficiencies (conversion from solar radiant energy to water-power) of a number of solar thermal pumps manufactured in the 1970's. Some examples are:
Table 2.2: Some published examples of overall efficiencies of solar thermal pumps

<table>
<thead>
<tr>
<th>ORGANIZATION</th>
<th>CLAIMED EFFICIENCY (%)</th>
<th>POWER (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solahart (Western Australia)</td>
<td>3.5 - 3.88</td>
<td>130</td>
</tr>
<tr>
<td>Kishore (India)</td>
<td>0.7</td>
<td>100</td>
</tr>
<tr>
<td>Dornier (Germany)</td>
<td>1.8</td>
<td>1000</td>
</tr>
</tbody>
</table>

Most researchers and designers of these thermal solar pumps opted for fixed flat plate non-concentrating collectors for practical reasons. Collector efficiency diminishes with increasing plate temperature (for a given ambient temperature) according to the Bliss Equation (Duffie and Beckmann, B2-1974). However, thermodynamic cycle efficiency increases with plate temperature and has the upper theoretical limit of the Carnot efficiency, $\eta_C$, where $T_H$ and $T_L$ are the upper and lower absolute temperatures respectively:

$$\eta_C = 1 - \frac{T_L}{T_H}$$

In reality the cycle is even more stringently limited by the Curzon and Albhorn equation, which takes account of heat exchanger economics as outlined by Ibrahim et. al. (B2-1992).

$$\eta_{C&A} = 1 - \sqrt[2]{\frac{T_L}{T_H}}$$

This efficiency is even further limited in practical cycles using real fluids. The combined effect of these constraints can be summarized by an exergy analysis, as in Manfrida and Kawambwa (B2-1990), where, based on several different organic fluids, an ideal daily average Rankine cycle efficiency of a little less than seven percent is predicted. The Curzon and Albhorn limitations are not included in this figure (7%) and would further reduce it to three or four percent. This analysis gives theoretical support to the very low practical efficiencies claimed in Spencer's review.

One could argue that low efficiency may be acceptable because of the abundance of solar energy. However, for a given water power requirement, the lower the efficiency of the system, the greater will be the collector area required and hence the greater the cost.
Double glazed flat plate collectors become expensive on a per unit area basis, as they require robust design to withstand severe wind loading and to endure severe thermal conditions without rain intrusion or working fluid leakage.

2.5 THE FUNDAMENTAL MECHANISMS OF ENERGY CONVERSION FROM SOLAR ENERGY TO MECHANICAL ENERGY

The number of possible choices available to the designer/researcher looking for "the best" solution to the solar thermal conversion problem is very large. This is also the case for solar photo-voltaic conversion, which is still the subject of intensive research.

I asked myself the question "are there some simple generalizations, which will help determine the most promising direction to follow". In his book, "Conceptual Design for Engineers", French (B1-1998) would no doubt locate this approach to engineering design in his chapter entitled "Insight". There has been a great deal of scientific research on thermodynamics and the thermodynamics of engine cycles. However, the resulting literature does not appear to be useful to a solar engineering designer trying to decide which thermodynamic fluid to use, or which thermodynamic engine cycle is more appropriate. Since my early efforts, researchers have tried a very wide range of thermodynamic fluids, cycles and configurations, each with its own peculiar advantages and disadvantages (Spencer, B2-1989a,b&c).

My attempts to gain "insight" (apart from reading as many papers on solar engines, pumps and other solar energy topics as I could find) were as follows:

- Investigate a wide range of thermodynamic fluids to see if a trend related to, say, molecular mass, might reveal some useful information. As Pugh (B1-1991), indicates, this sort of analysis can be a powerful tool for gaining insight into the make-up and interrelationships between parameters involved in engineering design problems.
- Investigate the Second Law of Thermodynamics and its consequential limitation on thermodynamic cycle efficiency, related to the Carnot efficiency. In this respect, I was curious about the possibility that a more stringent (but general)
formula than the Carnot formula, could apply to low temperature solar engines. Eventually I came upon the Curzon and Albhorn constraint.

- Investigate a wide range of thermodynamic engine cycles and related practical issues like: heat loss; fluid loss; friction; power to mass or size ratio; and many more.

The thermodynamic fluid investigation revealed an interesting trend, supported by science based knowledge (e.g., the kinetic theory of gases) that, in general, fluids have better heat transfer properties if their vapours or gases have molecules of lower molecular mass. Hydrogen is of course, at the lowest end of a spectrum of candidate fluids. Hydrogen is used in certain engineering situations requiring excellent heat transfer (cooling of power station alternator windings, nuclear reactor cooling and Stirling engines). Hydrogen, of course, is not condensable in the temperature range of a flat plate solar engine. For many practical reasons a two-phase cycle seemed preferable, so I chose ammonia. It has excellent thermodynamic properties, is an agri-chemical and is therefore widely available, and it is environmentally safe. Ammonia had the lowest molecular mass of all valid candidate fluids and was known to have excellent heat transfer properties. One of the problems with thermal solar engines and pumps is that the solar energy input rate to the collector varies rapidly as clouds obscure the sun, and the (necessary) thermal mass of these systems results in a slow response rate to this variation. This seriously reduces the "daily average energy conversion rate", due to thermal mixing.

I became interested in the idea of considering the electron as belonging to the above spectrum of molecules. It is very much smaller in mass that the hydrogen molecule, so it sits out beyond the H₂ end of the spectrum. In a thermionic converter, the electrons pass through a thermodynamic cycle which is analogous to a continuous thermodynamic engine cycle (such as the Rankine steam cycle). Modified Carnot formulae may be used to estimate the efficiency of both thermoelectric and thermionic converters (Angrist, B1-1982).

In a photo-voltaic converter, the electrons pass through a cycle, but the system is not dependent on temperature in the way that thermoelectric and thermionic systems are. Instead, the incoming photons interact directly with the electrons, driving them to a higher potential. Thus, photo-voltaic systems do not have the thermal inertia problems
present in the thermodynamic engine systems. Electric current flow is very much faster than conductive heat flow and in practice much easier to contain than heat energy. The high speed of electric current flow may be viewed as being related to the relatively small mass of the electron, with its consequent high equilibrium velocity within the lattice of the conductor. This is well understood by physicists. The containment of electrons is easily accomplished, as we well know, by means of conductive and semi-conductive materials having insulating cover for protection. Fluid leakage is a big problem with thermodynamic systems, which require hermetic sealing to contain relatively small quantities of working fluids to be retained for many years. Hermetic sealing is well known by engineers to be difficult and expensive to achieve and maintain. Heat energy leakage is also well known by engineers to cause major problems.

All the benefits of a photovoltaic system could be expressed in terms of the insight gained by viewing the electron as a particle positioned on the end of the above-mentioned molecular mass spectrum.

With regard to the Second Law of Thermodynamics and its application to low temperature heat engines, a so far unpublished paper (Dartnall, 1979, revised 2002-to see, refer to author) presents my detailed views and findings. This paper was developed as a result of the frustration of trying to make early stage design decisions, based on the limited understanding that I had gained from my undergraduate classical textbooks engineering thermodynamics (Rogers and Mayhew, B2-1967; Holman, B2-1976; Duffie and Beckman, B2-1974). I have since come to the view that it would take too much time to gain the deep understanding that I would love to have, an understanding based on the foundation of a comprehensive and coherent mathematical structure. Designers need more efficient and less time consuming models of phenomena. Visual models may be an effective alternative. French claims that designers often think visually. He does note, however, that our education systems largely fail to take visual education seriously (French, B1-1994).

The analysis provided in my paper has two outcomes.

- The first is that it demonstrates the possibility of modelling the thermodynamic fluid in a heat engine using a macro-mechanical model, with just one perfectly
elastic sphere representing the fluid, and giving up rebound energy to a perfectly elastic piston. It shows that a Newtonian mechanical analysis can effectively produce the Carnot efficiency. For me this cleared away the mysteries surrounding the Second Law of Thermodynamics as it applies to the Carnot limitation. The traditional engineering text book treats the Second Law somewhat mysteriously, justifying it using proof by contradiction rather than physical demonstration. In my opinion this approach is unhelpful for visual- and physical- thinking designers. Almost all the practising thermal engineers I have known have made comments like “never understood that” about concepts like entropy, exergy and The Second Law.

- The second outcome of my paper is that it shows us how to derive the entire family of thermodynamic engine cycles having Carnot efficiency and to present this family in a visual way that promises to give the designer a more efficient technique for comparison between cycles.

### 2.6 MOTIVATION TO CREATE A BETTER GROUND WATER PUMPING SYSTEM

I have explained how I became interested in the invention, innovation, design and development of solar pumping systems in the 1970s, when little was known about the practical complexities of solar-thermal and photo-voltaic systems. Many novel ideas were emerging and each of the solar-thermal and photo-voltaic technologies was a rich area for research. These technologies seemed like a paradise for researchers and inventors.

The engineering designer's object is not merely to find novel designs, but rather to find improved designs. In the 1970s the most common ground-water pumping system in use on Australian farms for stock water was the reciprocating piston wind-pump, which had been in use for over 100 years. One of the problems with wind pumping is the risk of prolonged periods of insufficient wind, referred to by farmers as "wind drought". The progressive cavity pump driven by IC engine was often employed in wind drought affected regions. The solar pump presented a promising renewable energy alternative for these regions. Another alternative to the wind-pump was the electric multi-stage
submersible pump, which was, however mostly limited to locations having ready access to the power grid.

The solar powered ground water pump looked very promising. However the design of an improved ground water pumping system, based on new and rapidly improving technology, required a complex hierarchy of critical design decisions. Because of cost and time limitations, these design decisions could only be made in an environment of incomplete knowledge and data.

In the 1980s, as my company designed and installed solar water pumping systems, I learned about many pump applications problems, problems which were quite distinct from those associated with the new solar technology. These problems related to the local hydro-geology, the local landforms, geography and wind and solar regimes. Designing an adaptable system became an increasingly attractive way to go. The situation was complex. The end clients, the farmers, simply want trouble free water for their stock at the lowest possible overall cost. They do not have time to be involved in the complexities of how this is achieved. This requires the satisfying of many requirements and constraints, using volume production methods to keep the cost to a minimum.

I read about systems engineering. Various authors (Blanchard et. al., B1-1990; Bued, B1-2000) describe how we have moved from the machine age, with its dependence on reductionism and mechanism, to the systems age with its teleologically-oriented systems approach. This confirmed some concerns that I had about the design directions that some of my competitors in the (low yield) ground water pumping industry were following.

I noticed a trend, in which most ground-water pump manufacturers were abandoning the older surface driven, low frequency reciprocating piston pumps, in favour of the relatively high frequency multi-stage centrifugal submersible pumps because of their apparent elegance for ground water pumping. In the case study (Chapter 7), I explain how the reciprocating pumps are more efficient in the low volume regime.

These manufacturers seemed to be optimizing their designs for their own manufacturing and marketing systems. They were following low cost approaches of adapting their
standard pump technologies (which evolved in relatively large flow regimes) to this special low yield regime. The trends I could see were further complicated by the fact that manufacturers were adapting their standard technologies to the as yet un-developed solar power technology. Their designs were not, in my view, the most suitable for this market. I could see a need to take an innovative design approach, involving a broad view of the issues, in contrast to the narrow views of the manufacturers.

I had reached a stage where I could see many problems with the way the manufacturers in this industry were designing (or not designing) and applying their systems. They seemed to me to be simply optimizing things for their own commercial benefit, rather than designing for the clients’ needs. My curiosity about the design process was kindled and I needed to know a lot more about it.

2.7 THE NEED TO INVESTIGATE DESIGN METHODOLOGY

During the time that I have been reading and researching the views of various engineering designers and the recommendations of researchers on engineering design processes, I have been working on my own low yield pump design as a real problem and thinking about it as a case study.

Some time ago I drew the chart shown in Figure 2.3. This was based largely on my own experience, rather that on the design theory literature.

My perspective was that of an engineering designer working for a relatively small engineering manufacturing company. Such a company could be a family company like the wind pump manufacturer that I am associated with. The designer in this type of company will usually be multi-skilled and may be involved in many functions including original conception of new ideas, marketing, selling, costing and manufacturing as well as design and development. I began to think of how the designer operates in terms of Figure 2.3.
## Table 2.3: A table produced in 1995 showing the range of knowledge, tools, procedures, activities and representations that an engineering designer deals with.

<table>
<thead>
<tr>
<th>KNOWLEDGE BASES</th>
<th>PROCEDURES</th>
<th>ACTIVITIES associated with invention</th>
<th>LANGUAGES OF DESIGN</th>
</tr>
</thead>
<tbody>
<tr>
<td>Natural sciences</td>
<td>Cross's model of the design process</td>
<td>Abstraction from concrete objects to objects, words, symbols</td>
<td>1 SEMANTIC</td>
</tr>
<tr>
<td>Applied sciences</td>
<td>Burger's model of the design process</td>
<td>Definition; usually from concrete objects to words, symbols</td>
<td></td>
</tr>
<tr>
<td>Engineering sciences</td>
<td>Fugels model of the design process</td>
<td>Analogy from concrete objects to objects, words, symbols</td>
<td></td>
</tr>
<tr>
<td>Technologies</td>
<td>Ulman's model of the design process</td>
<td>Pattern recognition of objects, words, symbols</td>
<td></td>
</tr>
<tr>
<td>Specific technologies</td>
<td>Pat and Bick's Model</td>
<td>Symmetry of objects, words, symbols</td>
<td></td>
</tr>
<tr>
<td>Patent System</td>
<td></td>
<td>Inversion of objects, words, symbols</td>
<td></td>
</tr>
<tr>
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<td>State of the art</td>
<td>Finite element methods</td>
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<td>in the technology</td>
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The product of the designer may be the detailed description (in the form of drawings and specifications) that establish a product for many years. Consider the wind pump. The concept is centuries old. The galvanized steel wind pump which is popular on Australian farms has scarcely changed in over 100 years. The product of the designers of about 100 years ago has stood the test of time. It is still valid for those companies that still produce to those early designs and to their clients.

A product such as the wind pump has influenced the way of life of many people for many years. Stakeholders of wind pump manufacturing companies include owners, investors and employees, as well as farmers and other users of wind pumps. Figure 2.3 indicates that the engineering designer of a product may need access to a very wide range of skills, knowledge bases, tools, modes of thinking and means of communication, in order to achieve a good design. Could the design have been different than the one that we are familiar with? Figure 2.4 shows the design of a wind pump driving gear of an obsolete pump, known as the Canadian Imperial Pump (Butler, 1913), which is different from the common direct and geared heads that have been in use for over 100 years. Figure 2.5 shows the Yellowtail, which is representative of the standard geared wind pump and is manufactured by W D Moore in Western Australia. In 1903, tested by the Royal Agricultural Society against the common wind pumps that have been so widely used since, the Canadian Imperial machine was found to produce nearly twice the water flow rate of other machines of comparative wheel diameter and height and under similar wind conditions.

Why did the Canadian Imperial machine not become the standard for the industry? Why did the manufacturers settle for the poorer designs? It would, no doubt have been more expensive to produce its more complex double rack arrangement than to produce a direct acting or geared heads of the others. However the extra expense of the Canadian Imperial driving gear could perhaps have been compensated by using a smaller wheel and lighter tower than the competitors required for a particular water delivery rate. Many tonnes of galvanised steel could have been saved over the years. The crucial feature of the Canadian Imperial machine is its long stroke. In addition, the long stroke is accomplished at predominantly constant velocity, so that the torque requirement is relatively uniform. In the other machines, the torque requirement is approximately
sinusoidal. Because of this more even torque requirement, the Canadian Imperial machine was also able to pump at lower wind velocities than its competitors.

**Figure 2.4:** The long stroke Canadian Imperial pump manufactured in the late 1800s.
**Figure 2.5:** A Yellowtail pump of conventional design produced by W.D. Moore and Co. of Western Australia.

**Compare the Features... Yellowtail Windmills... Outstanding in the Field.**

- **Wheel:** The wheel turns in the lightest breeze, yet is rugged enough to withstand gale-force winds. It is perfectly aligned and enclosed close to the center of the main bearing for even weight distribution and greater efficiency.
- **Spokes:** Strong; one-piece "A" frame arms make the unit easier to assemble and hold the windwheel sections rigid.
- **Sails Built into the Wheel:** These galvanized steel sails, built into the wheel for rigid positioning, are spaced, shaped and curved to give maximum pumping efficiency with easy starting.
- **Hub:** Hinged on special techniques, the hub spindle is pressed into the hub and pressed in order to achieve positive bonding.
- **Turntable:** The windmill rotates on a piece of a welded stub tower. Steel thrust washers carry the weight of the head and allow it to move smoothly with the slightest change in wind direction. Adequate lubrication during operation is provided.
- **Rigid Stub Tower:** Bolted to the top of the windmill tower, the welded steel stub tower forms an apex for the tower proper and prevents the windmill from being hit by an existing tree. The stub tower is available in three or four post towers.
- **Twine Pinions:** Cast in one piece and secured to the hub spindle using high-tensile dowel pins. This ensures that the teeth are always in line and allows easy transfer of load to each of the main self-aligning gearwheels.

**Simple Erection and Assembly.**

- **Galvanized Steel Head Cover:** Protects the mechanism from excessive wear usually caused by the entry of rain and dust. Quickly and readily removed for servicing. The cover, when removed and attached to the tail bone, serves as a convenient tool box.
- **Main Casting:** Is lined for the hub shaft and fitted with high-quality replaceable, push-in bearings. This enables all bearings to be replaced without bringing the gear tubes down from the top of the tower, thereby saving valuable time and reducing maintenance costs.
- **Guide Loop:** Round section guide loop has been used for greater strength and stability. It provides larger bearing surface for the guide roller, prevents side movement, and significantly reduces wear.
- **Crosshead Oiling:** The crosshead controls in the oil reservoir pick up oil, transferring it to the oil rings as they break and turn on the gearwheels. Oil is then carried to the crosshead, guide loop and guide roller.
- **Automatic Self-oiling System:** Change of the oil once a year and no further oiling is required. The hub spindle bearing is slid automatically by a wiper which picks up oil from the pinion and delivers it through a specially designed sleeve. The correct quantity of oil is supplied with each new head.
- **Double Self-aligning Gearwheels:** The gearwheels operate independently of each other. This ensures that each gearwheel transfers an equal part of the load via the connecting rods to the crosshead assembly to which the pump rod is connected.
2.8 CONCLUSIONS

I have found continuing challenge and motivation in design work. It is exciting to discover how important and how complex the design and development of a new product or engineering system can be, particularly in an area where the technology is developing rapidly.

During the evolutionary process leading to the concepts of the pumping system known as UniPump, and to the design methodology I have called TREND-MORPH-PDS, I have dealt with the following challenges:

- Designing, constructing and patenting an innovative solar thermal ground-water pump.
- Learning the physical fundamentals of thermal and solar-thermal engineering.
- Learning the limitations of solar thermal systems.
- Involvement with the early commercial introduction of photovoltaic systems.
- Learning how the knowledge, skills, science and processes required for good engineering design differ from those generally understood to be necessary for the more narrowly-focussed but still important engineering sciences.
- Learning the importance of the influences of the stakeholders on any engineering design/development venture. In my experience, this is an extremely important area. I believe that the type of project that I have chosen is inherently a long term project. The first factor suggesting this is the fact that the wind-pump was virtually the only solution and remained unchanged for approximately 100 years. This has been the case with other mechanical machines such as the beam pump for artificial lifting of crude oil. The clients such as farmers and oil harvesters do not want pumps that are short lived, unreliable and require constant maintenance. They have preferred and would prefer pumps that they can easily repair when maintenance is required and for which spare parts and service are readily accessible when required. These factors equate to a long term approach to the entire business of serving the farmers with their pumps. This type of business does not seem to be understood by the stock market stakeholders in Australia.
• Learning how to balance these influences carefully, in order to obtain the necessary resources to maintain the continuity of a project involving a new concept in order to achieve a commercial outcome. It is essential to have a clear goal and to keep this goal in mind in dealing with every sub-problem.

• Learning about the progress that design theorists are making toward Design Science and the many research efforts in developing computer based tools to support engineering designers.

• Learning how technologies that are not ideal can succeed commercially and in practice, even where it would have been better in the long term, to be more thorough at the design stage in order to produce a superior design.

• Learning how to avoid the above-mentioned inferior choices and persevere with a long term design development.

The one lesson that is supreme is: maintain enthusiasm, perseverance and adherence to the goal.
CHAPTER 3

LITERATURE REVIEW

3.1 INTRODUCTION

In recent years many researchers have investigated engineering design from a variety of perspectives. There is a widely held view that engineering design is simply a problem solving exercise, that the designer starts out with some dissatisfaction with some (usually physical) aspect of the world and sets about to improve the situation by designing a new artefact, machine, system or process that will minimise or eliminate the problem(s). Unfortunately this model of design, as a problem solving process with simple routine procedures, is impossibly simplistic. The reality is usually much more complex, particularly if a design is expected to meet the needs of a broad spectrum of stakeholders. It is unusual for the problem to be completely understood at the start, making it more difficult to decide how to proceed in trying to solve it. Even when the problem has been defined, there are usually several solutions whose suitability needs to be evaluated in order to decide on the most appropriate one.

There are time, economic, social, stakeholder and technical reality constraints on design. Thus the efficiency and effectiveness of the design methodology to be used is of special interest to people who specialize in design or who depend on the outcomes of design.

In this chapter I review some of the main paradigms related to design methodology and discuss the merits and limitations of the various approaches to engineering design situations.

Finally, I summarize research efforts in the area of design process and methodology theory.
3.2 SOME DEFINITIONS RELATED TO ENGINEERING DESIGN

Before discussing the various design paradigms I will give some of the common definitions related to engineering design. Design is such an ubiquitous human activity that definitions abound. The ones below are sufficiently representative and have been gathered from authors such as: Dieter, B1-2000; Roozeburg and Eekels, B1-1995; Otto and Wood, B1-2001.

Engineering design:

- Design establishes and defines solutions to problems and pertinent structures of problems not solved before, or new solutions to problems which have previously been solved in a different way.

- To conceive the idea of some artifact or system and/or to express the idea in an embodiably form.

- Original design (or inventing): involves elaborating original (new/novel) solutions to a given task. The result of original design is an invention. Examples are: the transistor; the automobile when first invented. Few original designs occur over time and when they do they can disrupt the market, as the transistor did with the valve market.

- Adaptive design (or synthesis): involves adapting a known system to a changed task or evolving a significant subsystem of a current product (such as antilock brakes). Adaptive systems can be very novel but they do not require massive restructuring of the system within which the product operates.

- Variant design (or modification): involves varying the parameters (size, geometry, materials properties, control parameters etc.) of certain aspects of a product to develop a new or more robust (or cheaper) design- e.g., re-sizing a bearing to a larger size to accommodate an increased load.
• Redesign: is a term that is used to mean any one of the above. It simply implies that a product already exists that is perceived to fall short on some criterion, and that a new solution is needed.

3.3 THE NATURE OF ENGINEERING DESIGN

Engineering design is about problem formulation and solution, where the solution is in the form of an artifact or engineering system. This artefact or engineering system is to offer an improvement to people who are stakeholders, primarily the clients or the end users of the product. The process of problem solving in design is usually complex and elusive for a number of reasons that have been observed by many authors:

• The design problem to be solved is often ill-defined

Well-defined problems have a clear goal and often only one correct solution. In addition well-defined problems have rules or known procedures that will generate the answer(s). The following are characteristics of ill-defined problems in general and design problems in particular (Cross, B1-2000: pages 14 - 15):

• There is no definitive formulation of the problem

When the problem is initially set, the goals are usually vague, and many constraints and criteria are unknown. The problem context is often complex and messy, and poorly understood. In the course of problem solving, temporary formulations of the problem may be fixed, but these are unstable and can change as more information becomes available. For example, the client may be an end user of a product such as an engine, with initial concerns about cost. However this client will also be concerned about: running costs; fuel economy; availability and costs of spare parts and maintenance labour. The client may also be directly or indirectly concerned about environmental matters such as engine emissions and noise pollution. The client usually does not readily articulate a well evaluated view of his requirements.

• Any problem formulation may embody inconsistencies

The problem is unlikely to be internally consistent; many conflicts and inconsistencies have to be resolved in the solution. Often, inconsistencies emerge only in the process of
problem solving. In the engine example above, how much emphasis should be placed on each aspect? Improving the fuel economy or reducing the noise pollution of an engine usually results in an increase in the capital and maintenance costs. How should the designer balance (trade off) these inconsistencies?

- Formulations of the problem are solution-dependent

It is difficult to formulate a problem statement without implicitly or explicitly referring to a solution concept. The way the solution is conceived influences the way the problem is conceived. Again, different conceptual designs/subsystems of an engine will need considerable detailing before reasonable evaluations of the relevant costs can be made.

- Proposing solutions is a means of understanding the problem

Only proposing solution concepts can expose many assumptions about the problem and specific areas of uncertainty. Many constraints and criteria emerge as a result of evaluating solution proposals.

- There is no definitive solution to the problem

Different solutions can be equally valid responses to the initial problem. There is no objective true-or-false evaluation of a solution; but solutions are assessed as good or bad, appropriate or inappropriate.

### 3.4 "DESIGN SCIENCE"

The concept of a "design science" has been proposed (B1-Hubka and Eder, B1-1999). Simon, (B1-1969) has claimed that the science of design is possible and that some day we will be able to talk in terms of well-established theories and practices. Kuhn, (B1-1969) concluded that design was at a pre-science phase and must go through several stages before it constituted a mature science.

If we had a mature science of design, it would have a coherent tradition of research and practice which would be of value in teaching novice designers, and would embody law, theory, application and instrumentation. It would explain why design should be done in a certain way. It could specify how design should be done and it should even be general
in its application to various branches of engineering including civil, mechanical, electrical, electronic, computer systems etc.

Design research is being conducted from a wide range of perspectives. This is illustrated in Figure 3.1, which was produced by Roozenburg and Cross, (B1-1991) and modified by Konda et. al., (B1-1991) in their paper on shared memory in design. The diagram shows that some researchers have focused on the artefact, others on the process of design.

Researchers who have focused on the artefact have concentrated on representations leading to knowledge-based expert systems (KBES), grammars suitable for high-speed computation and procedures leading to such areas as computerized optimization and artificial intelligence (AI) in design.

On the process side of the diagram we have descriptive and prescriptive categories. The systematic morphological (German) group includes Pahl and Beitz (whose diagram is included below as Figure 3.2) and Hubka, one the authors of "Design Science". Also on the process side are descriptive researchers studying either the individual designer at work, or design and its relationships with society. Some individuals, like Cross (see section 3.5.1.2), work within more than one category.
Industry tends to ignore design science (Eder, B1-1998; Maffin, B1-1998; Frost, B1-1999). The research by Maffin and Frost attributed this to the following:

- Lack of awareness of the methods arising from research in design science.

- Many companies are specialized and projects do not involve substantial design changes. The problem-focused methods of design science are seen to be too complex.

- Industrial companies often develop design practices that are driven by the time and cost constraints of the industrial context and the problem-focused methods of design science are seen to be too time consuming and costly.

- Incremental designs are often driven by market oriented imperatives in a fairly obvious way without the need for complex fundamental methods.

On the other hand, it is my view that the above trends are all related to short term thinking. This often leads to companies becoming “locked in to” poor designs of products, families of products, technologies and systems (both manufacturing and marketing). In these cases, the cumulated investment at the point in time when decisions have to be made will cloud objective thinking about new designs, even though these designs could offer overall benefits to the stakeholders.

3.5 DESIGN PARADIGMS AND DESIGN PROCESS MODELS

Many design theorists outline processes of design with diagrammatic models that are centered on stages such as: clarifying the problem, conceptualizing, embodiment and detailing. Although important to our understanding, the diagrammatic models usually give no indication of the complexity of designing indicated in section 3.3.1 above. It is this complexity that has aroused so much interest in recent years. Particularly in original design, there are very many issues to be considered in a thorough approach to the design of a product.

A recent overview of design paradigms (a paradigm may be defined as: an agreed conceptual structure; a model; a pattern; or even a standard) is given in Braha and Manion (B1-1998). These authors place all paradigms into six categories. In the sub-
sections below I have used their paradigm categories to structure my review of the literature. An additional, seventh, paradigm was added after review of Petroski, (B1-1994), Bucharelli, (B1-1984) and Konda et. al., (B1-1991).

3.5.1 The Analysis- Synthesis- Evaluation (ASE) Design Paradigm

Cross (B1-2000) sums up the meaning of the terms as follows:

- Analysis: listing of all design requirements and the reduction of these requirements to a complete set of logically related performance specifications.

- Synthesis: finding possible solutions for each performance specification and building up complete designs from them with least possible compromise.

- Evaluation: evaluating the accuracy with which alternative designs fulfil performance requirements for operation, manufacture and sales before the final design is selected.

The ASE paradigm is very widely accepted by design theorists. It is unlikely that there is any design paradigm that does not contain analysis, synthesis and evaluation within its procedures.

The ASE model is iterative. It is rarely possible to produce and finalize all design requirements and specifications "up front". The problem is usually ill defined. Seriously performed synthesis never produces a unique solution. It should always produce alternatives to choose from. Solving the design problem is a learning process, in which the designer is learning about: the problem definition; the knowledge bases related to the problem; and the processes that are most appropriate for the occasion. Evaluating the solutions naturally leads the designer back to re-analysing the problem. The cycle will in practice be started at the point which the designer sees as most effective in the circumstances. It will then be repeated until an acceptable solution has been produced.

Many researchers have produced block diagram models that help to illustrate the ASE paradigm. Three of these are now discussed.
3.5.1.1 The Model of Pahl and Beitz (Pahl and Beitz, B1-1997)

This widely accepted prescriptive model (Figure 3.2) was originated by Pahl and Beitz about 1977 and advocates that design can be treated as a complete and strongly systematic process with provision for looping between stages (B1-1996).

One of the most significant contributions of this model is the idea of mapping customer needs to functional descriptions. This is known as "functional decomposition". The resulting function structures are used to generate sets of technologies that satisfy the functional requirements (Otto and Wood, B1-2001; Hundal, B1-1997).

Some of the advantages, claimed by Otto and Wood (pp. 148-150), for this "top down" approach are:

- The designer is required to concentrate on what is to be achieved by the product rather than coming forward too soon with how it should be achieved - i.e., pre-empting the solution. Functional modelling provides a solution- (form-) independent definition of the design problem and drives the designer to a comprehensive search for solutions.

- Functional modelling facilitates a "concurrent engineering" approach, by providing a basis for breaking down the design problem into independent modules. Interfacing specifications between modules are readily written using the function structures as a basis.

- Function structures may be derived directly from customer needs by modern QFD [quality function deployment] methods.

- Creativity is enhanced by the modular approach because each module, being smaller, is less complex and possible solutions become more apparent to the designer

- Because functional modelling is inherently an abstracting process it drives the designer/design team toward the "real" problem and minimizes individual biases.
• This "function to form" approach leads to the systematic generation of a greater number of solutions to the design problem, thus increasing the likelihood of finding a better one.

• Because of the way in which modules may be explicitly defined from the function structures, trade-offs between competing modules may be explored early in the design process, in keeping with the ideals of concurrent engineering.

These advantages are agreed, however it must be remembered that the context in which the authors list these advantages is reverse engineering, implying that the designer already has some physical form and the designer’s objective is the move away from this design with improvements. An emphasis on function provides a way of putting the existing form to one side and focussing on what the new product is required to do.

Some of the criticisms of this methodology are:

• The systematic methodology tends to be unnecessarily complex and time consuming.

• The problems related to corporate indifference mentioned in section 3.4 apply to the Pahl and Beitz methodology.

• Functional reasoning models are not, as yet, able to generate completely new solutions (inventions) (Chakrabarti and Bligh, B1-2001).

• Sometimes functional reasoning is unnecessarily tedious and time consuming without parallel reasoning about form. (Al-Salka et al., B1-1998).
3.5.1.2 Cross Model of the Design process

In his diagram of the design process (shown here as Figure 3.3), Cross (B1-2000) reinforces his statements of section 3.3 about the ill-conditioned and ill-structured nature of design problems. The double-ended arrows between problem and solution and sub-problem and sub-solution show the iterative nature of the design process. Cross
advocates a more "laisse-faire" approach than Pahl and Beitz. He recognises that, as more information comes to light during the solution processes, there is usually a need to go back and reassess the problem. This model also indicates that, because of the complexity of design problems, it is usually necessary to break the overall problem down into sub-problems of manageable size.

![Cross model of his more flexible ASE process](image)

**Figure 3.3: Cross model of his more flexible ASE process**

Birmingham et. al., (B1-1997) suggest that this model is the result of a more recent trend in the evolution of design models. While it contains the ASE cycle and shows a general structured directional trend, it also recognizes the need for designers to form an interactive problem/solution relationship early in the process.

My own view is that the Cross approach is somewhat of a reaction against the apparently rigid, structured methodology of Pahl and Beitz, who in turn were reacting against the tendency of designers to fixate on a particular design solution too early in the process, without proper investigation of alternatives. Focusing on the functional requirements rather than possible (known) solutions to the problem on hand is a disciplined way of abstracting, in order to take a broader view. However, this too has problems, related to the complexity of the abstraction process. Burger, discussed in the next section, advocates a detailed methodology more in line with the ideas of Cross.

### 3.5.1.3 Burger Model of the Design Process (Burger, B1-1995)

The Pahl and Beitz model is highly respected, but many subsequent researchers and authors have added methods and modifications of specific aspects of it (Shooter, B1-
1995; Dixon, L. A., B1-1997; Al-Salka et al., B1-1998). It should be noted that many of these researchers and authors are involved in developing software to support the design process, or in research related to the use of artificial intelligence in the design process.

Figure 3.4: Burger model of his process involving parameter analysis

The Burger model (shown in Figure 3.4) (Burger, B1-1995) introduces a methodology which focuses on "critical design parameter" identification, with a view to improving the effectiveness and efficiency of the innovative design process. The right hand region of Figure 3.4 is adapted from Pahl and Beitz: it classifies the sequential stages of the design process but does not show how best to proceed inside each stage (Pahl and Beitz outline their own methods).
"Design methodology is concerned with improving the level of performance within each of the activities in this framework; from need analysis to the development and evaluation of more than one conceptually independent and strongly competitive solution, culminating in a final selection, and the realization of the chosen concept assembly/system and detail drawings." (Burger, B1-1995)

The left side of Figure 3.4 outlines the methodology advocated by the Burger model. Abstraction is used to generate a function structure for the design need. Functions are generally expressed in terms of parameters of a general nature.

Burger gives an example of an automotive brake system, described in functional terms as "a device that transforms a vehicle's kinetic energy to other energy states at a sufficiently rapid rate". The kinetic energy transfer rate is identified as the critical parameter, amongst a hierarchy of parameters present within the generated function structure.

![Figure 3.5: Creative synthesis in the Burger Process](image)

Burger illustrates the creative design process with the model shown here as Figure 3.5. The designer is required to satisfy the function containing the critical parameter by discovering the best of a variety of configurations that he/she can generate: drum brakes; disc brakes; disc brakes with coolant etc. Innovation in both concept and configuration is helped by the process of switching between the two modes of thinking shown in Figure 3.5, as the designer searches his/her way through the various parameters related to the function structure.
The conceptual design proceeds by identifying a suitable technology, usually as a result of generating the function structure followed by generation of ideas, using methods such as brainstorming. A concept begins to take shape with successive parameter analysis loops. Sketches are usually drawn at each stage. Order of magnitude analysis and testing for functional independence are useful in evaluating the configurations.

Burger uses the terminology and axioms of Suh (B1-1990) in his paper:

- **Functional Requirement**: "FR"
- **Design parameter**: "DP"
- Axiom of independence: "An optimal design always maintains the independence of FR's. In an acceptable design, the DP's and FR's are related in such a way that a specific DP can be adjusted to satisfy its corresponding FR without affecting other FR's."

Burger recommends that designers employ a short list of the most general rules for embodiment design. The rules appear in French, B1-1999 and Pahl and Beitz, B1-1996:

- Maintain Functional Independence
- Do Not Over-constrain
- Let Form Follow Function
- Provide Functional Symmetry
- Match Impedances
- Design For Self-help
- Design To Fail-safe

This methodology seems to have many of the advantages outlined in section 5.1.1 under the Pahl and Beitz model, some of which are mentioned by Burger.

A recent book by Kroll, Condoor and Jansson, (B1-2001) describes many interesting examples of innovative conceptual design using parameter analysis.

### 3.5.2 Case - based Design Paradigm

Most mechanical engineers involved in design tend to practice case-based design. Design problems often involve working within set of constraints. For example, consider the following problem:
PROBLEM: To select a pump for pumping water from a dam, a distance of 3 km to a tank that is elevated 35 m above the water level of the water in the dam. You are given only three (3) models of pump to select from and two (2) diameters of pipe. You are given costs for all items as well as energy costs (as functions of head and flow) to run the pumps. Select the best combination to minimise total cost (capital and running) over a five-year period. Performance and data tables are available for pumps and pipe friction losses.

In the above problem, a high capital outlay will usually lead to lower running cost and vice versa. Two types of solution will probably compete with each other. In one, more money is spent on a larger diameter pipe system in order to save on energy cost. In the other, money may be saved by installing smaller diameter pipe, but more money will be spent on the energy needed to pump the water against the higher friction losses. The constraints in this problem are the limitations of what is available.

Now suppose we can choose from a wider range of pumps:

NEW PROBLEM: Consider a more open problem. The pump may be driven by any one of the following sources: wind, solar, I C engine or mains power grid. A complete range of pipe sizes is available. In addition, we broaden the problem so that it becomes a total system design for watering an orchard.

Do we need the tank? We could pump direct to the trees from the dam and save the cost of the tank. There can now be many competing designs and analysis of alternatives becomes tedious. Additional constraints may be wind and solar regime limitations in the vicinity of the dam.

People (engineers included) faced with a wide range of combinations of system components and numerous constraints will tend to draw on their experience of previous cases similar to the one under investigation.

If we use an engine driven pump, we will want a tank to gravitate to the orchard because the minimum sized engine-pump gives a relatively large flow rate (too large to directly water the orchard). Another constraint on this system is the need to keep to a minimum the frequency with which the owner needs to travel to fuel and start the pump. This will influence the size (and cost) of the tank.
If we choose the solar or wind option, the capital cost of these items will be considerable, however we will not need the tank and will save the cost of fuel. Additionally, if either of these sources has a reliable daily availability during the critical time of the year when the orchard needs water, it may provide an "automatic system", saving the owner the need to travel regularly to attend the pump.

As a design problem becomes more complex due to increasing number of requirements, constraints and available configurations, it is clear that solving it by adapting previously tried solutions to similar problems is a sensible way of avoiding tedious repetition. The designer thus solves the problem by drawing on his/her experiences (cases) rather than solving the new problem from scratch.

The mechanical designer is often dealing with tightly coupled and interacting situations, and in these situations "decompose and recombine" methodologies are unlikely to be as effective as case based approaches.

Case-based reasoning (CBR) has become a recognized paradigm and is an area of significant design research because of the increasing viability of developing computer software to manage knowledge bases for storage and retrieval of past designs (cases). Many authors are investigating the use of CBR with computer based design, Purvis, B1-1999; Goel, B1-1997; Simina and Kolodner, B1-1996; Goker and Birkhoffer, B1-1995; Smyth and Keane, B1-1995; Wills and Kolodner, B1-1994.

### 3.5.3 The Cognitive Design Paradigm

A number of design researchers have carried out protocol studies of engineering designers at work, doing design, in order to produce cognitive models of the design process. Ullman employed protocol studies in order to:

- Cognitively model the mechanical design process (Ullman et. al, B1-1988).
- Propose an ideal mechanical engineering design support system (Ullman, B1-1995).
- Investigate the decision making processes of engineering designers during the design process (Ullman, 2003; Ullman et. al., B1-1997).
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. I 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 3.6.

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.” His 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 3.6: Ullman’s diagram related to design decisions

As the design progresses (moving outwards in Figure 3.6), information related to manufacturing, assembly, materials and cost of the current concepts need 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 3.6 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.

Cross (in Eastman et al., B1-2001) summarizes the cognitive studies of design researchers from areas such as architecture, industrial design, mechanical engineering, electronic engineering, software design and others. Their observations were derived from design case studies, psychologists’ protocol studies and some design performance tests. Cross summarises three areas studied:

- **Problem formulation**

  The experienced designers appear to be ‘ill behaved’ problem solvers, in that they do not seem to put a great deal of effort into defining the problem. Rather, they both set and change goals as they gather problem information and prioritise criteria. They appear to be solution-focused rather than problem-focused. Experience in a specific problem domain aids designers in this approach, in which the problem and the solution seem to co-evolve.

- **Solution generation**

  Fixation on, rather than generation of, many solution concepts is regarded by many design theorists as undesirable. However, outstanding creative designers, and particularly engineering designers, seem to focus on conceptual bridging between problem space and solution space, whilst to some extent giving an appearance of attachment to early solution concepts. Sketching is shown to be a very important design aid. It seems that the traditional designers sketch is an efficient and effective tool for identifying essential features of the developing concept and for understanding, recording and communicating the various exploratory stages of design.

- **Process strategy**
Design success seems to be produced by flexibility of approach, rather than rigid (over-
structured) approach, whilst following a reasonably structured methodology. Opportunistic behaviour may be a characteristic of expert designers, particularly when their work results in quality outcomes. Creative productive design behaviour seems to be sometimes associated with frequent switching of types of cognitive activity. This may relate to the need to make rapid simultaneous explorations of both problem and solution space.

3.5.4 The Creative Design Paradigm

There have been many creative design heuristics proposed over the years. They include methods such as brainstorming, synectics, method 635, gallery method, delphi method, analogy, and many others. These methods are outlined in most of the textbooks on engineering design processes.

French (1998) devotes a whole chapter, entitled “Combinative ideas”, to the systematic generation of tables of options. These may be generated on various bases:

- Alternative means of performing critical functions.
- Alternative designs arising from sub-problems.
- Categorization of known solutions to the current problem or allied problems.
- Alternative configurations for essential components in a design.
- Various combinations of any or all of the above.

Zwicky, (B1-1971), outlines methods employing the “morphological matrix”. Zwicky was a great advocate of this kind of (combinative) approach to design problems and his morphological matrix approach is mentioned in most texts. The morphological matrix is usually associated with the second method listed above, in which alternative designs are listed against a number of sub functions of a design problem. Pahl and Beitz discuss the Zwicky approach in their section on “Methods of Combining Solutions”.

In recent years methodologies based on the work of Altshuller, (B1-1988, 1996, 1997, 1999) have attracted considerable attention. In the following paragraphs I discuss two methodologies that derive from the work of Altshuller.
3.5.4.1 **TRIZ (Theory of Inventive Problem Solving)**

The first of these methodologies is known as TRIZ. TRIZ is an acronym for the Russian words Teoria Resheniya Izobretatelskikh Zadatch which translates approximately into English as: Theory of Inventive Problem Solving. Altshuller began developing TRIZ in 1946. He and his colleagues studied tens of thousands of author’s certificates and patents granted in the Soviet Union. He noticed that inventive problems could be codified and classified. He realised that suitable codification and classification could help designers to search for analogous inventive solutions to a problem by making available to them the fruits of specializations other than their own.

This feature of TRIZ is illustrated in Fig 3.7 below. The designer starts with a specific inventive problem, as at the bottom left of the diagram. The problem is then stated in abstract terms, with the aid of categorized tables developed by TRIZ researchers.

![Figure 3.7: TRIZ Principle of Solution by Abstraction](image)

Altshuller defined five levels of solution to inventive problems. His definitions roughly paralleled those of section 3.2. At the lowest level is routine design and at the highest level is discovery. He calls discovery "pioneer invention" and states that it usually involves new science. At the lowest level, the methods used to arrive at the solution (design) to the problem are well known within the speciality. At the highest level, discovery is seen to involve wide searching, well outside the speciality. This usually involves breaking down the problem into functional requirements, then searching for physical (or chemical, or biological or other effects) that satisfy the function(s).
A central idea in TRIZ is that an inventive problem arises from what TRIZ practitioners call a contradiction. One type of contradiction, known as a technical contradiction, occurs where two parameters involved in a particular design have been adjusted to optimize some aspect of the design and further improvement may be achieved only by inventing a new component, machine or system. Optimization and trade off methods are considered by Altshuller to be standard engineering approaches to solving design problems.

In order to overcome contradictions, TRIZ practitioners identify the two contradicting parameters, one of which, when improved, has a degrading effect on the other. These two are entered on a TRIZ Contradiction Matrix, on which they point to several speculative Proposed Solution Pathways. These Proposed Solution Pathways act as prompts to the designer endeavouring to invent a solution to the problem. Another type of contradiction is referred to as the physical contradiction. This is where a parameter is in contradiction to itself. Its effect on the design is such that it is desirable to both increase and decrease the parameter at the same time. Many papers and examples of TRIZ applications are available at the web site below.

Altshuller outlined eight laws of development of engineered systems, and they are published in the references above. I will only mention one of them here, the seventh. This was "the law of transition from macro to micro level". An example of how this law functions is the way the transistor superseded the vacuum tube in most electronic equipment. Another example is the use of floatation on a bath of liquid tin to support solidifying float glass. This principle (suspension of the molten glass on a very large number of micro “rolling elements-molecules”) replaced the use of metal rollers which had the problem of the glass sagging between rollers. Two more of Altshuller's laws are discussed in section 7.3. Additional laws have been put forward by his followers of in recent years, and their published work is freely available on the TRIZ journal website:

http://www.triz-journal.com/
3.5.4.2 SIT (Structured Inventive Thinking)

SIT (Structured Inventive Thinking) is my second example of methods deriving from the work of Altshuller. SIT is simpler to apply than TRIZ. Only two fundamental principles (sufficient conditions) drive the SIT process:

- The Closed World (CW) condition. This means that the inventor must not add any new object to the system in the process of improvement.
- The Qualitative Change in Problem Characteristic (QC) condition. This means that a problem characteristic must be reducing or become stable after the design improvement (invention).

These sufficient conditions resulted from research by the developers of SIT involving empirical categorization of routine and innovative solutions to numerous engineering problems.

An example (Braha and Manion, B1-1998 pp. 46-57) will suffice to illustrate the method.

PROBLEM: Excessive Wear of Elbows in Pneumatic and Hydraulic Solids Transportation Systems.

The elbows of pneumatic and hydraulic solids transportation systems tend to wear more severely than the straight runs of pipe. This is due to impingement of the solid particles on the outer internal walls of the elbows as illustrated in Fig 3.7 (a).

![Figure 3.8: SIT Example of Wear Problem in Elbow of Hydraulic or Pneumatic Solids Transport System](image-url)
The way in which the system is improved using SIT involves the following steps:

Step (1) SIT problem reformulation:

- List the parameters giving undesirable effect (UDE): cost of production, erosion rate, solids particle flux, solids hardness.
- List the system neighbourhood objects: pipe, solids particles, fluid flow.
- Construct the reformulated problem: make erosion rate unrelated to or a decreasing function of solids particle flux. Do not add any new object to: pipe, solids particle flow, carrier fluid flow.

Step (2) SIT strategy selection:

Here the SIT expert thinks how to obey the QC and CW conditions whilst striving to achieve the desired physical end state. The SIT guide lists a number of general strategies for reference by the designer/user in searching for ideas. Some examples of strategies are: extension strategy; restructuring strategy. The extension strategy requires that the designer attempts to bring to his or her imagination an object that extends the current system in providing the required improvement. In this example, we choose to separate the solid particles from the pipe by following step (3) below.

Step (3) Select and apply a SIT idea provoking technique:

- The designer follows the next process outlined in Figure 3.9. This requires a choice between the unification and the multiplication strategies. Suppose that the unification strategy is chosen.

- This requires that the following sentence is completed. “The (‘item from list in Step (1)’….pipe, solid particles, fluid flow) will separate the solid particles from the pipe”. Try “solid particles” between the brackets…..Then we have an invention as illustrated in Figure 3.8 (b). Completing the above sentence acted as a cue and provoked the inventor to think of making a pocket or a square elbow, which will trap some of the solid particles so that they will protect the elbow from wear due to impingement.

The SIT process is simple enough for a user to memorise during practice on a range of standard problems. It is summarised in Figure 3.9
3.5.5 The Algorithmic Design Paradigm

An algorithm is a sequence of steps or a procedure that always solves a problem if followed correctly. It is an old concept. The modern concept of an algorithm has added meaning, in that for many problems it involves a huge number of (often repetitive) steps being processed at high speed by an electronic computer. Algorithmic techniques, which have been well known to mathematicians since early times, were soon recognized by engineering designers as being valuable both at the problem formulation and the evaluation stages of quantitative design problems. Setting up computer simulation models of systems during the design process, for example, is often aided by the use of numerical approximation algorithms. In recent years older, mathematically difficult, analytical methods have often been replaced by computational methods, where the high speed of the computer working with judiciously chosen and repetitively used algorithms has immensely increased engineers’ ability to evaluate designs with respect to critical parameters.

Well known examples of the use of algorithms (Akin, B1-2003; B1-Dieter, B1-2000; Hyman, B., B1-2003) for problems involving both single and multiple variables are: the Newton-Raphson algorithm in differential calculus; the simplex method in linear programming; and the Davidson-Fletcher-Powell method (later upgraded to the BFGS method) in non-linear programming. There are many others, used with both continuous and discrete data.
A very interesting development has been the addition of computer based optimizing algorithms to traditional FEA software packages. The FEA software enables the approximation of critical performance measures such as von Mises stresses for an initial design of an artefact. The question then for the designer has always been “which parameters should be changed in order to improve the situation?”

Figure 3.10 illustrates that, after assessment of the performance measures yielded by the FEA, a sensitivity analysis should be performed to see which parameters of the current (initial) design have greatest influence on the troublesome performance measure. This involves a design search. Most FEA packages now offer optimization routines that integrate design simulation (eg FEA stress analysis), optimization (size, shape, and topology) and design sensitivity analysis into the one package. The scope for adding analysis and optimizing features to these packages seems to be essentially unlimited.

An increasing amount of sophisticated and powerful commercial and public domain software is emerging in all aspects of simulation, performance measurement/representation and optimization.

![Figure 3.10: Algorithmic application in CAE](image-url)
A most interesting approach to the optimizing problems, developed by John Holland and his colleagues in the late 1960s, is the genetic algorithm (GA) approach (Onwubico, B1-2000). This method involves random events like those which occur with natural selection in genetics. GAs are search methods. They were developed because of the lack of robustness of traditional optimization algorithms. Compared to many traditional approaches they have the following benefits:

- They are relatively computationally efficient.
- They perform well over a wide range of problems.
- They may cope with larger problems.
- They may cope with a mixture of continuous and discrete variables as well as non convex design spaces.
- They are more likely to find global optimums rather than become distracted by a local optimum.

An interesting paper related to structural design in buildings, towers, bridges etc. (Krishnamoorthy, in Wang et al, vol. 2, B1-1999) explains how configuration and topology optimization is performed using GAs in conjunction with FEA packages.

### 3.5.6 The Artificial Intelligence Paradigm

Various aspects of the use of artificial intelligence (AI) in engineering design have been attracting considerable research effort over the last two decades. Artificial intelligence approaches involve attempts to program computers to perform tasks normally requiring human intelligence. For engineering design, this involves capturing the knowledge of experts in a particular domain and using it to generate or search for trial solutions to specified design problems, and to evaluate these solutions. However, as already discussed, one of the main challenges in design is to specify the problem clearly. The computer cannot reason at this level unless human experts have programmed it with appropriate knowledge and reasoning rules.

Where early computer aided design systems aimed to replace the drafting board (McMahon and Brown, B1-1993) in order to assist the design engineer, modern CAD techniques focus on implementing numerical analysis tools and intelligent design systems. Despite the fact that artificial intelligence in design is still subject to broad
controversy, extensive research is being carried out to make AI systems practicable for engineering design. The trend is to implement AI systems on a larger scale and in the early stages of the overall design process. However, AI in engineering design has not yet been implemented commercially. Existing systems are limited and still in their prototype phase.

In general, AI systems seem intended to adapt and adopt human design activities. They incorporate problem decomposition, decision making, and problem solving techniques (e.g., case based reasoning, CBR).

An early architecture for AI in design (Dixon et al., B1-1984) was built around the need for iterative evaluation and redesign. This architecture had six independent knowledge sources: initial design, evaluation, acceptability decisions, redesign, user design input and flow of control.

The resources in the right hand column provide inputs to the decision making process. AI can automate the design process (in Figure 3.11) through numerical iteration, as outlined in Figure 3.12. An initial concept is evaluated and redesigned until an acceptable solution is found.

**Figure 3.11: Schematic of the design process after Dixon, B1-1984**

The resources in the right hand column provide inputs to the decision making process. AI can automate the design process (in Figure 3.11) through numerical iteration, as outlined in Figure 3.12. An initial concept is evaluated and redesigned until an acceptable solution is found.
The application of this early system was limited by the high requirement for human interaction and the need for an accessible digital knowledgebase. Its architecture is shown in Figure 3.13.

The basic concepts of AI in engineering design have been described by Brachman and Levesque (B1-1985) and Buchanan and Shortliffe (B1-1984). They outline "expert systems" or "knowledge-based systems" for the representation of 'rule of thumb'
knowledge. The architecture of such a knowledge-based system is illustrated in the following figure.

An inference engine acts as an interface between knowledge base and user, managing design data and parameters. The knowledge base itself is fed and updated by a knowledge acquisition process, and interacts with expert systems.

Whereas the earlier systems required considerable human interaction and were very specialised, many of the more recent proposals illustrate systems with many packages and tools interlinked to central process management modules that are capable of drawing on the sub-modules as required and recording and even directing the design process (Al-Salka et al., B1-1998; Netten and Vingerhoeds, B1-1998; Bracewell and Sharpe, B1-1996; Balazs and Brown, B1-1996; Zha, Du and Qui, B1-1998).

A diagram from the paper by Bracewell and Sharpe, in Figure 3.15. The progress of the Schemebuilder development can be seen on the website of The Engineering Design Centre of Lancaster University at:

http://www.comp.lancs.ac.uk/edc/publications/index.html
Schemebuilder is representative of where AI is leading the engineering design profession. AI in engineering design, whose ultimate aim may be to “compete with humans” in doing conceptual design is compared with human designers in the diagram of the promotional material on the web at the above address as shown in Figure.

Figure 3.16: “Schemebuilder” computer skills compared with human designer skills
General objectives of AI systems are:

- Assist design activities with the aid of computerised tools
- Accelerate the overall design process
- Document and share knowledge
- Cover broad knowledge areas
- Improve human-computer interfaces

Problems:

- Universal AI design tools have not been developed yet, i.e., a variety of different specific tools are required to cover various design areas.
- Computer generated concept is only as good as the knowledge base (input), extensive databases are required to perform AI design
- Decomposition and abstraction tools are limited.

### 3.5.7 The Paradigm of Design as a Social Process

Referred to as the “consensus paradigm”, this paradigm contends that design is a social process, in the course of which designers, client(s), and other organizations (e.g., standards associations) have negotiations, discussions and evaluations that lead to the creation and refining of shared meaning (and shared memory) of the requirements of the engineering design.

One of the issues in the design process is that the different experts and company departments contributing to a design, even different types of engineers, conceptualize a common problem differently (Bucciarelli, B1-1995; Konda et. al., B1-1991 in EDRC Tech. report).

The social constructivist approach aims at what may be called a "formal model of design”, whereby the accuracy, intent and mutual consistency of an engineering design are investigated and documented so that a shared understanding of the problem(s) takes place.
Some empirical findings on how designers work supports the social constructivists' views (Braha and Maimon, B1-1998):

- Vocabularies of designers differ when they describe the same thing.
- Engineers typically spend more than 50 percent of their time in documenting and communicating, often in formal or informal negotiations.
- The norms and values of a social group are shaped by the socio-cultural, political, legal, and ecological situation. This can influence the development of the designed product.
- The modern and popular concept of concurrent engineering, where the different factions within the company work simultaneously, reaping the benefit of coordinating computer software, and overcoming the past problems of serial development, supports this view.
- Some interesting publications on collaborative product design are appearing on the World Wide Web, promoting the benefits of future distributed software (Monplaisir and Singh, B1-2001).

A model that fits well with the Social Process Paradigm and possibly elsewhere is illustrated in Figure 3.17 from Pugh, B1-1991 and B1-1996.

Pugh introduced the term “total design”. He was concerned that the emphasis on discipline related design that had become prevalent in the teaching of engineering design during the 1960’s to 1980’s by the various educational institutions had concentrated rigorously on what he called “partial design”. This partial design enabled the student to calculate, for example, inertia forces, fatigue life, complex stresses, vibrational characteristics and to optimize material selection etc. with rigour of the highest order, but with very little emphasis on the real needs of the market, the client, the related disciplines, the stake-holders, the environmental requirements etc. Pugh saw the need for the designer to work at both partial and total design with rigour of the highest order. The central column and discs of Figure 3.17 are referred to as the “design core”.

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Pugh produced a number of different versions of an activity diagram containing the design core surrounded by different shells to emphasise the different environments that influence the design process. Some examples from his 1996 publication are: business activity model, design activity model (research activity added) and models comparing dynamic with static concepts.

### 3.6 CONCLUSIONS

“Systems Engineering” should perhaps be added as a further paradigm. An interdisciplinary approach, and a means to enabling the realisation of successful
systems, systems engineering is a means to deal with the development of the increasingly large, complex and interdisciplinary systems that are typical of much of modern engineering practice.

Indeed, there seems to be no end to the possibilities for proliferation of paradigms. However, I see them as means to the end of practical design, not as an end in themselves and so, as much for practical reasons as anything else, I want to draw this literature review to a close, and sum up where it has brought us to.

With such a wide range of ideas and methodologies of design process being investigated, the question on many minds is: are we likely to arrive at a universal theory of design? Such a theory or science should interact with other sciences and arts, so as to become a source for deriving, ordering and providing the knowledge for and from other disciplines. I have mentioned (section 2.5) how I discovered that the body of knowledge in engineering thermodynamic science (thorough treatment of Rogers and Mayhew, B2-1967, Duffie and Becknam, B2-1976 as well as Holman, B2-1974) that I had learned as a student was not presented in ways that were useful to me when I attempted to design my early photo-thermal pumps.

Knowledge that results from the investigations of classical and engineering science commonly needs reorganizing in order to become useable by engineering designers. This knowledge could also be presented in ways that would make it more immediately useful for other users: students, teachers and practitioners.

Assuming that we did eventually establish a design science, one good result would be that designers would be more readily able to teach students how to design.

Each of the paradigms of this chapter emphasises different aspects of design, and all have been shown to be valid. The methodologies of the different paradigms appear to be best matched to specific classes of design. For example, when designing a structural element, such as the steering arm for a motor vehicle, the designer would most likely start with available knowledge from previous cases (CBR) followed by solid modelling, followed by FEA including shape-structural optimization (Algorithmic process). On the other hand, a designer attempting to design a new silent one-man submarine would most
likely treat it as a systems design and thus follow a process containing elements of Pugh’s methodology, ASE and others.

I have found the large number of approaches of the researchers of design theory very enlightening and even intriguing. Some, such as the process and ASE researchers have amassed a vast support that is steadily documenting the detail and intricacies of process. Others, such as the cognitive researchers look to the designers and the teams of people involved in design to study how they do their design. The Algorithmic, CBR and AI researchers tend to focus on the massive speed and storage abilities of the computer and can see its potential to support the human conceptual designer as it has the solid modeller, stress analyst, manufacturer etcetera. However, these computer-directed researchers often study human designer behaviour in order to gain ideas that form the bases of the computer architectures and processes.

Again, I point out that my focus is on mechanical and electro-mechanical design. Many good mechanical systems have been stable or near stable for a century or even much more (wind pumps, beam pumps for artificial lifting of oil, railway rolling stock etc. Mechanical systems have some rather unique characteristics and problems such as “function sharing”. Function sharing is described in Ulrich and Seering (B1-1990) and illustrated with examples where designs are greatly simplified by its application. Ulrich and Seering illustrate function sharing with an example of the automobile body that acts as an electrical ground and conductor, structural frame, aerodynamic fairing, weather protection sub-system, an aesthetic design as well as providing other functions.

When designing an essentially functional device, where functions relating reliability, ease of maintenance, and cost, including initial cost and operating cost are of prime importance, intricate knowledge of the fundamental (structural) elements and all aspects of their viability for the design including possibilities like function sharing are of importance and may lead to considerable product simplification and cost saving.
CHAPTER 4
"TECHNOLOGY EVOLUTION" AND THE CLASSIFICATION OF TECHNOLOGICAL FAMILIES

4.1 INTRODUCTION

The central issue in this chapter is how various technical systems evolve and how an understanding of this may assist in improving the design process. It is accepted that classification (particularly to a chronological base) of appropriate knowledge bases and inventions (designs) can be of great use in the design process. This can be very helpful in defining an engineering product design specification (PDS). Further, I as argue later in this thesis, arriving at a good PDS is a centrally important stage in the product design process. Unfortunately for the designer, this arrival is likely to involve a major effort in thoroughly searching for and evaluating different ideas and configurations.

I look here at some typical classifications that are important to engineers. The first type of classification is simply as ordered charts (lists) of various engineering products, e.g., pumps, bearings, fasteners, springs, etc.

Next, various taxonomies have been proposed for use in design science. A widely held view is that design methodologies vary for good reason. It is important to match particular methodologies to specific design situations. A designer should be able judiciously to choose optimal processes that are appropriate to the problem on hand. In mechanical system design I would claim that, even though they are incomplete, the taxonomies and classifications that have evolved and continue to evolve can form an important basis for design process.

My major interest is in innovative conceptual mechanical machine (system) design. In this area, I argue that the first major stage of each design problem should be for the overall problem to be broken down into sub-problems/areas, and for each of these to be investigated chronologically.
The major sub-areas within the machine itself are traditionally: power source, prime mover/engine transmission, working system, control system. To these I would add gearing and matching. In addition, I would include categories for the near and larger environments of the proposed mechanical system. My proposal is that this process is highly likely to be fruitful in defining the key areas requiring morphological analysis and subsequently in producing valuable invention.

4.2 CLASSIFICATION TABLES AND CHARTS FOUND IN DESIGN HANDBOOKS

Many areas and topics of mechanical engineering are characterized in literature by classification tables and charts like that of Fig 4.1.

This is just one example of many existing classifications that can be constructed for a particular technology. In machine design handbooks (eg Norton, B1-1996) classification charts can be found for brakes and clutches, bearings, springs, fasteners and most machine elements. Classification is usually succinct, efficiently conveying a number of themes. For example, there are three levels of classification in Fig 4.1: the highest level classifies the general physical principle; the next level classifies, in a general way, the means of implementation; and the third level classifies the particular forms. This format is quite common for mechanical machines and elements. A classification such as that in Fig 4.1 has grown with time. It will no doubt continue to grow as more pumps are invented.

Such classifications have considerable value for over-viewing a situation. For example, Fig 4.1 may assist a designer in assessing the search field when choosing and sizing a suitable pump. However, in selecting a pump, a designer would need much more information than is available than in Fig 4.1. This further information may reside in his/her expert head, or from sources that include handbooks, textbooks, manufacturers’ catalogues, journal articles, patent documents and practical test results. Without supporting information, this figure is of little value to any one except an expert in the area, who has the additional knowledge in his/her head and/or has ready access to the published information.
4.3 SOURCES OF DESIGN INFORMATION

On the basis of examining some 50 books mainly from the mechanical engineering area, in their "Design Science" Hubka and Eder (B1-1996) point out some of the limitations (for the designer) of existing publications:
“….many important questions remained unanswered or appeared only as disconnected remarks, for example statements about operational properties (e.g., reliability, service life, suitability for maintenance), appearance, ergonomic and economic characteristics, or suitability for transport or packaging of the products.

"Still more unsatisfactory is the situation for some works which the authors declare as being about design, and contain no (or only very sparse) instructions for the procedures of designing. Further relevant statements, for example about designers, methods of representation, working means, organization, administration (management) and similar questions are often ignored.”

The depth of technical treatment in the books varied. Hubka and Eder go on to say:

“For example, the books on thermal turbo-machines contain predominantly knowledge about thermodynamics and fluid mechanics, but in other areas, such as cranes, the emphasis of the treatment concerns the partial and total systems.”

They conclude:

“In summary we can state that the existing knowledge systems (especially books) that are available about objects of designing (i.e., the process and technical system) only deal with this for some specialties, and have remained on a plane which is accessible to the sense perceptions. The processing differs too much in content, form and depth, and in any case it does not (or only in individual partial areas) cover the information needs of the designer.”

Hubka and Eder list some of the publications researched. These publications contain many classifications in the various families. One of their most interesting references is Wankel’s book, *Rotary Piston Machines* (B1-1965). Wankel provides a very comprehensive chart which graphically summarises rotary machines. This work is unique: I have met many inventive mechanical design engineers over the years who were inspired by it.
### 4.4 CLASSIFICATIONS AND TAXONOMIES IN DESIGN SCIENCE

Hubker and Eder produce some valuable generalized classifications in their discussion of concepts like "technical system" (TS), "machine system" (MS) and "hierarchy of objects".

<table>
<thead>
<tr>
<th>General Hierarchy of Technical Systems</th>
<th>Example</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Level of Conceptualization</strong></td>
<td><strong>Designation of level</strong></td>
</tr>
<tr>
<td><strong>0</strong></td>
<td>Technical System (TS)</td>
</tr>
<tr>
<td><strong>0.2</strong></td>
<td>Phylum of TS</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>0.4</strong></td>
<td>Class of TS</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>0.6</strong></td>
<td>Family of TS</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>0.8</strong></td>
<td>Genus of TS</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
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</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>1</strong></td>
<td>Species of TS, or Serial Size</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Figure 4.2: Taxonomy of Technical Systems, Hubka and Eder, B1-1999*
Figure 4.2 shows a taxonomy of technical systems (TS). This diagram goes further than Figure 4.1. It shows how, in general, technical systems may be categorised into hierarchies, where the highest levels are the most general and relate to the function(s) of the technical system. As a taxonomy, it envisages a wide range of elements at the individual levels. In Figure 4.2, the ordering (Phylum, class, family, genus, species) is analogous to the classifications that are used in botany and zoology. As one moves down the hierarchy, the definitions/descriptions change from function to (general) organ to (particular) form. The lowest level, one of the species, is described in great detail including specifications for parts and arrangements, forms, materials, dimensions, tolerances etc. An experienced design engineer is very familiar with this concrete level.

Figure 4.3 illustrates the types of models that are used by Hubka and Eder to represent particular technical systems. The models of a vice demonstrate the various methods of representation.

The different structures that Hubka and Eder cover are evident from this figure.

- "process structure" -- what transformation processes take place within the TS; structure elements are the TS-internal processes;

- "function structure" -- what internal capabilities does the TS have (it only uses these capabilities when it is actually operating); structure elements are the functions;

- "organ structure" -- what active locations implement the capabilities; structure elements are the organisms and/or organs as function carriers;

- "component structure" (also morphological or anatomical structure) -- what physical (material) parts implement the organs; structure elements are the assembly groups, components (constructional elements)."
Figure 4.3: Example of the various models of technical systems (after Hubka and Eder, B1-1999)
Figure 4.4: Classification of Connecting Organs containing the Genus: Ball Bearings, (Hubka and Eder, B1-1999)

Figure 4.4 illustrates how one particular genus (anti-friction bearings) of the mechanical engineering technical system fits into its portion of the entire taxonomy. Figure 4.5 shows how another genus, the hydrodynamic sliding bearing, may be included under a master function structure and a master organ structure. The elements in Figures 4.4 and 4.5 are designated as having elementary function. They are connecting organs and are the same phylum as fasteners. We generally call these organs machine elements and their theory is well documented in books on Machine Element Design (Faires, B1-1965; Spotts, B1-1998; Shigley and Mischke, B1-1996; Juvinall and Marshek, B1-2000; Norton, B1-2000; Hamrock, Jakobson and Schmit, B1-1999 etc).

Figures 4.4 and 4.5 reveal some very pertinent facts. They relate to elementary artefacts that are of very general use in engineering: connecting organs, which further classify into fasteners and bearings of different types. Design of these elements is largely at the selection rather than the invention level because they have such wide use, with such huge markets, are so well developed, with documented results and national/international standards.
Another type of categorisation is present in many design catalogues. Design catalogues are described by Roth as very effective aids to methodical designing (Roth, Chapter 8 in Chakrabarti, Ed., B1-2002). Roth mentions three types of catalogues: object catalogues, solution catalogues and operation catalogues. Each has its purpose. Object catalogues focus on physical and geometric details for particular artefacts. Solution catalogues contain a range of solutions for particular tasks. Operation catalogues contain process steps and rules as well as their application conditions.

Figure 4.5: Showing master function and master organ structure, master layout and detail for the genus of hydrodynamic journal bearings (Hubka and Eder, B1-1999)
Representation (structural, functional etc.) of the components of technical systems is a very important issue for designers. Experienced designers (practitioners) are constantly searching for ideas. They benefit greatly from the visual aspect of classification charts, which can improve the efficiency of this search process.

The ways in which knowledge is ordered, classified and represented, are vitally important to engineering designers. French (B1-1999) points out the importance of visual representation: he also discusses the extent to which it is undervalued in the education system. The engineering designer, particularly the designer aspiring to invent a new and better technical system, will need access to a wide range of knowledge bases to find new combinations of elements. These elements can include objects, functions, sciences and ideas. Specialised design science knowledge bases need to be suitably represented and classified to make the information in them accessible.

4.5 EVOLUTIONARY HISTORY OF TECHNOLOGIES

A number of authors have discussed the idea of evolutionary tendencies within technologies, including Ziman (B1-2000), Dasgupta (B1-1994, 1996), Altshuller (B1-1996, 1997, 1998, 1999) and Savransky (B1-2000).

Based on his research related to inventions such as the ENIAC computer, the Newcomen atmospheric engine and others, Dasgupta concludes that: “technological creativity is conditioned by evolutionary history”\textsuperscript{13}. In his book \textit{Technology and Creativity}, Dasgupta seeks to move towards a general cognitive theory of technological creativity. He points out that, historically, technological development has often preceded the growth of scientific knowledge: he questions widely held views, for example the idea that technology (engineering design) is merely the application of relevant basic science to the making of artefacts. He writes:

“Technology is concerned with the invention of artefactual forms - an activity that entails human goals, aspirations and wants and their satisfaction. The physical sciences, the basic and fundamental sciences have nothing to say about goals or wants. Each technological discipline, then – each science of the artificial, to use Simon’s term (Simon, B1-1981) – regardless of whether its domain of interest is alloys, bridges, cities, machines, satellites, software or whatever is basically teleological in nature.”
In the final chapter of this book, Dasgupta sums up and characterizes inventive processes in the following way:

- “Purposive endeavour.
- "Highly opportunistic in nature.
- "Gradualistic in nature- large insights composed of a network of small steps.
- "Involve reasoning processes.
- "Knowledge intensive.
- "The inventor is a cognitive being who searches freely about his or her knowledge body and, being opportunistic, retrieves and applies whatever knowledge tokens appear relevant to the goal of the moment.
- "The design/invention process is knowledge intensive and one particular kind of knowledge that is of great importance is that contained in the evolution of artefacts of the past, even those that are no longer in use.”

Buhl (B1-1960), states that “the only raw material available for solving problems is past knowledge.”

Savransky (B1-2000), in Chapter 8, ‘Evolution of Technique’, discusses the laws (trends) of technical system and technical process evolution as defined in TRIZ. The laws originally proposed by Altshuller are being further developed by the TRIZ community, who base them inductively on empirical correlations derived from analysis of a huge number of patents, scientific papers, technical reports, handbooks, textbooks and other published material. Savransky’s requirements for formulating the laws of technical system and technical process evolution are:

- "The laws must be based on profound study of different techniques' development history derived from substantial high level patent and technical information.
- "The laws must provide a basis for discovering new concrete heuristics for solving problems.
- "The laws should be of an open type, i.e., allow further modification as new source patents and technical information is accumulated.”

Savransky considers that the value of these laws is in four main areas. I summarise his comments on these four main areas below:
1. Qualitative technological forecasting.

The laws have been proposed on the basis of TRIZ and information analysis (of patents, technical reports and economical reports etc) and, although imprecise quantitatively and in time-scale, these laws contain explanations as to why and how changes are likely to occur. Following the TRIZ methodology will help discriminate between sub-systems that should or should not be pursued, indicate ranges of possible paths of evolution of the specific technology and assist in patent protection.

Traditional technological forecasting tends to be based on parametric trends and often fails as a result of “outside influences” such as economic, political and social influences. Additionally, quantitative trend predictions do not “see” the influences of detail breakthroughs [author].

2. Creation, including genesis and synthesis of inventions/designs.

Knowledge about evolution trends can help in finding more efficient and more rational structure of sub-functions of a system. The following steps are recommended:

- Use the laws to evaluate each sub-system in terms of its level of development, restrictions to its performance improvement and its progress towards ideality from both scientific/technological and socioeconomic points of view.
- Evaluation of the efficiency of introducing new functional sub-systems.
- Evaluation of the efficiency of material, information and energy flows with a view to improving the sequence of functional links.
- Evaluation with a view to possible replacement of older and less efficient subsystems.
- Evaluation with a view to integration of several sub-systems.
- Evaluation with a view to separation of a sub-system into several sub-systems.

3. Problem solving by way of selection of (TRIZ) heuristics.

Knowledge about evolutionary trends is useful in selecting the most promising solutions and in filtering out weak solutions that do not correspond to the trends. It must be remembered that our knowledge is incomplete, so these heuristic processes should be treated with caution.

The trends and paths of technical evolution available from TRIZ and the evolution laws are useful in the formulation, by marketing people, of questionnaires used in Quality Function Deployment (QFD). An innovator familiar with this approach can forecast the whole picture of socio-techno-economic tendencies and may even be useful in assessing the competition's product evolutionary situation.

4.6 CLASSIFICATIONS, TAXOMOMIES AND EVOLUTIONARY TENDENCIES IN TECHNOLOGIES

Before proceeding with this section, please recall that in this thesis my approach is based primarily on my own experience and my research into the historical development of mechanical systems. I believe that the insights associated with this knowledge also apply to modern electro-mechanical systems. My central interest is in the geometry and topology of both the elements and the working assemblies of mechanical machines. I believe that the way in which we visually represent, classify and delineate the geometry, topology and related functions of items can truly influence their value to designers.

There is no doubt that the evolution of technical systems is influenced by more than mere scientific discoveries or traditional engineering science, even though certain areas benefit greatly from scientific discoveries and traditional engineering science. The ‘high tech’ areas of modern aerospace equipment and large centralised power generation equipment are examples of areas where invention is based strongly on scientific discoveries and/or traditional engineering science. However, other areas of engineering do not operate in the same way. They do not have such co-ordinated influences on them from learned societies, government regulations, engineering design codes and corporate management. Nor do they have extensive documentation of the design, manufacture, construction, operation and maintenance of their systems.

Consider Figure 4.6. This figure approximates the evolution of ideas (inventions) up to the point of the early hand and wind operated water well pumps of around 1700 AD. The detail in figure 4.6 shows stages of pump evolution. The detailed sequence of ideas indicated in the early part of the figure is based on limited historical evidence, and is
therefore somewhat speculative. Note how the concept of a water container (bucket),
whose initial function was to simply to lift water by hand, could be progressively
extended by inventions such as the long handle, fulcrum and counterweight, rope, flap
valves and reciprocating rod. This progression is typical of many patent fields I have
researched.

Each of the first six inventions of Figure 4.6 involves the addition of a new artefact
form to the previous invention.

In the modern world inventions are quite often patented. It is common for an inventor’s
patent to be written in the following format:

- Outlines the state of the art.
- Points out a deficiency, or perhaps several deficiencies in the existing art.
- Outlines how his/her invention modifies the existing configuration to overcome
  the deficiencies and give improvements such as improved performance, added
  functions, reduction in manufacturing or operating costs.
- Describes in general principle the detailed claims of his/her invention.
- Describes one or more specific embodiments.
- Attaches well-labelled drawings.

Provided that a patent is valid (has novelty, etc.) and is useful it becomes a well
documented step in the historical record of the evolution of its relevant art. Of course,
not all good designs go on to be documented in the patent systems of the world.

The above example was constructed rather artificially. A second example, in the area of
one of my own patents, is given in Figures 4.7 (a), (b) and (c) below. It illustrates how
actual patents may incrementally follow an evolutionary process. It describes how an
endless flexible member passing over two wheels can be used to haul a carriage back
and forth (reciprocate), in a stable and reliable way, by rotating one of the wheels. This
is a long stroke rotary/reciprocatory motion converter. The conversion may be reversed
– from reciprocation to rotation.

The evolution of inventions is described in Figure 4.7 (a) and relevant diagrams
illustrated in Figures 4.7 (b) and (c). The essential invention is the use of an endless
flexible member passing over two wheels and carrying a shaft to haul a carriage in a
reciprocating motion. The first patent (in 1864) is the most basic and its weakness is revealed in the 1909 patent, where the instability of the single carriage engaging shaft is overcome by having two such shafts. Geometry then requires a gap in the scotch yoke at top and bottom dead centre.

There is a serious weakness in the 1909 patent. The carriage disengages at top and bottom dead centre. The 1912 patent overcomes the shaft instability and the disengagement problems by doubling the number of chains, along with necessary shafts, bearings and space to support these. This involves extra expense, space and weight.

The next patent (1930) has a similar general configuration to the 1912 patent and shows a novel hauling attachment to the chains. The advantage of this attachment is doubtful as it does not have smooth deceleration/acceleration motion when the carriage is near top and bottom dead centre. The 1990 patent overcomes all previous problems of carriage shaft instability, end region inertia and cost of duplication of the chain system. It does however, involve excessive skewing load on the wheels of item 58 due to cantilever loading from the single chain shaft (15). This part of the design would need to be bulky and expensively designed to cope with the large cantilever loading.
<table>
<thead>
<tr>
<th>Description of inventive event</th>
<th>Element</th>
<th>Function</th>
<th>Form</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Primitive man discovered the concept of a water-containing vessel and put it to use drawing water.</td>
<td>Bucket</td>
<td>Contains water</td>
<td><img src="https://via.placeholder.com/150" alt="Diagram" /></td>
</tr>
<tr>
<td>2 To this concept he added a stick-handle to increase his reach for drawing water.</td>
<td>Handle</td>
<td>Increases human's reach</td>
<td><img src="https://via.placeholder.com/150" alt="Diagram" /></td>
</tr>
<tr>
<td>3 Next, he added a counterweight and a fulcrum to balance the system so that he minimized his energy consumption. He did not waste energy in supporting the equipment he had invented.</td>
<td>Counterweight, Fulcrum</td>
<td>Supports and balances weight of machine</td>
<td><img src="https://via.placeholder.com/150" alt="Diagram" /></td>
</tr>
<tr>
<td>Now he replaced the stick-handle with a rope and he could vertically reach water at great depth. This was useful in reaching over cliffs. When did man discover the water well? QUESTION: Did man intuitively understand basic mechanics - levers, fulcrums, counterweights, flexible tension members (ropes)?</td>
<td>Rope (endless flexible member)</td>
<td>Vertically greatly increases human's reach</td>
<td><img src="https://via.placeholder.com/150" alt="Diagram" /></td>
</tr>
<tr>
<td>4 The pulley came next. This allowed more convenient horizontal pulling to lift the weight of the water plus bucket and vertical rope. Later, more that one human could apply force. Later, animals were employed to apply force. NOTE: The bearing and the shaft or axle were required to support the pulley. These had been invented at this time in another application - the wheel and axle.</td>
<td>Pulley</td>
<td>Changes direction of applied force</td>
<td><img src="https://via.placeholder.com/150" alt="Diagram" /></td>
</tr>
<tr>
<td>5 Next the windlass. Leverage was used to turn the pulley which was now used to wind the rope. This was a step beyond using the pulley to change the direction of the rope.</td>
<td>Friction drive pulley</td>
<td>Friction driving the rope</td>
<td><img src="https://via.placeholder.com/150" alt="Diagram" /></td>
</tr>
<tr>
<td>6 The chain of pots was the next inventive step. This required the attaching of many buckets on the one endless rope. The pulley was needed. The pulley was now hauling the rope by means of levers in the form of the windlass.</td>
<td>Endless chain, multiple buckets</td>
<td>Continuous hauling of buckets</td>
<td><img src="https://via.placeholder.com/150" alt="Diagram" /></td>
</tr>
<tr>
<td>7 The inertia type bucket pump was next. A flap valve was invented and placed at the bottom of a very tall thin bucket (pipe) reaching the water in the bottom of a well. Rapid vertical reciprocating movement caused water to be thrown upwards during the upward strokes. Sudden reversal caused the valve to admit more water, as the previously thrown water continued upwards, during rapid downward strokes. The valve then trapped this water on upward strokes. A pumping action resulted. Alternatively a pipe and a slidingly sealed bucket (shown) was used with a stiff tension member to lift the bucket.</td>
<td>Tall bucket (pipe) and flap valve ALSO pipe and slidingly sealed bucket</td>
<td>Traps and conveys water to elevation with skilled reciprocating motion. No need to lift the bucket the whole lifting distance.</td>
<td><img src="https://via.placeholder.com/150" alt="Diagram" /></td>
</tr>
<tr>
<td>8 The traditional bucket pump was the next inventive step. This eliminated the need to skillfully throw the water on each upward stroke. An additional flap valve at the foot of the pipe trapped the water and prevented it from flowing down after each upward stroke. A slidingly sealed bucket with valve was reciprocated by a stiff tension member.</td>
<td>Foot valve</td>
<td>Prevents backflow of water in the riser pipe. Eliminates need for skillfully executed reciprocation of rod.</td>
<td><img src="https://via.placeholder.com/150" alt="Diagram" /></td>
</tr>
<tr>
<td>9 The plunger pump had two valves and a riser pipe like the bucket pump. Like the bucket pump, it had a rod which was reciprocated by the operator at the surface. However, the downward motion of the sealingly engaged plunger, forced the trapped water up the riser pipe. Water in the riser pipe was then trapped by the delivery valve during the upward motion of the plunger, which allowed a new charge of water to flow in through the inlet valve. A stiff rod (which could be weighted) was pushed during the pumping stroke. The rod needed guides to protect it from buckling.</td>
<td>Plunger ALSO drive rod and guides</td>
<td>The plunger forces trapped water to flow</td>
<td><img src="https://via.placeholder.com/150" alt="Diagram" /></td>
</tr>
</tbody>
</table>

**Figure 4.6: Tracing the evolution of the common bucket pump used in water wells**
<table>
<thead>
<tr>
<th>Patent Number</th>
<th>Date</th>
<th>Description of Invention event</th>
<th>New Element</th>
<th>Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1884</td>
<td>The eccentric pin and scotch yoke was already well known. The inventor wished to obtain a longer stroke than the eccentric pin and scotch yoke provided. By attaching a carrier pin to a wide flat belt, the pin was held (weakly) parallel to the two shafts. The reciprocating motion was able to be extended to any desired length by suitably spacing the sprockets. The velocity could also be made to be constant between the sprocket centres.</td>
<td>Combination of known elements: Belt and two sprockets; Attach pin to belt; Scotch yoke.</td>
<td>Long approximately constant velocity long reciprocating stroke.</td>
</tr>
<tr>
<td>2</td>
<td>1893</td>
<td>This patent achieves the same as pat. 41,835. However a connecting rod is used in preference to a scotch yoke to transform the rotary motion of the drive sprocket to long reciprocating stroke motion.</td>
<td>All elements known. The connecting rod and chain combination is now.</td>
<td>As above</td>
</tr>
<tr>
<td>3</td>
<td>1902</td>
<td>Both patents 41,835 and 622,089 have weak pin attachments to their endless flexible members (belt and chain respectively). In patent 915,181 the carrier pin protrudes from both sides of the chain and is engaged into rigid frame (4) containing two scotch yokes. These stabilise the carrier pin. Unfortunately the carrier pin disengages from the scotch yokes at both top and bottom dead centres.</td>
<td>Rigid frame containing double scotch yoke side.</td>
<td>Stabilises the carrier pin.</td>
</tr>
<tr>
<td>4</td>
<td>1912</td>
<td>In this patent the carrier pin is stabilised by engaging it into two coordinated chains. A complication in this drawing is that there are two opposed motion reciprocators. The reason for this is that these opposed reciprocators drive the two piston valves of a concentric pump. Note that the scotch yoke has some curvature to modify the top and bottom end motion of the pistons. No detailed reason for this is given in the patent text.</td>
<td>Double chain with bridging carrier pin. The concentric pump and opposed reciprocating motion was already known.</td>
<td>As above</td>
</tr>
<tr>
<td>5</td>
<td>1930</td>
<td>In this patent the carrier pin is supported by a double truss arrangement from a coordinated pair of chains. The arrangement would create a misaligned stress on the chains and cause unnecessary chain tension due to skewing of the chain. There is a balance weight acting on the cables via the head pulleys. The balance weight would be approximately equal to the total rod weight and adjusted so that the engine worked evenly on both up and down strokes. This system would have large inertial forces during top and bottom end motion.</td>
<td>The only new element is the truss arrangement which may not have turned out to be an improvement due to its structural deficiencies and due to large inertial forces near TDC and BDC.</td>
<td>Not valid</td>
</tr>
<tr>
<td>6</td>
<td>1930</td>
<td>There is no fundamental novelty in this patent except perhaps the item (70), which is referred to as the knuckle in the text. The patent is the basis for the Rotaflex oil-well pump that is widely used in the oil industry.</td>
<td>Knuckle and slider block.</td>
<td>Stabilises the carrier pin.</td>
</tr>
<tr>
<td>7</td>
<td>1931</td>
<td>This patent achieves the advantages of patent 915,181 due to the double carrier pin and compact, guided double scotch yoke. In addition, guide members at TDC and BDC regions to overcome the problems of patent 915,181. The wording and shown embodiments of the patent cover all anticipated embodiments that overcome carrier pin instability in the TDC and BDC regions of their movement.</td>
<td>Shown means and all conceptually similar means of guiding the carrier pin near TDC and BDC.</td>
<td>Robust stabilisation of the carrier pin throughout its entire motion including TDC and BDC.</td>
</tr>
</tbody>
</table>

Figure 4.7 (a): Description of some of the series of US patents about long stroke rotary/reciprocatory motion converters. In each case the main new element of the invention and its function(s) are listed.
Figure 4.7 (b): Earlier US patents of the long stroke rotary/reciprocatory motion converter class
Figure 4.7 (c): Later US patents of the long stroke rotary/reciprocatory motion converter class
The 1991 patent reverts to a double shaft on the chain to give balanced loading (not skewed as in the 1990 patent). Geometry requires a gap on the shaft side of the wheels in the cross slide (16): this would cause disengagement at top and bottom dead centre, so the 1991 patent describes various methods to overcome this by use of bridge (18) and an embodiment having long sliders that bridge the gap (see the full patent). Compactness, cost and reliability are the driving objectives in this patent and in further work by the author.

The example of the rotary/reciprocatory motion converter illustrates that there are trends during the evolution of a particular type of design such as this one. These trends are influenced by constraints and objectives that are well known to machine designers. They include the following:

- Increase of efficiency.
- Availability of increasingly appropriate materials - (price, stability, quality etc.)
- Availability of components and sub-systems - (price, stability, quality etc.)
- Increase of reliability and durability.
- Reduction of volume - compactness.
- Reduction of mass.
- Geometrical/topological possibility.
- Limitation of shape.
- Manufacturability.
- Assemble-ability.

Many engineering design textbooks (e.g., Dieter, B1-2000) contain check-lists and summaries that include the above items. Most of the items are general, applying to all products, although often requiring trade-offs between them. The higher items of the above list relate more to the product's external world, which is of course where the demand for a new product might well originate. The lower items relate more to the detail design of the product. This gradation of the influences on design trends, from external environment to product detail design, led me to summarize the situation with Figure 4.8. This format became the basis for the first part of my methodology.
4.7 STAGE ONE OF THE TREND-MORPH-PDS METHODOLOGY

This first stage of the TREND-MORPH-PDS methodology involves dividing up the problem into sub-problem areas and sub-systems and researching the TRENDS in these areas and sub-systems. This division will normally be done into clearly established areas. For example, in any energy driven mechanical machine designed to do physical work these will be: Socio-economic, near (machine) environment, energy source, prime mover, gearing matching, transmission, working sub-system and control system.

This first stage of the design process has the following aims:

- To assist the designer to investigate the socio-economic implications of the proposed design. There have been many examples of technically excellent designs (particularly but not only in developing countries) that have failed through lack of research and understanding in this area.
- To search for possible trends (TREND ANALYSIS) in each area and to consider their influences and possible effects on the design process.
- To break the problem down into manageable sub-problems. Once the sub-problems are sufficiently small they will always be able to be systematically managed by a morphological method. (As I will show in sections 4.7.1 and 4.7.2, some designs require extensive research (morphological analysis) in all or most sub-areas/ systems, involving complex interaction between areas/ systems/ sub-systems. In these cases, the designer will be constantly iterating at all levels. The resulting complexity is best handled by clear sub-division of the problem.)
- To enable clear and consistent documentation of the design process and the design decisions, along with the reasons for them.
- To consistently categorise the sub-problem areas in terms of the various branches of design science.
- At the end of each area to document at least one design idea.
Figure 4.8: Diagram summarising the elements of TREND analysis, stage one of the author's TREND-MORPH-PDS methodology

In my case study I have found that, in following this process, I was frequently directed to new ways of looking at and solving problems that had eluded me for years. I found that the direction provided by this stage was very fruitful and had the effect of reducing the complexity and frustrations that otherwise seem to occur.

4.7.1 A design example where conceptual sub-modules are generally well known and have few options

Suppose we set a design problem, to design a low cost, single rider, three wheeled vehicle suitable for families living on small holdings (2 ha). The reason for setting this design problem could be that small farmers waste a lot of time on such properties in walking and carrying garden tools as well as gardening products and wastes.

The vehicle should be able to pull a light trailer. The vehicle could be broken down into the following: Chassis, suspension, steering, brakes, wheels, engine, transmission, body, controls and accessories. Because of our familiarity with the concepts of wheeled vehicles, this is a sensible breakdown. The specification of “three wheels” has been
stipulated because of the low cost requirement. However the layout of the three wheels could be 1 front/ 2 rear, 1 rear/ 2 front or motor bike/ side car. Each arrangement will interact heavily with the chassis and the steering design and to a lesser extent with other sub-modules. All sub-modules will be influenced by market size, and our ability to either manufacture or otherwise obtain their supply.

Figure 4.1 illustrates how the design problem could be broken down into areas such as those under LABEL and historical trends in each of these investigated. The further columns enable the designer to initially categorise each area, to see how complex/difficult in might be and if it is likely to require innovation.

<table>
<thead>
<tr>
<th>ITEM</th>
<th>LABEL</th>
<th>EXTERNAL OR INTERNAL</th>
<th>INFLUENCE ON DESIGN</th>
<th>RESEARCH REQUIRED</th>
<th>OPTIONS</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>World</td>
<td>External</td>
<td>Very general impact</td>
<td>small</td>
<td>n/a</td>
</tr>
<tr>
<td>2</td>
<td>Where used</td>
<td>External</td>
<td>Small farm terrain</td>
<td>small</td>
<td>few</td>
</tr>
<tr>
<td>3</td>
<td>Power Source</td>
<td>External</td>
<td>Little/no influence</td>
<td>small</td>
<td>few</td>
</tr>
<tr>
<td>4</td>
<td>Engine</td>
<td>System hardware</td>
<td>Little/no influence</td>
<td>small</td>
<td>From suppliers</td>
</tr>
<tr>
<td>5</td>
<td>Transmission and gearing</td>
<td>System hardware</td>
<td>Flatly depends on layout</td>
<td>little</td>
<td>From suppliers</td>
</tr>
<tr>
<td>6</td>
<td>Chassis</td>
<td>System hardware</td>
<td>To be designed</td>
<td>Linked with layout</td>
<td>many</td>
</tr>
<tr>
<td>7</td>
<td>Suspension</td>
<td>System hardware</td>
<td>Little/no influence</td>
<td>small</td>
<td>From suppliers</td>
</tr>
<tr>
<td>8</td>
<td>Brakes</td>
<td>System hardware</td>
<td>Little/no influence</td>
<td>small</td>
<td>From suppliers</td>
</tr>
<tr>
<td>9</td>
<td>Steering</td>
<td>System hardware</td>
<td>After chassis/layout</td>
<td>small</td>
<td>Internal</td>
</tr>
<tr>
<td>10</td>
<td>Wheels</td>
<td>System hardware</td>
<td>Little/no influence</td>
<td>small</td>
<td>From suppliers</td>
</tr>
<tr>
<td>11</td>
<td>Body</td>
<td>System hardware</td>
<td>After chassis/layout</td>
<td>small</td>
<td>Internal</td>
</tr>
<tr>
<td>12</td>
<td>Controls</td>
<td>System hardware</td>
<td>Little/no influence</td>
<td>small</td>
<td>From suppliers</td>
</tr>
</tbody>
</table>

**Table 4.1: Sub-modules for a three-wheeled vehicle for use on small holdings**

Where do we start? We may choose to start by researching the topic of three wheeled vehicles, to see what engineers/people have already learned from experience with them. Early tractors were essentially three wheeled vehicles (two wheels together at the front).
A single wheel at the rear would eliminate the possible need for a differential transmission. What about traction and stability of these two options?

Once we have made a (tentative) decision on wheel layout the rest of the sub-modules will most likely be satisfactorily treated as reasonably independent problems. We should probably produce an early prototype for our own assessment and for a pilot market survey with select people. A computer stylized model to illustrate improvements not in our prototype will be an advantage when demonstrating to the initial people. A product design specification (PDS) should be set up in conjunction with the market survey.

There are not a lot of conceptual alternatives for each sub-module, although the chassis and the transmission system will have quite a number. For most of these sub-modules there is an abundance of technical information and suppliers available.

For most of the sub-modules it is traditional for the OEM to buy in the sub-modules. The chassis, assembly, body, some brackets, shafts, painting and packaging are about as much of this product as the OEM is likely to manufacture on premises unless the quantity is very large.

4.7.2 The case study of this thesis: the majority of the conceptual sub-modules are not well known or have a large number of options

In the pump system design of my case study (Chapter 7) the main sub-modules of the system, as stated above, are: Socio-economic etc, well, power source, engine, balancing/gearing/matching, transmission, pump and control system. Table 4.2 summarises the sub-modules involved.

Notice that the majority of the sub-modules/areas require a large amount of research and/or have many options. Also, although not revealed by this table, there is considerable interaction between these, yet to be designed sub-modules. As my design process progressed it became evident that invention and innovation was appropriate in a number of these interdependent areas. This situation would categorise this design as requiring a high degree of innovation according to Frost’s taxonomy (see section 4.8, Frost, 1994). It could be said that the design case of this thesis is one in which several different known stereotypes need to be adapted and integrated to form a new type of
entity. I show in appendix A 7.2, that patentable material has resulted from my design work in at least four areas: long-stroke reciprocating wellhead drive unit, double acting pump drive cable, down-hole pump, fluid seals.

<table>
<thead>
<tr>
<th>ITEM</th>
<th>LABEL</th>
<th>EXTERNAL OR INTERNAL</th>
<th>INFLUENCE ON DESIGN</th>
<th>RESEARCH REQUIRED</th>
<th>OPTIONS</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>World</td>
<td>External</td>
<td>Very general input</td>
<td>Large</td>
<td>Many</td>
</tr>
<tr>
<td>2</td>
<td>Well</td>
<td>External</td>
<td>Variable with site</td>
<td>Large</td>
<td>Few</td>
</tr>
<tr>
<td>3</td>
<td>Power Source</td>
<td>External, System hardware</td>
<td>Variable with site</td>
<td>Small</td>
<td>Few</td>
</tr>
<tr>
<td>4</td>
<td>Engine</td>
<td>System hardware</td>
<td>Optional dependent on site</td>
<td>Small</td>
<td>Few</td>
</tr>
<tr>
<td>5</td>
<td>Gear</td>
<td>System hardware</td>
<td>To be Designed, Standardised</td>
<td>Large</td>
<td>Many</td>
</tr>
<tr>
<td>6</td>
<td>Down-hole transmission</td>
<td>System hardware</td>
<td>To be Designed, Standardised</td>
<td>Large</td>
<td>Many</td>
</tr>
<tr>
<td>7</td>
<td>Pump</td>
<td>System hardware</td>
<td>To be Designed, Standardised</td>
<td>Large</td>
<td>Many</td>
</tr>
<tr>
<td>8</td>
<td>Control system</td>
<td>System hardware</td>
<td>To be Designed, Standardised</td>
<td>Medium</td>
<td>Medium</td>
</tr>
</tbody>
</table>

*Table 4.2: Sub-modules for a pump design case study (Chapter 7)*

The above two design cases illustrate how two mechanical designs can differ. The first is more routine the second, more innovative. This difference may not become apparent until the design process is under way- perhaps until morphological analysis is applied to some or all of the sub-systems. However, the diligent trend analyst is likely to gain a very good idea of the critical areas where morphological analysis is likely to bear fruit in the form of a good design.

4.8 FROST’S PAPER AND THE NEED TO CHARACTERIZE THE DESIGN PROBLEM

Frost’s paper (B1-1994) suggesting a taxonomy for engineering design problems is definitely worth thinking about at this stage. He suggests establishing an eight factor taxonomy. These factors are:

- Type of entity being designed
- Degree of innovation involved
- Extent to which the designed entity can be conceptually decomposed into sub-systems
- Availability of adaptable solution concepts
- Simplicity or complexity of the designed entity
- Degree of interaction within the solution being considered
- Looseness or tightness of the constraints or requirements which the design must satisfy
- Number of times the designed entity will be built

In his paper, Frost illustrates the various factors with examples ranging from *routine* like designing a centrifugal pump to *revolutionary* like designing a helicopter and from as *simple* as designing a hose fitting to as *complex* as designing a chemical plant.

The level of each of the above factors will greatly influence the path that the design process takes. My experience, particularly with my case study has confirmed the need to characterize a design project early in the design process so that the designer can clearly see whether it is routine or revolutionary, simple or complex, one off or volume production and accordingly, choose the appropriate tools and methodology. This characterization will help the designer decide how to tackle the problem.

### 4.9 DIFFICULTIES WITH DECOMPOSING (AND SPECIFYING) THE DESIGN PROBLEM

Many authors have pointed out the difficulties that the designer faces when attempting to set up a PDS or a complete list of functional requirements at the beginning of the design process. However all agree that it is wise to break the problem down in to sub-problems – a divide and rule approach.

In a paper by Chakrabarti and Bligh (*B1*-2001) the three main functional reasoning schemes to that time were outlined. These are:

1. The *Freeman and Newall scheme* in which the designer starts with a search among known structures for ones that can meet a defined set of desired functions.
2. The Paradigm model of Yoshikawa in which the problem is defined in terms of a set of functional requirements. The example given by Chakrabarti and Bligh is the design of an animal that runs fast, peeps and swims fast. An initial solution is a dog because it seems to be the closest to fulfilling the requirements. However the dog needs modification by replacing its mouth with a beak for peeping and its legs by frog’s legs so that it will swim fast. The process involves identifying the wrong components and improving them.

3. The widely accepted Pahl and Beitz (systematic) model. Here the design problem is expressed in terms of a set of solution neutral functions. These functions are progressively expanded into combinations of sub-functions and various function-structures are produced from these. This process is repeated until the sub-functions are sufficiently simple. The optimum function-structure is chosen during this process and from this, possible solution alternatives to each sub-function in the optimum function-structure are found. These are then combined into alternative solution concepts and evaluated for selection of the most promising solution.

Each of these schemes assumes that the problem end of the process is reasonably clean cut. This assumption seems to be widely taken to be valid. Chakrabarti and Bligh challenge the operability of the above processes, unless guided by knowledge of existing solutions. They propose a model that can support design, employing recursive problem re-definition, while incorporating existing solutions. However they see problems with completely new solutions (inventive problems).

My focus at this point is on the problem end of design. My experience with my case study is that designers’ tendency is to focus on solving detail problems rather than challenging them. In some cases, the tendency is to take a “popular” course of action, rather than to question the existing course of action. Zwicky’s comment comes to mind: “leave no stone unturned”. Find all possible courses of action.

4.10 CONCLUSION

This section has pointed out the significance of categorization of the elements and sub-systems and systems of engineering with emphasis in the mechanical area. The section
has also considered the importance of analysing the functional and other structures of these objects. Next, the section has observed how inventions, over sometimes very long periods of time, involve incremental additions and improvements to the initial inventive artefact or system.

As a result of these tendencies, I see technology in terms of an ever-expanding assortment of tree-like diagrams, representing families of artifacts, machines and systems. Some branches go on growing, as engineers/inventors refine and improve the basic invention(s) that defines the particular branch. This refinement has been shown in the examples of this chapter. Some branches stop growing, for good reason, because another technology has demonstrated a significant improvement. I claim that this happened with the piston pump, which at one stage dominated the pumping industry but was challenged in many industries by the centrifugal and other rotary pumps. Some temporarily curtailed branches recommence growing later, as new ideas or technologies improve their prospects.

In my mind, this tree-like categorization with its ever spreading branches is perhaps the most scientific fundamental facet of the emerging design science. Technology and the physical elements of technology and systems exhibit trends as has been well established by researchers such as those involved with TRIZ.

From this background I have formed the idea of the TREND part of TREND-MORPH-PDS. Whereas TRIZ would direct the designer to abstract the problem and look at very general trends and catalogues of causes and effects, that range across the range of technologies and sciences, my suggestion is to examine trends related to the particular existing technologies of the design problem, at all times looking for opportunities that may improve the design and of course, not ignoring the radically new inventions that might come from the wide searches that methodologies like TRIZ enable.

The older technologies, like the pumps of my case study have had so much input from so many individuals over many years that I feel comfortable with an approach that considers the trends that emerge from researching the history of their efforts.
CHAPTER 5

MORPHOLOGICAL APPROACHES

5.1 INTRODUCTION

In the design process, engineers constantly face situations that require intelligent compromise between conflicting requirements. Engineers have traditionally dealt with parametrically defined situations in which they seek to optimise existing values by means of trade off techniques. More recently, optimization and trade off methods have benefited by considerable research and development, particularly employing the computer, increasing their usefulness to design engineers. This chapter and the previous one are not about these more traditional approaches. The focus here is on strategically finding search spaces and thoroughly searching out conceptual designs in order, with reasonable confidence, to home in on good designs. I am arguing that one good way to do this is firstly to take a broad view of the problem on hand, using the history of the specific art to help provide the necessary perspective. This approach which I call the TREND part of TREND-MORPH-PDS was explained in the previous chapter.

Partitioning the overall problem into sub-problems or sub-systems, and studying the evolutionary trends in each sub-problem/system, offers potential benefits in two ways:

- The trends may reveal some valuable contributions to the product design specification.
- The sub-problems/systems may provide the bases for manageable morphological analysis.

This chapter is about the morphological approach. It is my belief that, after identifying worthwhile sub-systems as outlined in the previous chapter, morphological analysis, involving both analytical and rapid graphical (computer assisted) methods will prove to be valuable in both executing and recording the design process.
5.2 WHERE DID THE IDEAS OF MORPHOLOGICAL AND COMBINATIVE CONCEPTUAL DESIGN ORIGINATE?

Many of the textbooks on engineering design process give a basic introduction to what earlier advocates of the morphological method proposed (Ullman, B1-2003; Otto and Wood, B1-2001; Cross, B1-2000; Dym and Little, B1-2000; Wright, B1-1998). 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. More often than not, the FRs are the basis for the first 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, B1-1996; Hubka and Eder, B1-2000; Dieter, B1-2000; Roozenburg an Eekels, B1-1995) offer a broader view. French, (B1-1999) 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, B1-1994).

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 (B1-1969) 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’s third, and final category, is entitled “The Method of Negation and Construction”. He writes: “dogmas and the impeding influence of half truths and conventional dictatorial restrictions stand in the way of constructive progress. Such dogmas, therefore must be negated at all cost.” One of his examples here is the negation of 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 (Zwicky, B1-1964, 1964,1966).

5.3 HOW MAY MORPHOLOGICAL METHODS BE APPLIED IN CONCEPTUAL MECHANICAL DESIGN?

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, B1-1996; Al-Salka and Cartmell, B1-1998). This will reduce the number of evaluations from m raised to the power n to m X n in a situation where the number of FRs is n and the number of solutions to each FR is m.

Zwicky was concerned that in any problem solving process “no stone should be left unturned”. He describes the morphologist as “the specialist of the impossible”.

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.
However, if we are dealing with, say, a mechanical design, the most elementary subsystems are machine elements: shafts; bearings; brakes etc. These are well known, and selection and parametric design procedures are well established. As mentioned in section 4.4, the morphology of many machine elements and sub-systems is reasonably well documented in textbooks on machine element design. However, some elements and sub-systems have not been well documented or researched, or may simply have not evolved. There are many possible reasons for this lack of progress in specific areas:

- Attractive competing technologies cause the predominant enterprises to transfer their resources away from the specific area.
- Institutional or government support was diminished.
- Market support for the undeveloped product was diminished.
- Dedication of area expert technologists was transferred to a seemingly sunrise area, so the undeveloped product was abandoned.
- Lack of funding for publication in the area.
- Secrecy about know-how and intellectual property by specialist people and organizations commercially involved in the area.

When researched, some of these areas may be found that have great potential with the benefits of modern materials, manufacturing processes, electronic technologies, scientific knowledge, and understanding of systems engineering.

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.

### 5.3.1 The Long Stroke Reciprocatory/Rotary Motion Converter of the Case Study of this thesis

Although it is not detailed here, the discovery of this invention involved extensive morphological analysis, and such analysis continues on progressively more specific,
critical sub-systems of the device. Several improvements and patentable discoveries have been made as a result of sustained development of the original concept. This is really an applied morphological approach.

The original morphological analysis was about finding a long stroke, mechanical improvement on the conventional crank and connecting rod mechanism which is so extensively used, sometimes with a cross-head. Many configurations were explored. Some had complex gear boxes, friction clutches, bar linkages; others were hydraulic or pneumatic incorporating reversing valves. The electronically managed reversing linear motor was extensively investigated. About 20 major categories were considered. Many of them had inertial problems and many were considered to be more complex that my chosen system of U.S. Patent No 5,063,792. A comparison between reciprocating mechanisms employed in IC engines can be seen on my website under LSRM 1 and LSRM 2:

www.eng.uts.edu.au/~johnd

In its abstract, U.S. Patent No 5,063,792 identifies the critical sub-system requiring further morphological analysis with one word “continuously” in the sentence containing: “support means being provided to support the slider within the carrier continuously throughout movement of the carrier”. This one word will eventually lead to a new patent (after further morphological research and development) in which the best way to satisfy the requirement implied by this word has been discovered and rigorously trialled. This work is already at an advanced stage.

Various embodiments of the detail design are illustrated under Power point UniPump 1 and Power point UniPump 2, on my website. There have been many more embodiments covering the various sub-systems of the reciprocator.

An alternative long stroke reciprocator mentioned in section 4.6 (U.S. Patent No 4,916,959 of 1990) has been commercialized by Weatherford for the oil industry under the trade name, Rotaflex. Some of the advantages of long stroke systems are illustrated on a Rotaflex power point presentation on the Weatherford website under: Products and services/ Artificial lift/ Surface pumping units/ Rotaflex long stroke units/ Rotaflex long
stroke pumping unit – (walk through the web pages manually, as most are large, requiring patience):

www.weatherford.com

I have mentioned Rotaflex as the existence of such a long stroke system has had a very encouraging influence on me in pursuing my project in an environment where commercially powerful competitors to my long stroke ground-water system are predominantly promoting the very different rotary technologies.

I did not know of the Rotaflex system until about 1993. Since then access to this type of information has become much easier. The Rotaflex system does not conflict with my patent(s) and requires a more cumbersome system to achieve the same objectives. It is the only system in the world being commercialised for long stroke ground-fluid pumping. It has been a great encouragement to me because of its demonstrated great advantages and commercial success.

Theoretically, one of my modules, in a large size, could be designed and installed as a sub-system in a Rotaflex system, to provide only the reciprocating motion. I am convinced that this could offer a reduction in manufacturing cost and increased reliability – i.e., a more robust design. However, the company is unlikely to come to a commercial agreement on this idea, as it is already supporting about 1000 Rotaflex units in the field, and such a change would require supporting two systems rather than one.

Morphology is fundamental, not only, to achieving a good design, but also to planning a strategy for the (costly) protection of intellectual property.

My company may not be able to achieve a commercial licence with Weatherford – Rotaflex, but a joint technical agreement to share information related to long stroke ground-fluid pumping is likely to occur, bringing benefit to all concerned. This will provide the basis for the ultimate design evaluation process: field experience and the sharing of this experience.
5.4  RAPID SKETCHING AND MORPHOLOGICAL ANALYSIS IN CONCEPTUAL DESIGN

Earlier, in section 3.5.3, the work of Ullman and his co-workers was discussed. They were concerned that computer based systems should be developed to assist designers and design teams in their work. One of their conclusions was that the computer software should support the graphical documentation (and construction) of sketches in a speedy and non-burdensome way and allow recording of reasons behind the ideas and decisions. They considered this to be important because 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.

When I started to generate the morphology of down-hole piston pumps (Appendix 7.2), I initially employed two techniques:

1. The use of an Excel spread sheet and careful symbolic labelling of all combinations and permutations to represent the different pumps.

2. 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 of communication to others.

Construction of the solid models was time-consuming – taking times ranging from about 1 hour to one day for each model. I realised early that there were in excess of 60 models involving a large amount of tedious work.

However the designer needs to do a lot more than the tedious construction of solid models. 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), 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. For convenience Ullman’s diagram of Section 3.6, representing the designers’ activities, is repeated here.
In his publications in this area, Ullman sees the designer(s) as constantly investigating (suggested) architectures that might satisfy required functions. The idea of architecture is somewhat abstract (the stick diagram that can easily be manipulated and changed before the shape is refined). Often, after the architecture, the designers add shape which implies geometry and detail. At this stage, DFM, DFA, materials and cost can be queried and a further evaluation of the current state of the design may take place.

During the stick diagram and shape part of the above process, Ullman sees an opportunity to extend CAD systems to work quickly from function to form, including the effortless production of engineering sketches and diagrams.

In Appendix A7.2, I show how, in the conceptual design of the down-hole pump, computer sketches were constructed in Microsoft Word, after defining a graphical code of the basic elements such as valves, valve elements, tubes, seals etc., that are common to all conceptual piston pumps. The various down-hole pump configurations were then rapidly built from these by copy and paste operations. In this way, the rapid computer sketching of conceptual was not burdensome.

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 as discussed in section A7.1.3. 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 and 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.

5.5 CONCLUSIONS

Morphological analysis is a detail activity. As Zwicky has pointed out it is thorough. The morphologist is to leave no stone unturned in his/her endeavour to investigate every way to find a good design. One of the driving influences on the company is that your competitor may find the good design that your company overlooks.

It appears that if this approach is not taken, a “natural evolution of the product” will take place incrementally as the field users, maintenance personnel and others involved with the product discover its improvements one by one. The MORPH approach will speed up this process and can be regarded as a simulation of the real time situation. However it must be carried out carefully and the many interactions with other sub-systems and the product’s near and far environment considered. Each step must be
evaluated. The rapid sketching will assist the designer to have time and energy to think about and document the necessary issues and decisions along the way.
CHAPTER 6

PRODUCT DESIGN SPECIFICATION (PDS)

6.1 INTRODUCTION

The PDS is an essential part of the design process. For many years, engineering specifications have been used by engineers for legally defining the contents of engineering projects, complex systems, individual machines and other requirements. During the design process for innovative design, the PDS may be treated by the designer as an evolving and guiding record which clearly and efficiently specifies the requirements for the product of his work. In my experience it should be produced as the designer iterates between the broad view of the problem (TREND), the exhaustive analysis of the sub-problems (MORPH) and the synthesis and ongoing evaluation that refines the PDS. Eventually it becomes a firm and concise statement of the requirements and constraints of the design. By the time this has been achieved, detail designs of sub-problems may already have been trialed and evaluated, but the final detail design may now be performed. When it has been achieved, detail designers, sub-contractors and suppliers can productively accelerate the final detail design.

6.2 GOALS: BROAD STATEMENT OF THE DESIGN INTENT

Innovative projects always start with some goal, a goal that may originate from any of a variety of sources – usually as a result of discontent with a current situation. The originator may be the management or marketing department of a company, attempting to improve their product in order to maintain or gain market share. If the original concern is with market share, then the term “market pull” is often used. Alternatively, the originator of a new project and its goals may be a group (or an individual) who have invented or developed some new artifact or technology that promises improvement over an existing product or system. The term “technology push” is used in these situations.

For many products that are used either directly or indirectly as aids to production, for example agricultural machinery or process plant units, operators and maintenance personnel routinely find ways to improve or even redesign the products. Farmers in
Australia are famous, even in these days of global high volume production, for building improved agricultural implements, with considerable success in the Australian market. This kind of push is not necessarily technology push. It often indicates a lack of design for maintenance or a lack of understanding of the local operating environment by the global designer. Another source of "inventor push" is where dominant corporations in a market have simply not invested in research and development for many years, leaving opportunities for users and inventors to do what the corporation should be doing.

Whatever the driving force, intelligent design involves goal orientated processes.

Some interesting questions are: who is/are the driving forces? Who will benefit from the goal(s)? The shareholders? The clients? The employees of the company?

Design is very much a trade-off process. In the case of a volume produced product requiring operating and maintenance expenditure, the need for trading-off between capital cost and running cost is well known. One of the risks of powerful driving forces is that the “trading off” may not be performed in an even-handed manner. Pugh (1996), states that “all designers, whatever their label, should continually monitor and bear in mind all these factors from the start to the finish of any design”. He is referring to general design factors like those of Table 6.1 in the next section. In other words the “trading-off” is really a balancing process between many, often competing factors.

6.3 SUMMARY - A GENERAL CHECK LIST FOR THE PDS

Table 6.1 is a general PDS, or rather, a check list to be used by the designer to aid the construction of the specific PDS for the design on hand. This type of list has a history dating back to an early British Design Council standard that showed very similar factors, spaced around the circumference of a circular template. This kind of list is mentioned in many textbooks on engineering design process, often in conjunction with Quality Function Deployment (QFD), (see Dieter, B1-2001). Such lists indicate the need for initial and ongoing check lists and procedures to aid and guide the designer, so that he/she does not create a design that fails due to the neglect of just one of these factors. Pugh gives examples of such cases of failure.
6.4 CONSTRUCTION OF THE (PRODUCT) PDS

A number of authors, for example, Pugh (B1-1996), Wright (B1-1998) and Dieter (B1-2000), emphasize the need to construct the PDS before commencing the design work. Thus the PDS is an initial, direction giving document. It should be constructed with the guidance of a more general PDS and in association with the company’s market and competition analyses. Wright has a chapter on requirement trees which help the designer to get the marketing information into a form that is more useful to the engineer. Requirement trees enable the designer to reveal in detail, the objectives and constraints of a design project.

My proposal, based on my experience, especially in the case study, is that having constructed an initial, specific product PDS or simply PDS, this will evolve during the iterations that occur as the designer executes part of the TREND and MORPH analysis. The TREND might trigger an idea - “is it possible to do such and such?” - which, perhaps leads to some MORPH analysis, leading to a further evaluation or idea, that may lead to a statement (functional requirement or constraint) in the PDS that may simply identify a sub-goal. At this point the designer may not know if this sub-goal is achievable. However he/she may have a degree of confidence that a way will be found to achieve it and if this goal is met the product will have a competitive advantage.

As I constructed my PDS of the case study, I found scenarios like the one above. In effect, the sub-goals were part of the process of breaking the job down into manageable sub-problems and the PDS, along with the TREND analysis, was helping the designer to document the process. Separately detailing each of the items as I have in Chapter 6 has become part of the documentation process.

Wright’s chapter on requirement trees emphasizes that the PDS should be objective, independent of the perceptions of the designer (and others). He also mentions that one of the reasons for constructing requirement trees is to explore the problem rather than look for solutions at the requirement tree stage.
<table>
<thead>
<tr>
<th>Factor</th>
<th>Typical questions or comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Performance</td>
<td>What functions are required of the product? What parameters will be assessed? How fast, how slow, how often, continuous, discontinuous?</td>
</tr>
<tr>
<td>Environment</td>
<td>During manufacturing, storage, transport, installation, how will possible ambient conditions interact with the product? Effects of hazards?</td>
</tr>
<tr>
<td>Life Expectancy</td>
<td>How long does the product have to last, at what performance level? How intensively will the product be used?</td>
</tr>
<tr>
<td>Maintenance</td>
<td>Is regular maintenance available or desirable? Should planned maintenance be used? Which parts require access for maintenance? Should replaceable modules be used?</td>
</tr>
<tr>
<td>Target product cost</td>
<td>Is the costing valid? Can sufficient quantities be sold to meet the target cost? How does the target cost compare with competitors?</td>
</tr>
<tr>
<td>Availability of components?</td>
<td>Is any one component of the manufactured product likely to become restrictive? Are there any critical supplied components that may have unreliable supply?</td>
</tr>
<tr>
<td>Packaging</td>
<td>Required? What does it protect against? Effect of volume of product on transport cost?</td>
</tr>
<tr>
<td>Transportation</td>
<td>Domestic or export market? Any special manufacturing requirements? Special care in handling?</td>
</tr>
<tr>
<td>Quantity</td>
<td>Cottage industry? Batch production? High volume production?</td>
</tr>
<tr>
<td>Manufacturing Facilities</td>
<td>Use existing facilities? Build or rent new facilities? Sub-contract components? Licence?</td>
</tr>
<tr>
<td>Size and weight</td>
<td>Any restrictions on size or weight? Human lifting limitations? Access to difficult sites like islands, mountains? Will it require air transport?</td>
</tr>
<tr>
<td>Aesthetics and finish</td>
<td>This is always important as it gives first impressions to the customers.</td>
</tr>
<tr>
<td>Materials</td>
<td>Special materials required? Certain materials forbidden?</td>
</tr>
<tr>
<td>Product life span</td>
<td>How long will the product be marketable before it is superseded?</td>
</tr>
<tr>
<td>Standards and Specifications</td>
<td>Which national or international standards apply?</td>
</tr>
<tr>
<td>Ergonomics</td>
<td>Consider peoples’ perception, understanding, use, handling of the product</td>
</tr>
<tr>
<td>Quality and reliability</td>
<td>What levels does the market expect? Mean time between failure? Failure modes, and effects on functioning? Convenience of repair procedures?</td>
</tr>
<tr>
<td>Shelf life</td>
<td>Specific requirements for long storage times? Perishable components?</td>
</tr>
<tr>
<td>Processes</td>
<td>Any special manufacturing processes?</td>
</tr>
<tr>
<td>Testing</td>
<td>100% testing or sample testing? Who will witness? Cost of testing allowed for?</td>
</tr>
<tr>
<td>Safety</td>
<td>Mandatory and desirable levels for user? Balance between safety, accessibility and limitation on usage</td>
</tr>
<tr>
<td>Company constraints</td>
<td>How will the product fit in with current company practice? Is it different? Effect on personnel? Constraints on production?</td>
</tr>
<tr>
<td>Market constraints</td>
<td>Specific components unacceptable? Problems from overseas markets? Technological level acceptable?</td>
</tr>
<tr>
<td>Patents</td>
<td>Have necessary searches been done? Should patenting be done?</td>
</tr>
<tr>
<td>Product liability</td>
<td>Have all unintended consequences of production, operation and use been checked for manufacturers liability?</td>
</tr>
<tr>
<td>Installation, operation</td>
<td>What will be necessary to supply, advise, train people for installation and operation of the product?</td>
</tr>
<tr>
<td>Reuse, recycling and disposal</td>
<td>Have these issues been properly considered during the design process?</td>
</tr>
</tbody>
</table>

Table 6.1: A general check list to assist the development of the PDS
Wright shows how by constructing requirement trees the design engineer can take the requirements from the marketing department, construct broad functional requirements then break these down into detail FR’s.

At the top of a requirement tree are the broader requirements (FR’s) and at the bottom are the elaborations in detail in the form of detail FR’s.

The requirement tree is both useful to the designer in gaining a better understanding of the problem and in communicating the issues along the way. Its aim is to facilitate the construction of the PDS and it is an example of a useful tool that may be used in conjunction with TREND-MORPH-PDS (Wright, B1-1998).

6.5 TYPES OF PDS

It is convenient to view three levels of generality of the PDS.

- The highest level of generality of the PDS is where it assists the designer in looking at the broadest possible range of solutions to the overall problem. In the case study this may involve considering all the pumps of Figure 4.1 and perhaps some novel ones such as the use of the magnetohydrodynamic principle as part of a photovoltaic system. Wright calls this the product alternatives level.

- The next level is the product type level. An example of this from the case study would be the construction of a PDS for the down-hole piston pump. The PDS here is limited a particular solution-type.

- The lowest level of generality is the feature level and is more aligned with the specification of individual artifacts for manufacture.

In innovative design such as the case study, the product type level seems to be appropriate.

6.6 THE VALUE OF THE PDS TO THE DESIGNER

A good PDS will specify requirements without implying any type of form that might meet these requirements. It will help the designer to broaden his/her vision and look
further a-field for solutions. It will not bias the designer towards preconceived ideas that are the result of vague assumptions and prejudices.

The PDS is an evolving, working document that can help the designer and his co-workers to keep on track and to set strategic goals and sub-goals. In this way it can help to avoid the confusion of not being able to decide what to do next and also what has already been achieved. The PDS can help the designer to prioritize the sub-problems and to communicate issues and progress to others.

One of the most important values that I see is the use of a master PDS to guide the designer in initiating the specific PDS of the project. The systems engineering textbooks (Blanchard et. al., B1-1990) contain valuable and comprehensive check lists in this respect.

6.7 CONCLUSIONS

I have summarized briefly in this chapter the importance of the PDS in developing a systematic approach to the design process. More detail is given in the construction of the pumping system PDS in the next chapter.

I note here that the PDS does not come out of the blue. In a case like the UniPump it will be an evolving document commencing with an assessment of the market needs (the clients needs). For a volume produced product, this may be done by employing methods like QDF and may even be triggered by people with intimate knowledge of the clients’ environment and the problems that are present in the products that are currently on the market.

Without a doubt, no designer or organization should attempt to produce an innovative design without a guiding PDS. In which the items have been carefully selected.
CHAPTER 7 - CASE STUDY:

INNOVATION, DESIGN, DEVELOPMENT AND TESTING OF A RANGE OF RECIPROCATING GROUND-WATER PUMPS

7.1 INTRODUCTION

This case study is about the design, development and testing of a range of reciprocating ground water pumps suitable for operation in tube wells. Primarily, the pumps are to be appropriate for use in remote watering situations, where wells yield relatively low flow rates, often in the range 0.05 to 2 litres per second. During the design process, which is outlined in the following pages, a central design objective becomes apparent. This requirement is that the pumps should have the ability to accept a variety of power options (solar/photo-voltaic, engine, wind, human etc). A further important requirement is for the pumps to operate at high efficiency over a wide range of operating conditions, with a minimal product size range and configuration effort. Other design issues are: minimization of capital and running costs; reliability; maintainability; and suitability for "low technology" manufacture and installation.

After a discussion of some of the main trends and problems in the Low Yield market, in this chapter I demonstrate the application to the pump design case study of the TREND-MORPH-PDS design methodology proposed in this thesis.

Before starting this chapter it may be helpful to read the description of my earlier experiences in designing and building solar thermal ground water pumps, covered in Chapter 2.

7.2 BACKGROUND TO THIS CASE STUDY

An early phase of the project of this case study is outlined in Chapter 2 and Appendix A7.3 of this thesis. Shallow ground-water aquifers are widely used around the world to
supply relatively small volume flow rates of pumped water. Typically, the water inflow rate to such wells is limited to about 1 litre per second and the pumping head is less than about 60 metres. These wells are important for supplying water for stock (such as cattle and sheep on Australian farms), for supplying clean drinking water for villagers in the developing countries and for supplying water to irrigate small lots.

Historically (from the 1800s), reciprocating piston hand pumps and wind pumps have been used to pump water from such wells. These devices were developed before electrical power was available. Nowadays, other sources of energy may be available at well sites, including: centrally distributed electricity; solar (thermal and electric) power; wind; and internal combustion engines.

Modern motors and engines are usually designed for operation at relatively high rotational speeds and thus are well matched for direct coupling to centrifugal and other suitably designed rotary pumps. Sealed electric motors can be close-coupled to multi-stage versions of centrifugal pumps to give slim, integral units known as "submersible pumps". A pump of this type is readily lowered into a tube well, with a delivery pipe and electric cable rising to the surface. Internal combustion engines are obviously unsuitable for submerged use.

Most ground-water pump manufacturers have abandoned the older surface driven, low frequency reciprocating piston pumps, in favour of relatively high frequency rotary submersible pumps. This is because of the apparent elegance of this approach to the problem, and the compactness of the design, involving close coupling of the submerged electric motor and controls.

For low volume flow rate situations, it is reasonable to question the above design trend, particularly where power sources other than centrally distributed power are appropriate. At low specific speed, submersible (multi-stage) centrifugal pumps have low efficiency, as illustrated in Fig 7.1. This results in high capital and/or running costs. A typical operating region is indicated at the lower left hand corner of the graph. This efficiency is for the bare shaft pump. After allowing for electric motor loss, delivery pipe loss, electrical control and transmission loss, the instantaneous electricity to water efficiency of a multi stage centrifugal system in the above range is likely to be of the order of 10 percent.
After taking into account motor and controller efficiency, real electric submersible pumps operating in this regime have an electric power to water power efficiency ratio in the order of 7 to 15 percent. This efficiency is further reduced when we take into account applications issues, such as varying head and varying power input, as occurs with solar and wind power (Bloos et al., B2-1996; Kerndl et al., B2-1994; Whitfield, et al., B2-1996). The performance of roto-dynamic pumps is sensitive to these varying inputs.

Figure 7.1: This chart is derived from an updated version from Karrassik (B2-1986) of a chart originally known as the "Wislicenus Chart". Note: US parameters including specific speed.

The chart is for bare shaft single impeller pumps

I had previously (Chapter 2) investigated two design issues of solar ground-water pumps: efficiency and reliability, both of which influence the capital and operating cost of systems. The trend for manufacturers to apply electric submersible pumps to the low yield ground-water market seems to me to ignore both these issues. The emphasis seems
to be on compact, compactly packaged, direct coupled systems that are readily distributed and stored. Ironically when one goes to a pump shop to buy a small multistage centrifugal bore-hole pump, there is always a waiting period of several weeks while the supplier orders the pump from the manufacture. This delay is because the supplier does not stock the wide range of pump sizes and stages necessary to accommodate varying heads and flow requirements. The cost of holding the large range of stock is considered to be prohibitive.

As regards the reliability issue, the relatively shallow tube wells of the low yield market are notorious for causing pump problems, due to the presence of corrosive and abrasive elements in the water pumped and for problems due to varying water level and seasonally discontinuous system use. Submerging the electric motor, and in some cases the intricate pump elements, in these environments leads to failures due to corrosion, abrasive wear and frictional seizure (Vetter and Wirth, B2-1993).

Concern about the above issues caused me to review the history of ground water pumps to see if this history would reveal some reasons for this situation. Farmers who had been content with the windmill for over one hundred years, are now “trialling” many new submersible ground water systems, some with submerged control systems, and so far these systems are proving to be much less reliable than the windmill (Moore, 2002-discussion).

As I investigated this history, looking for meaningful trends, thinking about how machines and systems evolve and reading of the work of design/invention researchers who have focussed on such trends, I came to the conclusion that this evolutionary trend seeking approach would be valuable in many design situations.

7.3 THE USEFULNESS TO THE DESIGNER OF INVESTIGATING THE HISTORY OF THE SPECIFIC ART (GROUND WATER PUMPING)

A summary of the history of ground fluid pumps is shown in Fig 7.2. One of the premises of my thesis is that research into the history of the specific art will improve the designer's prospects for quality execution of the design process. Careful research of the history can show the progression of invention and innovation in the area. It can also
reveal the logic behind the various designers' decisions. In this case (the low yield ground water pumping system), I originally looked at four main areas of development. These areas are familiar to mechanical engineers and were the subject of the first evolutionary “law” of the Russian invention theorist, Altshuller:

- **Engine** (photo-voltaic, photo-thermal, wind, internal combustion etc),
- **Working organ** (pump),
- **Transmission** (mechanical, electrical, hydraulic, pneumatic etc)
- **Control system** (mechanical, electro-mechanical etc).

In his research during the late 1940's, based on reading and coding some 4,000 patents, Altshuller (B1-1988, 1996, 1997, 1999) concluded that all viable (mechanical) systems must include these four basic sub-systems. He called this law "The law of completeness of parts of a system".

Altshuller observed that "technological systems evolve in accordance with certain patterns [or laws]. These patterns can be revealed from the world's accumulation of patent information, and intentionally applied for the purpose of advancing a system through its evolutionary stages."

Another of Altshuller's laws is: The Law of Increasing Ideality, which states that "A system evolves in such a direction as to increase its degree of ideality"

\[
\text{Ideality is defined as: } \text{IDEALITY} = \frac{\Sigma UF}{\Sigma HF}
\]

\(\Sigma UF\) (= all Useful Effects) includes all the valuable results of the system's functioning.

\(\Sigma HF\) (= all Harmful Effects) includes capital cost, running and maintenance cost, space that the system occupies, pollution that it produces etc.

Altshuller's laws and other general laws assist in finding a good direction. My own proposal is that from a study of the specific histories of the sub-systems the designer can summarize and learn the progress of the inventions and specific developments. This will help the designer to see where future improvements should be made.

In other words, the specific history and laws based on the general history of technology development are helpful in defining the boundaries of the system to be designed (invented) and in setting up the functional requirements and constraints. The specific
history tells us where designers of the past have been directing their efforts and the laws indicate, at least in a general way, where the current design should be directed.

There has been much discussion on the above evolutionary laws in the TRIZ technical papers, which are freely available on the TRIZ Journal website:

http://www.triz-journal.com/

7.4 HISTORY OF WATER PUMPING

The information in Fig 7.2 is extracted from a number of publications (some rather old) with interesting sections outlining the historical developments.

Information was obtained from Smith (1817), Mathews (1835), Winton (1883), Worthington (1887), Weisbach (1897), Rogers (1905), Cox (1905), Futers (1909), Butler (1913), Gibson (1925), Lea (1934), Deming Pumps Catalogue (1934), The War Office Britain (1936), Lewitt (1958), Addison (1959), and many other more recent publications listed at the end of my Bibliography-B2.

With reference to Fig 7.2, prior to the 1700s, pumps were generally of the positive displacement class powered by animal, human, wind power or moving water, the power being transmitted by ropes, chains, shafts and rods to simple elements such as scoops, buckets and screws.

During the 1700s the steam pumps of Savary, Newcomen and Watt emerged. A long line of historical ideas, experiments and constructions preceded these inventions. These included:

- Ideas such as those of Solomon de Caus, who proposed that "the steam of boiling water could be used for the navigation of ships, the driving of carriages and a host of other miracles".
- Experiments such as those of people like Pappin, with his experiments on pressure, Torricelli, with his experiments on atmospheric pressure and Otto von Guericke demonstrating properties of a vacuum.
- Constructed devices such as Hero's aelopile from the first century AD.
Dasgupta (B1-1996) gives an excellent outline of the evolutionary improvements to the steam engine [pump] that took place during the Savery, Newcomen and Watt era. The steam pumps of this era were largely applied to the de-watering of mines. Both the Newcomen and Watt mine de-watering pumps were rod driven by surface steam engines. The pumps were usually single acting plunger pumps, driven via heavy rod strings that were guided in structures built in open shafts. The weight of the rods was used to force the water to the surface and the engine lifted the rods. These pumping systems were heavy and cumbersome, compared to more recent pumping systems such as the relatively modern American multi-blade wind pumps, whose rod strings are inside the rise pipes which fit down bored tube wells.

<table>
<thead>
<tr>
<th>ELEMENT</th>
<th>TIME</th>
<th>BC</th>
<th>AD</th>
<th>1700's AD</th>
<th>1800's AD</th>
</tr>
</thead>
<tbody>
<tr>
<td>SOCIO-ECONOMIC, DEMOGRAPHIC, APPLICATIONS</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Casual irrigation, mine de-watering, drinking and bathing water</td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>DEMATERING WARES, TOWN WATER SUPPLY, FOODED HAND PUMPS</td>
<td></td>
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<td></td>
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<tr>
<td>INDUSTRIAL REVOLUTION, POWERED MINE DEWATERING</td>
<td></td>
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<tr>
<td>WELL CONSTRUCTION</td>
<td></td>
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<tr>
<td>OPEN WELL, MINE DEWATERING</td>
<td></td>
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<td></td>
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<tr>
<td>OPEN WELL</td>
<td></td>
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<tr>
<td>POWER SOURCE</td>
<td></td>
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<td></td>
</tr>
<tr>
<td>MANUAL, ANIMAL, ROPE</td>
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<td>STEAM ENGINE</td>
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<tr>
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<td>TWO PISTON AND QUICK RETURN</td>
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<td>TRANSMISSION OF THE POWER DOWN THE WELL</td>
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<td>STEAM DRIVEN DOWN THE WELLS, RECIPROCATING PISTON</td>
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<td>SCOOP, EUCKET, CHAIN BUCKETS, ARCHIMEDEAN SCREW, STEELEUS RIM</td>
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<td>VARIOUS RAM, AS WELL AS PISTON AND CYLINDER CONFIGURATIONS</td>
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<td>CENTRIFUGAL PUMP, VISITORS PUMP, AIR LIFT PUMP</td>
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<td>CONTROL SYSTEM</td>
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<td>MAIN EVENTS</td>
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<td>WATER WHEEL</td>
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<td>STEAM ENGINE INVENTIONS OF SAVERY, NEWCOMEN AND WATT</td>
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<td>TUBE WELL PUMPS, I. C. ENGINE DRIVEN PUMPS, AMERICAN MULTI-BLADE WIND PUMP AND CENTRIFUGAL PUMP</td>
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Figure 7.2 part (a): Chronological classification from ancient times to the nineteenth century of major events of each category relevant to the ground-water pump
Figure 7.2 indicates how, in an evolutionary way, discoveries were made for each of the four main Alshuller sub-systems of the ground-water pumping system.

One important discovery that occurred during the 1800s was the discovery of the principle of centrifugal pumping (Rogers, B2-1905; Henshaw, B2-1987). Like the discovery of the bladed propeller for marine propulsion, a rapid evolution of ideas for improvements followed initial demonstrations of the principle. Theories were proposed to explain the principles and formulae for analysis and design. These were modified and improved in an evolutionary way with time.

Initially, the centrifugal pump principle was thought to offer inferior efficiency than that offered by well-designed piston and other positive displacement pumps. Its advantage was thought to lie only in its comparative simplicity of construction. Also, it was thought to be of limited use, in that only single stage pumps were available and these were viable for relatively low head situations. Then the foundations of modern turbo-
machinery theory were developed, and multi-staging was invented. In time, it was shown that the centrifugal pump could perform as well or better than its more cumbersome counterpart, the piston pump. The latter was, as we know, restricted to applications where operational parameters such as specific speed, fluid properties and volume flow rate were appropriate. In many industries the centrifugal pump has almost entirely superseded the positive displacement pumps of the 1800s. It has been suggested (Karassic, B2-1995) that the trend away from positive displacement pumps toward centrifugal pumps may have gone too far. One of the reasons for the historical swing of expertise away from the older piston pump industry was the attraction for personnel of working in the “more modern” centrifugal pump industry, where money was available for developing new systems. However, the positive displacement pump continues to have a significant place in the market where conditions of service require it. Certain industries, such as the artificial lifting of oil, still predominantly use piston pumps (Brown, K. E., B2-1980).

7.5 ADVANTAGES OF RECIPROCATING GROUND-FLUID PUMPS.

Lea and Minissale, (B2-1992), confirm that one of the advantages of employing reciprocating ground-fluid pumps in the oil well industry, involving relatively high lift as well as relatively low flow rate (ie, situations having low specific speed), is that the reciprocating pumps have greater energy efficiency than other of pumps types (e.g., centrifugal pumps) with which they might be considered to compete.

Ground-fluid pumping situations are often harsh on pumping equipment, involving corrosive fluids, suspended abrasive solids, high-pressure gas, as well as the occasional risk of the pumps running dry. Reciprocating Pumps, with the motor at the surface, are used in 80 to 90 percent of all oil wells where the oil is artificially lifted.

The fact that these pumps are so widely used in this highly developed industry (Day and Byrd, B2-1980) is considered to be partly due to their greater reliability in harsh conditions. It supports a case for their more general suitability in these environments, and their wider use in the ground-water industry.
Simplicity of design, construction, operation and maintenance is important in pumps for community water supply in the villages of developing countries. The United Nations Development Program (UNDP), along with the World Bank and other major donors, is involved in a project known as The Community Water Supply Project. This consortium has promoted a concept called VLOM (Village Level Operation and Maintenance). Nearly all of the hand-pumps submitted and tested for this project are of the reciprocating type, (Arlosoroff et.al., B2-1987). Again, the fact that such a highly funded and professionally supported project has consistently employed reciprocating hand-pumps supports the case for their suitability.

7.6 PROBLEMS WITH RECIPROCATING GROUND-FLUID PUMPS.

Most of the engineering problems associated with reciprocating pumps emanate from the intermittent nature of their pumping strokes in moving the fluid. This makes it difficult to establish continuous flow with smooth head and leads to inertia loads on pump components and associated pipelines and pipeline equipment, loads applied by both the components of the pumping machine and the pumped fluid.

The very earliest engine driven ground-fluid pumps, such as Watt and Bolton’s Cornish mine de-watering pumps, were reciprocating. They operated at very low speeds, so these inertia loads were not a major concern (Smiles, B3-1878).

In the latter half of the nineteenth century, Henry Worthington of New York recognized the significance of these problems, (Worthington, B2-1887) and addressed them practically in his direct double acting steam surface pumps. He introduced the idea of multiple valves in order to minimize valve closure time. He also made a number of mechanical inventions for rapidly reversing the steam driving engine, so as to minimize time between pumping strokes. He also devised steam force compensating measures to produce steady motion during the pumping strokes of his direct acting steam pumps.

Another method of addressing these problems, which became popular in ground-water pumps last century, was the employment of multiple cylinders, with overlapping pumping strokes (Weisbach, B2-1897).
One of the most interesting of all the inventions that evolved in the designers' efforts to overcome these problems was the Pomona deep well pump, developed in America for steady pumping from city water wells during the 1870s. It is illustrated in Fig 7.3. It had two pistons in a single vertical cylinder. These pistons were surface driven, respectively by a slender tube and a rod in this tube, connected to two Whitworth Quick Return Mechanisms at the surface. Thus, overlapping of the pumping strokes could be effected. This machine illustrates the length to which engineers were prepared to go in order to address these problems. Large Pomona pumps (24 inch [610 mm] diameter cylinders, and 36 inch [915 mm] stroke), were capable of pumping up to 1,000 US gallons [3,785 litres] per minute and deliver heads up to 350 ft [107 metres] (Etcheverry, B2-1915).

The above examples all occurred before the end of the nineteenth century. Another common practice was to install air chambers with associated non-return valves, both before and after the pumps, to protect equipment and produce a smoother flow. This practice, like many of the others, is still used with piston or diaphragm pumps today.

With mechanically driven ground-fluid pumps operating in tube-wells, it has been traditional to haul the fluid using a valved piston, in a cylinder with a valve fitted to its lower end. Both wind driven pumps and oil-well beam pumps virtually standardized on this principle from the latter half of the 1800s onwards. The first drilled oil-well was in 1859. The oil flowed freely to the surface as it did in many of the early oil-wells. All early pumped wells, both oil and water, were relatively shallow.

During the first quarter of the twentieth century, pumped oil-wells became deeper. In 1931 a paper was published recognizing another problem of reciprocating ground-fluid pumps: the elongation of rods and tubes during pumping (Marsh, B2-1931). Many papers followed, each refining our understanding of this complex problem. One of the important papers is that by Gibbs (B2-1963). Gibbs used a flexible mathematical model involving the one-dimensional wave equation. The boundary conditions for this equation are the motion of the polished rod (at the surface) and the assumed loading conditions of the down-hole pump. The equation is solved by computer, using partial difference equations. The technique may be used to simulate a variety of pumps in a variety of operating situations. Many papers have followed from Gibb’s first paper, refining the models to take in to account additional physical effects (Gibbs and Neely,
7.7 THE TECHNICAL PROBLEMS WITH RECIPROCATING PUMPS CAN BE OVERCOME

The literature about reciprocating pumps, and the operating experience with them, shows that problems such as valve slam, pressure pulsation and other inertial problems related to the reciprocating motion of these pumps can be kept to acceptable levels. However, all the methods discussed above involve additional machine complexity, increases in machine size and weight, and higher capital and operating cost. They involve trade-off methods, and fall short of eliminating the problems. The Pomona pump (Figure 7.3 (a)) illustrates the trade-off of complexity and capital cost to achieve smooth flow.

(a) Pomona pump  
(b) Downie pump

*Figure 7.3: (a) Pomona Two Piston Quick Return Smooth Flow Pump. (b) Downie Double - acting Direct Connected Steam Borehole Pump fitted with two plungers having Ashley valves*
The Downie pump (Figure 7.3 (b)) is another example of the trade off designs of the 1800s. Like the Pomona pump, the Downie pump had two down-hole pistons (in fact plungers). These plungers were fitted with many small non-return valves rather than one large one. The movement of many small valves was less than that of a single larger one of equivalent flow area. This arrangement minimized the valve slam problem. This style of pump was known as a concertina pump. Like the Pomona pump, it was popular for city water supply installations.

As the designer/inventor works down to the level of increasingly specific embodiments, a study of the relevant patent literature (looking only at "serious" patents) reveals that the progression of patents is a series of improvements, each patent overcoming a remaining problem not addressed by the previous patents.

7.8 DECISION IN FAVOUR OF RECIPROCATING GROUND WATER PUMP

As long ago as 1985 I had decided that the reciprocating tube well pump was well worth pursuing as an appropriate pump for the “low yield market”. My reasons were as follows:

- The wind pump after a hundred years of success in this market was still competing and favoured by many farmers. It was a reciprocating tube well pump. Why not examine its weaknesses and improve it, to make it even more competitive?

- I had ruled out photo-thermal pumps. Many of these had been proposed and constructed, often as the subject of higher degree thesis projects and government sponsored research. L. C. Spencer (B2-1989a,b&c) lists more than 50 such devices. Despite the large amount of research and development effort, these systems, have not succeeded commercially. One deficiency of photo-thermal pumps is that they are not flexible in adapting to the varying site conditions. (On the other hand, photo-voltaic systems have been increasing in popularity since their commercial introduction in the mid 1980s.)
Although promoted by some companies, submersible multi-stage electric motor driven bore-hole pumps had the problems mentioned in section 7.2. An additional deficiency of these systems is that they require a generator at the surface, introducing unnecessary complexity and significantly reducing overall efficiency. They are unsuitable for use with animal and human power.

Submersible progressive cavity pumps, although more efficient than the multi-stage submersible pumps, have the problem of having a narrow operating range (efficiency vs head curves are narrow). Progressive cavity pumps also have very high starting torque, particularly after a period of non-operation. So far, submersible progressive cavity pumps have a very poor reliability record, associated with submerged electronics failure and electrical/electronic burn-out during high torque starting (Moore, 2002-discussions). They also have the deficiency of all submersible pumps, in that they require a generator at the surface. They are unsuitable for use with animal and human power.

A good mechanical well-head reciprocator, matched to a piston pump, has the potential to be flexible with regard to all power sources and have a wide range of high operating efficiency. Such a system also avoids the problems of down-hole electrical equipment.

The above comments summarize the situation with pumps that are competitive with the reciprocating tube well pump. The situation they describe gave me the incentive to pursue my ideas, resulting in a number of innovations to improve the viability of the reciprocating tube well pump for the “low yield market”.

7.9 DETAILED EXAMINATION OF EVOLUTIONARY TRENDS RELATED TO THE CATEGORIES OF FIGURE 7.2 (a) & (b)

Many factors have influenced the design of ground-water pumps. Fig 7.2 lists eight elements which categorize knowledge and inventions that have come to light over the years. These eight elements are: 1. socio-economic etc; 2. water well construction; 3. power source; 4. prime mover; 5. gearing & balancing (matching); 6. power transmission; 7. pump configuration; and 8. control system. A study of these elements
and the reasons for the various changes provides a valuable knowledge base for the designer of new (ground-water) pumping systems.

Other influences including major technological advances, such as mechanized farming, large scale electric power generation and distribution, introduction of railways and consequent spread of civilization, remote gold rushes, natural disasters and wars, etc. The designer must be careful to conserve time in assessing the most relevant external influences.

In order to systematically outline the above influences on the design of ground water pumps, I discuss (in Appendix 7.1) each of these eight elements in turn and then summarize their main influences on ground water pumps. They may be represented by a more general diagram such as Figure 7.4, in which the first element includes possible wide range external influences on the design of the proposed product. The second element is the near-environment (water well) of the proposed product. The remaining elements are the relevant sub-module categories of the proposed product. The sub-modules given above are well known to mechanical engineers.

![Figure 7.4: The general categories for trend examination during product design](image)

Figure 7.4: The general categories for trend examination during product design
7.10 FUNCTIONAL REQUIREMENTS FOR REMOTELY LOCATED LOW VOLUME FLOW RATE GROUND WATER PUMPS

The idea that design starts with a clear cut set of objectives is erroneous. In fact my experience is that the clarification of the "problem" is often still happening well into the design process and most likely will continue even after the product is in preliminary production, particularly in an innovative design.

The following design specification sheet (Table 7.1) has been produced as a result of many years of involvement with the Australian stock watering industry and many discussions with farmers and ground water consultants, as well as a result of following the TREND-MORPH-PDS methodology and studying the specific technology history and the laws of technological evolution.

In pursuing the goals of this design project it would not be practical to simply construct a list of FRs (and constraints) early in the process, then expect that satisficing sub-solutions and solutions would be found.

However a guiding check list such as Table 6.1 has proved to be useful when following the method of TREND-MORPH-PDS.

The PDS of Table 7.1 really details and adds to the draft promotional that appears on my web site under Power point, UniPump1:

<table>
<thead>
<tr>
<th></th>
<th>Table 7.1: Product Design Specification sheet (PDS) for the pumping system</th>
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</thead>
<tbody>
<tr>
<td>1</td>
<td>Pump ground water to the surface and above/beyond for stock, domestic use, small-scale irrigation and other &quot;low volume&quot; uses.</td>
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<tr>
<td>2</td>
<td>Down-hole equipment size: Equipment to fit with clearance in a 100 mm ID tube well which may be exposed rock or cased.</td>
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<tr>
<td>3</td>
<td>Flow rate: 0.05 to 2.0 l/s</td>
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<tr>
<td>4</td>
<td>Pumping water level below ground: normally 5 to 40 m, possibly up to 80 m.</td>
</tr>
<tr>
<td>5</td>
<td>Pumping head above ground: 0 to 50 m</td>
</tr>
<tr>
<td>6</td>
<td>Total head: Maximum head is to be 100 m?</td>
</tr>
<tr>
<td>7</td>
<td>Wide operating range* of highly satisfactory operation: <em>(Head and flow - see items 3 to 6)</em></td>
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<tr>
<td>8</td>
<td>Adaptable: May be configured as hand, wind, solar, P.C. engine or grid electric pump. Common sub-systems for surface and dam pump.</td>
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<tr>
<td>9</td>
<td>No more than two sizes of any of the major sub-systems. Most competitors have sub-systems each requiring a range of at least five elements in order to span the operating ranges - see items 3 to 7.</td>
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<tr>
<td>10</td>
<td>Overall system efficiency: To exceed the equivalent of 50% electricity to water efficiency under normal operating conditions and over, say 80% of the head and flow conditions.</td>
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<tr>
<td>11</td>
<td>Minimal harmful effects: Total life cycle design including the following:</td>
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<tr>
<td>12</td>
<td>Capital Cost: The pricing structure must including reteller's make-ups must be competitive with windmills, solar centrifugal, progressive cavity, sucker rod and submerged piston pumps.</td>
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<tr>
<td>13</td>
<td>Manufacture: Use materials and processes appropriate for developing countries. Follow guide lines as outlined in Ackeroff et al.</td>
</tr>
<tr>
<td>14</td>
<td>Assembly: Use materials and processes appropriate for developing countries. Follow guide lines as outlined in Ackeroff et al.</td>
</tr>
<tr>
<td>15</td>
<td>Distribution: Design for transport by truck, trailer, rail and for storage on the reteller's shop floor.</td>
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<tr>
<td>16</td>
<td>Reliability: Mean time between failures (unattended) to be of the order of two years. Regular inspection and adjustment will be necessary and acceptable. Overhaul every 5 years will be acceptable.</td>
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<tr>
<td>17</td>
<td>Maintainability: Eliminate need for over-well lifting equipment. Design so that one person (female) can extract (and install) down-hole equipment. All sub-systems serviceable by the typical Australian farmer in his workshop.</td>
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<tr>
<td>18</td>
<td>Supportability: Simple maintenance procedures with easy to follow documentation supplied. Replaceable items to be readily accessible by post (for immediate dispatch) to the purchaser.</td>
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<tr>
<td>19</td>
<td>Environment: Minimal environmental impact. Atmospheric, ground-water, noise, Recycle sub-systems and components.</td>
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</table>
A detailed explanation of each of the items of the table follows:

**Item 1:  Pump ground water to the surface and above/beyond for stock, domestic use, small-scale irrigation and other "low volume" uses.**

This is an overall definition of the application markets for which the system is to be used. While the product development has been taking place, my knowledge of potential markets and specific applications problems has been continually updated. For example, my initial vision was limited to the local (Australian) market, of pumps for stock watering bore-holes. When an early batch of pumps was produced and promoted for this market, a number of inquiries were received from developing countries, where the technical requirements varied (India, Sri Lanka, African continent, Philippines, and various islands). My awareness of the market, the stakeholders and many technical issues was greatly increased by reading about the UNDP hand-pump project, thinking about my Socio-economic evolution category, direct discussion with pump experts, farmers, developing country water supply engineers and pump manufacturers such as G. H. Moore. These influences helped me to define the “Low Yield Pump” concept.

**Item 2: Down-hole equipment size:**

The size of the bore-hole (cased or un-cased) has reduced over the years. As one might expect, cost of a bore-hole increases with size. In the Newcomen – Watt era, open wells were common. These provided plenty of room to manipulate and secure equipment down the well and for people to descend and work on the equipment. Equipment was bulky and there was no perceived need to reduce the cross-section.

Drilled bore-holes became popular once it was recognized that slender equipment could be designed and that the water could be accessed at reduced cost by drilling.

Earlier drilled holes [in low yield situations] were typically larger than modern ones. The trend towards drilling smaller bore-holes has been cost-driven, and enabled by the availability of more slender pumps. The competitors’ submerged motor pumps are all larger in diameter and require clearance for cooling water flow.

**Item 3: Flow rate:**

The flow rate of the pump is to be within the range 0 (realistically 0.05) to 2 litres per second. A number of factors have contributed to this decision.
Firstly, the wind pump, which has serviced the Australian, American and other stock watering markets for 120 or more years, conforms to this specification for bore pumping.

Secondly, the inflow to most inland rural bore-holes is limited to within this range by the surrounding hydro-geology.

Thirdly, this specification agrees with the practical upper limit of drinking water required by the maximum stock that can be held on the land surrounding a particular water source without the risk of over grazing.

Fourthly, many developing country water wells supplying (nominally) 2 Ha lots for crop irrigation are mostly limited hydro-geologically to this range.

The limitations of submerged multistage centrifugal pumps within this range are discussed in section 7.2.

**Item 4: Pumping water level below ground:**

Pumping level below ground to be normally in the range 5 to 40 metres, but possibly up to 80 metres.

This specification reflects typical pumping depths for stock watering wells and small lot irrigation wells in developing countries, as well as village hand pumped wells. A small percentage (of the order of 5 percent) of the wells of these markets have deeper pumping levels, up to about 80 metres.

One matter that has come to my attention is that the pumped water level in some wells can vary, sometimes very significantly. This variation is usually seasonal and can cause problems to centrifugal and progressive cavity pumps if the water level falls below the pump position and the pump is run in a dry condition.

Piston pumps can be designed and manufactured to operate efficiently over a large pumping head range, whereas all the competitors (submersible centrifugal pumps, progressive cavity pumps and submersible jack pumps) have inferior peak efficiency as well as limited range of peak efficiency.
**Item 5: Pumping head above ground:**

Pumping head above ground to be 0 to 50 metres:

Like the depth specification above, this specification reflects the typical range of applications in the field. Some special designs (rag pumps, chain of pots pumps and many hand pumps) deliver only to the well-head and are not designed to provide well-head pressure. Many surface, mechanically driven pumps require a sliding seal at the well-head. In some cases (municipal turbine bore pumps this requires constant maintenance). The UniPump is capable of meeting this specification.

**Item 6: Total head:**

Maximum total head for which the pumps are to be designed to be 100 metres?

This decision will influence two important details. The first is the pressure rating of all pressurized fluid elements such as the pump body, valves and riser pipe. The second is the power rating of the pumping systems.

The total head will be the sum of the head due to water depth in the well and the above ground head. Only a very small percentage (from market knowledge) of applications will have both large depth and large above ground head.

**Item 7: Wide operating range* of highly satisfactory operation. (*head and flow - see items 3 to 6)**

The energy source is to be flexible. The pumping system is to be designed to operate from solar energy, wind energy, electrical grid electricity, IC engine, human energy or even perhaps animal power. The requirement to operate as a hand pump (later upgradeable to the other forms) and the requirement to operate as a wind pump strongly supports the piston pump concept. The IC engine requirement also supports this concept. Some farmers provide electrical power for submersible pumps from surface located IC generator sets, however this arrangement is known to be troublesome and very expensive to buy and operate. I cannot find any competitor that meets this requirement of my PDS. All this is to be achieved with high operating efficiency so as to reduce high capital and/or running costs.
Item 8: Adaptable:

The adaptability should extend to the Australian, or American style, broad acre farm that has many pumps, including surface pumps, pumping from dams and lakes. It will be beneficial to the farmer to have a common, modular system that can be reconfigured to operate at any pumping site, no matter that it might be shallow, deep, of varying flow requirement or surface* pump. This is a critical aspect of UniPump design.

*The UniPump cable drive will be readily adaptable as a lake, river or dam pump. The reciprocator will be mounted (approximately horizontally) on the dam wall and the cable and polythene delivery pipe extended to a semi-floating, check valved intake, submerged just below the surface of the water.

Item 9: No more than two sizes of any of the major sub-systems.

Field experience with earlier Supertube installations has indicated that a new long stroke well head reciprocator (LSWH) of only one size can be detail designed to accommodate all field situations. This of course would be oversized for the smallest applications. However the small cost penalty would not be worth designing a light duty model considering the small quantities involved. This LSWHR will be bare shafted (with a 300 mm diameter driven pulley) and supplied with an inexpensive range of motor drive multi-vee pulleys for the client to choose from in order to match the system to the application. It may at some time be worthwhile considering the design of a very large LSWHR for very deep water wells (150 m deep) and shallow oil wells (300 m deep).

There will be one size of drive cable and one size (dia. 50 mm) of down-hole pump. For very shallow (near) surface, low head pumps, clients will be able to rod drive a large diameter low cost, highly efficient PVC pump offering high volume flow rate.

The simplicity of this system will be a very powerful advantage over the complex assortment of sizes and component combinations that all current competitors offer to cover only part of the range of field conditions at a lower operating efficiency than the UniPump offers.
Item 10: Overall system efficiency:

Overall system efficiency is to be high over a wide range of operating conditions in comparison to competitive pumps. Below, I have chosen to use the PMDC electric motor driven pump as a standard for comparison with competitors’ products. This PDS requirement should be stated as an instantaneous efficiency rather than just efficiency. It will need to be expanded to accommodate the incoming power fluctuations of both solar and wind pumps and also for the diurnal sinusoidal variations that occur with solar pumps. A more stringent criterion will be *daily average electricity to water efficiency*.

However an approximate comparison may be obtained from the following:

**Surface bare shaft Efficiency of UniPump System**

- Long stroke well head reciprocator (LSWRH) unit: 85% to 92%
- Anti-wear compact double acting drive cable (DAC): 90% to 96%
- Double acting down-hole UniPump (D-HUniPump): 80% to 90%

Multiply the above

- UniPump transmission efficiency: 61.2% to 79.8%

Now consider driving with a 90% efficient PMDC motor.

- Overall electricity to water efficiency: 55.1% to 71.8%

In round figures, the bare shaft efficiency of the UniPump system will range between 60% and 80%, whilst the “wire to water efficiency” will be in the range 55% to 70% when using a high efficiency PMDC electric motor. These figures have all been confirmed in the field from testing of the earlier Supertube installations.

The bare shaft efficiencies of competitive multi-stage centrifugal pumps are in the range of 8% to 20% (influenced by matching) and the daily average efficiencies are severely reduced by variations in power input.

The bare shaft efficiencies of the submersible progressive cavity pumps (which are reduced by rotor and stator wear) are in the range 20% to 70% (influenced by matching).

The influence of matching on the UniPump is minor compared to the severe influence that occurs with all known competitors’ systems.
In the past I have challenged competitors to dispute my figures and have even received their engineer’s signed agreement of confirming the validity of my estimates during contractual negotiations. I note my figures below.

In summary my estimate of the order magnitude of daily average wire to water efficiencies is:

- UniPump: 60%
- Multistage centrifugal submersible bore-hole pump: 12%
- Submersible progressive cavity bore-hole pump: 40%

The remaining items below will and have been considered be treated in a similar manner along with any further items. I briefly summarize them.

**Item 11: Minimal harmful effects:**

Harmful effects could be to the environment, to the owner and/or operator of the pump or to some other party. I’m treating this item as meaning harmful effects to the environment.

Thus some harmful effects are: over-pumping of the groundwater; unnecessarily high energy cost and unnecessarily high maintenance cost. However, the energy issue is covered under item 10. My belief is that the concept of low yield pumping fulfils the over-pumping requirement. Drillers always tend to drill to as great a depth as possible, often penetrating a deeper water table than necessary. They are often paid by the metre. However they are also aware that clients always seem to want as much water from a bore as they can get. The low yield philosophy may eventually cool this situation down. Again, excessive fuel and maintenance relates to unnecessary burning of oil with consequent environmental issues apart from its damage to the owner’s pocket.

**Item 12: Capital Cost.**

Based on experience with Supertube, the savings in purchasing expensive photovoltaic modules are very significant, due to the high operating efficiency. In analysing capital cost, the overall system cost should be used. Many evaluations of the proposed UniPump systems have been done. They indicate that the capital cost of UniPump is
considerably lower in its solar configuration and is competitive in all other configurations where its value is in reduced running costs.

**Item 13: Manufacture**

Manufacturing this product in Australia, for the Australian market has the problems associated with producing at a low volume rate with a market that fluctuates widely from year to year depending on the fortunes of the farmers and the weather conditions. Under these circumstances the entire design needs to have a low to medium technology flavour with no potential bottlenecks such as restricted suppliers.

As illustrated in Figures A7.2.3, A7.2.4 and A7.2.8, the availability of materials, components and sub-assemblies and the manufacturing processes required for this pump need not be exotic and will meet the requirements mentioned above.

**Item 14: Assembly**

The assembly issues in this product are very significant and are related to installation where it is planned that the farmer will, with high quality instructions provided with the product, be able to configure and assemble the sub-systems with ease that has not been previously experienced in this industry. The double acting cable drive is one example of this achievement.

**Item 15: Distribution**

Careful thought has been put into designing all modules in such a way that they can be readily handled by one person and so that they stack well for transport and storage. In addition, the high versatility that can be achieved by a very few sub-modules is again something that has not previously been seen in this industry. This is discussed under Item 8.

**Item 16: Reliability**

This has not been ignored but is more related to detail design and quality management in manufacture. Simplicity has been very much part of the philosophy of design. The design is to be such that simple owner service is possible at a frequency of 2 years, with overhaul every 5 years.
Item 17: Maintainability.

This has been a prime issue in the design process. It is illustrated on my website under Power point UniPump 1 at:  http://www.eng.uts.edu.au/~johnd

A copy of the relevant section of the website is included below in Figure 7.5 where simplicity of design, robust construction, on site maintainability, and other mentioned features all contribute to this important requirement.

Item 18: Supportability

As mentioned in Item 17, above this has been a prime issue in the design process. It is illustrated on my website under Power point UniPump 1.

Item 19: Environment

See Item 11

7.11 SUMMARY AND CONCLUSIONS

This project has considered that the piston pump, despite its appearance of being old fashioned when compared with electronically managed, multi-stage and other electric submersible pumps, still has many virtues: efficiency, adaptability and versatility, reliability, simplicity, low system cost in the solar configuration, and many others.

The weaknesses of the piston pump, as part of a pumping system have been accepted as related to flow discontinuities as check valves shut at the ends of each stroke and to the apparent complexity of the total system compared to the apparent simplicity of directly coupled rotary pumps.

However I have shown that the weaknesses can be overcome and that the apparent simplicity of the rotary systems is not at all simple when one considers establishing a versatile pumping system to accept the full range of power sources and operate efficiently over a wide range of well depths, flows and different well sites. Under these varying conditions the piston pump can be made to adapt readily without having to manufacture and stock the wide range of pumps and combinations necessary with its rotary competitors.
The virtues of the piston pump are outlined in the reference of Item 17. To realize all these advantages is not trying to do the impossible; it is just a matter of perseverance at good design and engineering practice.

The main advantages of the UNI-PUMP are:

- High efficiency, giving competitive advantage in both capital outlay and running cost. Most of the competitors' pumps are designed for optimal performance at higher yields.
- Simple and well-engineered down-hole equipment manufactured from modern polymers and stainless steel to minimise corrosion and wear.
- No down hole electrical or electronic items to fail in the wet and corrosive down hole environment.
- Robust construction of all parts of the pump thus minimising risk of breakdown.
- If a component in the pump does fail, then standard spare parts (replaceable by mail) are supplied on a shadow board. These parts are ready for on the spot maintenance by the user. It is not necessary to remove this pump from the well and send it back to the supplier for maintenance, as is the requirement for competitors submersible pumps.
- The design of the pump gives great flexibility in the field. One basic pump can be readily adjusted in the field to match a wide range of head and flow situations that may be met. This also allows the user to readily move the pump from one well to another if required. Competitors cannot do this and either do not have the range or require a number of models of their pumps to service the range.
- The pump is simple to install and does not require elaborate equipment or even a tripod and chain block over the well.
- There is virtually no risk of pump seizure due to components 'sticking' together after long periods of non-use.
- The pump has minimal starting torque and will start directly on its running amperage.

Most of the current competitors have shortcomings in nearly all the above points. This is considered to be because these companies have not started from scratch and designed their pumps specifically for this niche market involving low yield bore-holes.

Optional solar (photo-voltaic) sun tracking modular array.

Electric motor powered by the photo-voltaic cells or from mains electricity. Another very important option is our inexpensive propane gas engine, which may be run 24 hours per day at very low cost. The gas required for stock watering typically costs only one or two hundred dollars per year.

Long stroke patented reciprocating well-head unit. This is the heart of the Uni-Pump contributing to its exceptionally high efficiency. High efficiency offers huge savings on capital and running costs.

Polymer down hole column. Eliminates corrosion, easy to install or recover from the well during maintenance. This innovative column has low friction and is long lasting. Moving rods and riser tube are fully protected from wear by fluid borne abrasives.

Retained, long stroke, dual piston, stainless steel reciprocating down hole pump. Contributes to the high efficiency, reliability and flexibility of the Uni-Pump.

Heliseal Pty Ltd trading as Dartnall Engineering and Innovation
Email: John.Dartnall@uts.edu.au
CHAPTER 8

SUMMARY AND CONCLUSIONS

8.1 INTRODUCTION

This chapter sums up my work in the area of ground water pumping and mechanical technology, my contributions to these areas, and my innovative design methodology. It summarizes the main focus of this thesis, which is on innovative design methodology. In this final chapter I summarise the work performed on TREND-MORPH-PDS, its relevance, benefits, limitations and further possible research to be done in the engineering design area.

8.2 SUMMARY OF THE CONTRIBUTIONS OF THIS THESIS IN THE AREA OF LOW YIELD GROUND WATER PUMPING AND MECHANICAL TECHNOLOGY

Ground water pumping dates back to the very early civilizations. Many different techniques have been discovered that have enabled humans to bring water to the surface from the huge ancient wells such as Joseph’s Well in Cairo, Egypt that were carved in stone to depths in the vicinity of 100 m, to the millions of hand pumped wells that are so needed to combat disease related to polluted water with consequent infant mortality of villagers of the developing countries.

My interest in this technology started with an enthusiasm to apply solar energy to drive the relatively shallow and low powered pumps that have been part of the Australian and American farming scene, traditionally serviced by wind-pumps, since the mid 1800’s. My interest commenced in 1974, when the idea of employing a thermodynamic cycle to transform incoming solar energy to useful mechanical energy was beginning to become popular.

Eventually, after several prototypes I started a company which developed, produced and supplied more than 100 long-stroke piston photovoltaic-powered bore-hole pumps to Australian farmers and some to India and South Africa.
My contribution to this technology at this stage was to recognize and promote the idea that this market area needs special treatment, no matter what power source is used or what type of pump is used. I promoted and continue to promote recognition of the definition of *Low Yield* and its application to the wells of this category, for which high operating efficiency is difficult to achieve and in which there are special pump problems because of corrosive and abrasive contaminants in the water, the remoteness of the installations the variations of intensity of the incoming energy and water level variations in the wells.

My next contribution to this technology was to recognize that the simple piston pump had the potential to address the problems of the low yield market, provided it was developed appropriately for application to this market. The piston pump had previously only been applied in relatively short stroke, crank driven forms, with primitive check valves and seals and with very little in the way of fluid inertia management. My belief was and still is that this system can be improved to handsomely exceed the performance and the quality of all its rotary competitors for application in this market. (Here I use the term "quality" in the modern sense of fulfilling all functions required by the customer, reliability, reasonable price, timely supply of product and service etc.)

Following these early contributions to this technology, in the process of applying the design methodology of TREND-MORPH-PDS to the case study in this thesis I have continued to show how the piston pump can be improved to meet the requirements of this market. Some of the main outcomes I can claim from this process are:

- Further development of the long stroke reciprocator, with improved reliability as well as design for maintenance, involving patentable improvements that go beyond the claims of the original patent.

- Invention of a double acting extractable down-hole pump, capable of twice the volume flow rate for a given diameter of a conventional single acting piston pump. The pump will attach to the cable drive, which can be used to lower or raise it in the riser pipe for installation and servicing. This system negates all the practical installation advantages which are currently claimed by manufacturers of submersible pumps. This system also overcomes the balancing problem of piston pumps. It enables the manufacture of a single size of pump that is suitable
for a wide range of operating heads and flow rates, eliminating the need to manufacture and stock the many sizes of pumps required by the electric submersible competitors.

- **Invention of low-friction seals to address the starting and operating friction problems of down-hole pumps and accommodate wear so as to provide high operating efficiency with long service life.**

- **Invention of a double acting “cable drive” concept, to replace the current rod drive systems widely used in wind-pumps. This mechanical drive will be conveniently transported in coil form, will act as a light weight, easily handled, uncomplicated, one piece transmission from the LSWHR to the double acting down-hole pump. It will overcome the disadvantage of having to carefully screw connect each rod length and each pipe length during lowering of a rod driven pump, making installation and removal for maintenance very much more convenient.**

- **Recognition of the advantage to bore-hole pump users and possibility of developing a universal pumping system that efficiently accepts all power forms: solar, wind, grid electric, IC engine and human, and that this is best done by persevering with the development of the piston pump.**

- **Recognition of the severity of the matching problem for down-hole pumps and devising very simple and inexpensive methods to overcome it using “throw-away” multi-vee pulleys. ("Matching" involves optimizing the speed and torque relationships between the power supply, prime mover and the pumping units. It can be both complex and costly.)**

### 8.3 SUMMARY OF MY CONTRIBUTIONS TO THE AREA OF DESIGN METHODOLOGY.

During the design process discussed in my case study, I have reviewed a comprehensive collection of research papers and books outlining different techniques, methods, methodologies, diagrammatic models, paradigms, commercial software packages. The purpose of all these works was to improve the engineering design process. From all of
them I believe that I have gained useful knowledge. My view is that a designer will gain by reading widely in this area but should not become a slave to any particular method. I could compare the designer to a talented workshop enthusiast, standing in his or her workshop, surrounded by neatly painted shadow boards laden with tools, looking proudly at the many excellent machine tools and the neat benches and cabinets and wondering “which tool do I use for job on hand?”. On the other hand, if that same enthusiast had a simpler workshop, but with the key tools to hand, it would not be necessary to spend time choosing the tools, and the enthusiast could just get on with the job. Having a wide range of software packages, techniques and methods can be valuable, but the techniques can also tend to become an end in themselves, rather than the means to an end. It is valuable to know, in a general way, what is available. However, when it comes to inventing and developing a new and complex machine/system you have to start somewhere, taking design action to develop a feel for the problems that need solving. The designer does not need to be distracted by having to learn or follow unnecessarily demanding procedures.

Innovative design requires goals and sub-goals, and dedication. My view is that the innovative designer’s focus needs to be on challenging the current way of doing something, often driven by a hunch that there is a better way. I see technology in terms of an ever-expanding assortment of tree-like diagrams, representing families of artifacts or machines. Some branches go on growing, as engineers/inventors refine and improve the basic invention(s) that defines the particular branch. Some branches stop growing, for good reason, because another technology has demonstrated a significant improvement. Some temporarily curtailed branches recommence growing later, as new ideas or technologies improve their prospects.

Engineers and inventors tend to be strongly interested in the technologies, sometimes at the expense of client and stakeholder needs for the technology.

8.3.1 Problem Break-down and TREND Analysis

In my proposal of TREND-MORPH-PDS as a systematic approach for design, I have considered both the technology aspects and the client and stakeholder needs related to a new product. The TREND part of the process covers both the technology and the people ends of the scale, the MORPH part of the process is more technically oriented and the
PDS part of the process is intended to have normalizing effect, making sure that no technological, client, sociological or commercial area is overlooked.

Put simply, the process of design is hunting for and matching what can be done (what is possible), with what is wanted or needed. Often, if you don’t know what can be done you can’t define the future need.

One way to attempt to forecast the future is to look at historical and current trends. My idea of trend analysis is to look at as many trends as possible that relate to the area of the problem on hand. At the same time, there is a well understood need to break problems down into sub-problems, which are usually easier to handle. So the TREND part of my process is to look at the trends of the sub-problems or sub-systems. In mechanical systems the break-down format will usually be:

(1) Distant-external influences; (2) Influences of the near, external environment of the product; (3) Power source; (4) Prime mover; (5) Matching; (6) Transmission; (7) Working organ; (8) Control system.

Examining general trends can help the designer to take a broad view of the problem and not become introspective or biased toward a particular stakeholder’s view, or constrained by any of the many limiting driving forces, such as the company’s investment in their existing technology. The designer should keep an open mind, looking for opportunities.

Having examined the trends, or whilst examining the trends, ideas on how to improve the situation will occur. The TRIZ general laws of trends can assist the designer in reasoning why particular trends have occurred. Ideas can emerge that explain why a competitor has failed to see an opportunity, or why the competitor is following a risky trend, leaving you an opportunity to introduce a superior/more appropriate product to the market. The design knowledge that is now available offers a wealth of other techniques and methodologies that can be drawn on.

8.3.2 MORPH(ological) Analysis

Having defined sub-areas for the problem and commenced a historical trend analysis, the designer is now in a position to look at all possibilities within particular areas. In my
design, one such area was down-hole reciprocating piston pumps. I was aware that many configurations had been tried over the years, but I could not find any systematic publication which showed all their forms and evaluated their performance and that of their components (such as valves, seals, cylinders, pistons, etc).

I decided to try to perform a rigorous morphological analysis, on the assumption that any reasonable pump of this type must have the following five elements: a cylinder, a piston (in the form of a solid piston, a ram or a tube piston), an inlet valve, a delivery valve and a sliding seal (internal or external). Each of these items is either connected to another element, fixed so as to remain stationery, or driven by the drive rod (or tube). I commenced to generate a comprehensive tables (Tables A7.2.1 (a) and A7.2.1 (b)). At the same time, I researched very old literature in this area. Old literature was all that was available! Other engineers had ceased writing about piston pumps, but I persevered! I began to appreciate that the designer must keep an open mind. I had not allowed for pumps with two pistons, ganged together, driven independently or linked mechanically, so as to operate 180 degrees (or approximately 180 degrees) out of phase with each other. I had to enlarge my table.

I also discovered the need to make quick computer sketches of the various configurations. I set up my own graphical code (Figure A7.2.1) and constructed the various configurations by copying and pasting common code elements. A number of patentable configurations and ideas emerged. I was surprised that in 150 years of patents, some of these configurations and ideas had not been discovered, or at least had not been published. I developed a number of rules by which to evaluate the various configurations. As I became familiar with what was possible, my evaluation expertise, along with concurrent work on the TREND analysis and the PDS construction, directed me to what emerged as my favoured conceptual design, which appears in Figure A7.2.3.

I propose MORPH as a very powerful and much under-rated tool. In my opinion, a well conducted MORPH analysis, conducted with an open mind, that is looking for opportunities, in conjunction with the TREND analysis and the evolving PDS, can rapidly simulate the real-time evolution of the inventions associated with a particular class of machines.
8.3.3 Evolutionary Construction of the PDS

The PDS must start in the most general way, like the PDS of Table 6.1. An even more comprehensive, general PDS could be constructed with categories, sub-categories and check lists in the style that is recommended by systems engineering authors. This will help to steer the designer towards an even-handed, unbiased approach to the problem. By an "even-handed design process ", I mean that the designer must consider everyone who has some connection with the product, and every process that it will pass through, throughout its life. The general PDS is effectively a check list that helps the designer to avoid oversights. The oversight of one category may render the product uncompetitive.

The construction of the specific PDS calls on all three components of TREND-MORPH-PDS, including the guiding effect of PDS itself as it becomes an important document for keeping the design team on track, for recording critical decisions and for communicating.

8.4 THE DESIGN

In many ways a good design seems to be simply a fast-tracking on paper or in the laboratory of all the lessons that might have been learned and indeed have been learned in the field when a product is developed and put into the field without the careful effort that the design community recommends. The patent system indicates that designs are often quite slow incremental improvements that give an evolutionary appearance.

So the objective is to accelerate the process of learning all the lessons and quickly gain knowledge of how and why we have arrived at a good design. TREND-MORPH-PDS is an easily mastered heuristic for doing this.

TREND-MORPH-PDS should be used in an open-minded way, looking constantly for opportunities and breakthroughs. The designer may be very thorough with some parts (hopefully critical parts) of the project and pay less attention to detail where it doesn’t matter. The designer should read of the many design methods, methodologies and tools, choosing and using wisely. TREND-MORPH-PDS is an uncomplicated procedure leaving the designer free to search and think about the future product.
The objective is the design on hand. It must be good in every respect, because it has competitors to deal with. People talk about product champions. I’m not sure if this concept isn’t a fundamental truth. Companies or individuals need perseverance to realize a completely novel product or invention and the designer is at the centre of this process.

8.5 WHAT ELSE?

A large amount of effort is being expended on AI, FEA, CAD-CAM and improving designers’ computer tools. This is good for the TREND-MORPH-PDS designer because he/she, not being slave to a complex system, will welcome useful tools to choose from in order to facilitate the design process.

The development of a user friendly rapid sketcher that allows efficient setting up of codes for construction of the morphology of the object under investigation would be an excellent project.

Another good project would be to add a formal documenting package to either the TREND procedure or the PDS for documenting the history of the design process centring around the design decisions as Ullman recommends.

Another possible worthwhile project is the systematic cataloguing of machines like down-hole piston pumps in a way similar to Wankel’s efforts with rotary machines. If this is not done, people will keep re-inventing the wheel. In this respect the web will be a tremendous asset to future designers.

Yet another project will be to place TREND-MORPH-PDS into a software package that contains check-lists like a comprehensive master PDS.

8.6 FINAL COMMENT

I wish to emphasize that, much to my excitement, TRENT-MORPH-PDS actually worked and this was clearly so for the case study in the discovery of down-hole pumps of figure A7.2.3 and A7.2.4, page 173 as well as the column discussed in section A7.2.4, page 177.
APPENDIX A7.1

CASE STUDY BREAK-DOWN OF PROBLEM AND EVOLUTIONARY TREND ANALYSIS OF SUB-PROBLEMS/SYSTEMS

A7.1.1 INTRODUCTION

This appendix relates to the discussion of section 7.4. The diagrams are repeated for convenience. I have explained how the first stage of my innovative mechanical design process, TREND-MORPH-PDS, involves break-down of the problem into elements such as those in the left side column of figure 7.2 parts (a) and (b), followed by systematic research of the historical trends of each element. In this section my work is summarised along with design ideas resulting from each element.

<table>
<thead>
<tr>
<th>ELEMENT</th>
<th>TIME</th>
<th>BC</th>
<th>AD</th>
<th>1700’s AD</th>
<th>1800’s AD</th>
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</thead>
<tbody>
<tr>
<td>SOCIO-ECONOMIC, DEMOGRAPHIC, APPLICATIONS</td>
<td>DEWATERING M ARSHES, TOWN WATER SUPPLY, PEOPLES’ HANDPUMPS</td>
<td>INDUSTRIAL REVOLUTION, POWERED MINE DEWATERING</td>
<td>WIDE SPREAD GOVERNMENT CENTRALIZED MANAGEMENT OF WATER SUPPLY, POPULATION SPREAD</td>
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<td>WELL CONSTRUCTION</td>
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<td>OPEN WELL</td>
<td>OPEN WELL</td>
<td>OPEN WELL / TUBE WELL</td>
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<td>WIND, WATER STREAM</td>
<td>COAL, WOOD</td>
<td>LIQUID AND GASEOUS COMBUSTIBLE FUELS, SOLAR THERMAL</td>
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<td>PRIME MOVER</td>
<td>MANUAL, ANIMAL, WIND</td>
<td>WIND PUMP, WATER WHEEL PUMP</td>
<td>STEAM ENGINE</td>
<td>INTERNAL COMBUSTION ENGINE, ELECTRIC MOTOR, AMERICAN MULTIBLADE WINDPUMP</td>
<td></td>
</tr>
<tr>
<td>GEARING, BALANCING (MATCHING)</td>
<td>LEVER, COUNTERWEIGHT, WHEEL, PULLEY SYSTEMS, SCREW</td>
<td>CRANK HANDLE, PEDDLED GEAR PARS, WINDLASS, DIFFERENTIAL WHEELS, FLYWHEEL, DOUBLE ACTING, MULTIPLE PISTONS</td>
<td>DIFFERENTIAL PISTONS, AIR CHAMBER, STEAM COMPENSATOR</td>
<td>TWO PISTON AND QUICK RETURN</td>
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</tr>
<tr>
<td>TRANSMISSION OF THE POWER DOWN THE WELL</td>
<td>ROPE, CHAINS, SHAFTS, RODS</td>
<td>STEAM DOWN THE WELL, RECIPROCATING ROD</td>
<td>HYDRAULIC, ROTATING WELL SHAFT</td>
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<td>PUMP</td>
<td>SCOOP, BUCKET, CHAIN BUCKETS, ARCHIMEDEAN SCREW, CTESIBIUS RAM</td>
<td>PISTON AND CYLINDER</td>
<td>VARIOUS RAM, AS WELL AS PISTON AND CYLINDER CONFIGURATIONS</td>
<td>CENTRIFUGAL PUMP, VENTURI PUMP, AIR LIFT PUMP</td>
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<td>HUMAN</td>
<td>WINDMILL STEERING AND GOVERNING, SELF ACTING VALVES</td>
<td>STEAM ENGINE GOVERNING, PRESSURE PULSATION CONTROL</td>
<td>STARTING CONTROL, WATER-WELL LEVEL CONTROL AND MANAGEMENT</td>
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<td>MAIN EVENTS</td>
<td>WATER WHEEL</td>
<td>STEAM ENGINE INVENTIONS OF SAVERY, NEWCOMEN AND WATT</td>
<td>TUBE WELL PUMPS, I. C. ENGINE DRIVEN PUMPS, AMERICAN MULTIBLADE WIND PUMP</td>
<td>CENTRIFUGAL PUMP</td>
<td></td>
</tr>
</tbody>
</table>

Figure 7.2 part (a): Chronological classification of major events of each category relevant to the ground-water pump from ancient times to the nineteenth century-Dartnall, 2002.
Starting around 3,000 to 4,000 BC, permanent settlements began to be established near rivers or perennial springs. Early humans were concentrated around the Nile valley in Upper Egypt, where wild barley grew, in Mesopotamia by the Tigris and Euphrates, by the river Indus on the Indian sub-continent, and on the Yellow river in China. The rivers provided natural irrigation by periodical inundation. People constructed canals, particularly in ancient Mesopotamia, to spread the influence of these rivers. They learnt to dig wells and devise ways of raising water from the rivers and the wells.
As population increased, and cities such as Ur, Babylon, Assur, Mohenjo-Daro and others arose and as people took advantage of the rich soil of the river deltas, the need to de-water areas such as marshes was determined. The Archimedian water screw or tambour appears to have been used to de-water ancient Egyptian mines, sometimes with several screws in series.

My first AD period extends to the 1700s, and covers the main portion of the Roman Empire which lasted until the fifth century AD, followed by the middle ages. An excellent account of the Roman influence on technology is given in Kranzberg (B3-1967). The Romans were interested in hygiene and public health. Their large cities required water supplies and sewage systems, the earliest systems in Rome dating back to 600 BC. The first aqueduct to carry water from a small mountain river to Rome was built in 312 BC. People did not bathe in the river Tiber, as the sewers were discharged into it. In the year 226 AD there were eleven aqueducts supplying the city. The Romans managed the water supply and sewage of the towns that they occupied or built. Romans and Greeks provided public baths in their sports grounds. During the Roman Empire every town had its own public bath.

During the Roman Empire, large cities had luxurious, centrally heated baths. The piston pump, possibly invented by Ctesibius during the second century BC, was used in the plumbing of these systems.

During the middle ages, public baths vanished along with the emphasis on personal cleanliness that characterized the Greeks and Romans. Guillerme (B2-1984) points out that the old European cities such as Paris, Amiens and many others were surrounded by water in a far from hygienic way. These cities were on the banks of rivers or streams, were surrounded by moats and manifold with numerous canals. Originally this hydrographic system, which involved a gradient from the upper class end of the city, was worked out during the decline of the Roman Empire, with moats as a defensive measure against the West Europeans. As time went on (around the tenth century) this system facilitated the draining of swamps and the driving of water-wheels. During the twelfth to eighteenth centuries, the slow techniques of maceration (involving putrefaction) were used by artisans in textile production and parchment making. There were no sewage systems and the lower end of the cities, particularly, surrounded by
bodies of stagnant water containing various wastes, was extremely unpleasant and a source of the lethal diseases of the day. Even the upstream ground-water was liable to become contaminated.

The 1700s and 1800s were the era of the industrial revolution in Western Europe. Many developments took place at the same time: Arkwright and others developed spinning machines and mills, Crompton his mule. Coal mining and iron founding flourished. Mine dewatering and town water supply from Newcomen and Watt steam driven pumps were very significant developments of this era. It is interesting that the water wheel was still widely used throughout the period of the introduction of the steam engine. The demand for power was increasing and this demand was associated more with the water wheel which had been in existence for centuries. In fact, about mid nineteenth century Boulton and Watt steam engines were quite often used to return tail-water from water wheels, powering factories where water supply was limited. This extremely inefficient and expensive way of converting fuel energy to shaft power was nevertheless quite commonly adopted. Users of equipment took a long while to come to grips with the concept of energy efficiency. Smiles (B3-1878) describes the difficulties that Watt had in demonstrating the benefits of his more efficient pumping systems over the older Newcomen systems. My experience, nowadays, is that trying to explain the benefits of high efficiency to potential pump clients (farmers) is often too ‘technical’. It is better to talk about reduced running cost. The word efficiency may not have been used to Watt’s clients, however he certainly was able to demonstrate effectively that his systems could reduce the water level in flooding mines, to a lower level whilst burning less coal.

Towards the later half of the 1800s, the most significant water developments were widespread construction of clean city water supply systems and municipal sewage treatment and disposal plants. Water supply was often from wells, pumped by very large double-acting reciprocating pumps, driven initially by steam engines, and later by internal combustion engines.

The first half of the 1900s, through to 1974, were influenced by technical progress and by two world wars. In many countries there was mass production of smaller centrifugal and multistage centrifugal pumps, as well as piston pumps. These pumps were powered by grid supplied electric motors, or small IC engines. The expansion and modernization
of city water supply and sewage works continued, with large electric-motor driven centrifugal pumps becoming standard. Clean water was distributed to all in most western cities and farm people had a considerable range of mass produced pumps to choose from.

The first oil crisis was in 1974 resulted in increased environmental awareness. In Australian and American farming regions, the windmill bore pump had been popular since its introduction from California during the gold rush period. Early research into thermal solar pumps increased after 1974, followed by the commercial introduction of photovoltaic solar borehole pumps in the mid 1980s. Developing countries still widely lacked the reliable city water supply of the developed countries. Their farms and villages were (and many still are) often plagued by disease, related to lack of clean drinking water and adequate sanitation. Currently, 30,000 children die daily from diseases that relate to lack of clean drinking water (eg. dysentery). The 1980s were declared ‘The international drinking water and sanitation decade’ by the various international aid agencies. The aim through international aid agencies was to provide hand pumps for many villages in developing countries, so that people could stop drinking from polluted river waters.

**A7.1.2.1 DESIGN IDEAS RESULTING FROM THIS RESEARCH ON THE EXTERNAL INFLUENCES ON WATER-WELL PUMPS**

The trends analysis in this section has identified a number of remote markets, where water is extracted from tube-wells that are generally labeled as “shallow wells”. Although it is less commonly used, I prefer the term “low yield well”. The depth of the water in these wells ranges typically from 5 metres to 40 metres and their yield typically ranges from 0.05 litres/sec. to 2 litres/sec. Typically, because of their remoteness, grid electricity is not available at these wells, so alternative energy sources including wind, solar, human and hydrocarbon fuels must be considered. These low yield wells occur in the following places:

- Broad acre farms in countries like America and Australia.
- Village water in developing countries.
- Irrigation water for small farm lots in the developing countries
- Islands around the world. There are many of them, for example there are about 7,000 Philippine’s islands.

A7.1.3 THE WATER WELL CONSTRUCTION

Water wells were hand dug in the early BC times. To allow human access, minimum well diameter was at least 1.2 m. Sometimes wells were much larger. The ancient Joseph’s Well in Cairo, Egypt is massive, about 7 m X 5 m in cross-section, excavated through solid rock to a depth of about 50 m. This well does not finish there. It is enlarged to form a chamber containing a reservoir. From this chamber an additional well is driven a further 40 m, where it emerges through the rock into a bed of water bearing gravel. A spiral passageway of small gradient was cut through the rock around the well to allow human and oxen access. Oxen were worked in the chamber to haul water from the lower well to the intermediate basin.

Oxen may first have been used about 700 BC to haul a single bucket out of a well, using a rope and pulley. Wooden gear wheels were introduced around the fourth century BC. Oxen or camels, walking in a circle, turned a vertical shaft bevel gear, which engaged with a horizontal shaft gear, which turned the wheel of a chain of pots. In Egypt this system was known as a sakiya (Stowers in The IMechE, B3-1963). A similar system was used in China about 1000 BC. Later the water wheel was used to power such devices.

In the 1700s the wells of Savery, Newcomen and Watt were built to allow human access via stairways and ladders. Equipment was relatively large and required humans to access it and use tools for installation and maintenance (Rogers, B2-1905).

By the mid 1800s, the tube well became popular and powerful drilling equipment was developed by the end of the nineteenth century. The drilling of water wells benefited from the oil industry’s investment in the various drilling processes (Cox, B2-1906). These processes have been developed since the very first primitive oil well in Pennsylvania in 1859 (Suman, B2-1923). Early tube wells were constructed manually, using a spring board percussion technique initiated in China about 1000 years earlier. However, the early Chinese tube wells were not used for down-hole pumps, as they
were mainly employed to produce artesian water having sufficient pressure to rise to the surface.

Tube wells are generally less expensive to construct than open wells. The trend toward tube-wells influenced the design of pumps. The pump diameter is limited by the diameter of the tube-well, and human access to down-hole pump components is not possible, so the pump must be retractable to the surface for maintenance. Thus the tube well caused modification of the design of the associated down-hole pump.

The volume of earth removed when constructing a tube-well is proportional to the square of the diameter. The energy required to remove this material is also approximately proportional to the square of the diameter. An interesting manually powered drill rig has been developed at Cranfield University for the drilling of hand pumped wells for villages of developing countries (Ball & Danert, B2-1999; Carter, B2-2001; Rwamwanger & Carter, B2-2001). This Cranfield rig is known as the Pounder rig and is illustrated in Figure A7.1.1. Although not suitable for drilling though hard rock, it is intended for tackling jobs of intermediate difficulty thus filling a gap between existing hand-dug/hand augured shallow wells and conventional (high cost) deep wells. The rig offers an improvement on the primitive hand sludging methods which are of the class of the early Chinese well “rigs”.

The humans operating the Pounder rig rock the lever at the top of the pivot tube at a comfortable speed and stroke length, these parameters depending on factors such as earth constituency and sludging depth. Steel drilling tubes with a cutting tool at the bottom are caused to reciprocate and are approximately counterbalanced by the water barrel illustrated. Increasing the stroke length, stroking rate, depth of cut or cutting tool diameter requires an increase in human power input. Figure 1.2 illustrates the effects on human power for a cutting tool diameter of 4 inch and a stroking rate of 0.8 strokes per second. Since the average adult male can comfortably work at only about 75 W, his limitations are in the lower regions of Figure A7.1.2. The advantages of using the Pounder rig with a 4 inch diameter cutter, compared to the standard 10 inch diameter hand auger, can be seen from Figure A7.1.3.
Figure A7.1.1: Pounder manually powered drilling rig developed by Cranfield University

Figure A7.1.2: Human power required for conventional manual sludging estimated by researchers at Cranfield University
The most prevalent trend historically, in well construction, has been reduction of well cross-section and, in the case of tube-wells, reduction in bore diameter. I was consulted a few years ago about the need to reduce oil-well diameter. The driving issues were the need to reduce the weight and bulk of drilling, casing and pumping equipment, which were to be transported by helicopter and barge to sites with difficult access. Transport, construction and operating costs were significantly affected by oil-well diameter, which influenced the weight and bulk of all equipment.

**A7.1.3.1 DESIGN IDEAS RESULTING FROM THIS RESEARCH ON WATER-WELL CONSTRUCTION**

Clearly, minimizing the diameter of down-hole equipment is an important objective in pump design, as it will result in cost saving and greater convenience in well construction. It should also result in weight saving for all down-hole equipment and thus lead to easier handling of this equipment.

**A7.1.4 POWER SOURCE**

In the BC era power sources relevant to water pumping were initially human, animal, wind and water. Power was limited and the pumping equipment when employed for
pumping ground water was only accessible to humans by means of open wells. For ground-water, the bucket was the prime element of such systems, hauled to the surface by a rope. Sometimes many buckets were attached to ropes to form an endless loop, as in the chain of pots pump. There are a number of excellent publications about early pumps and well pumps (Weisbach and Herrmann, B2-1897; Rogers, B2-1905; Stowers, B2-1963).

During the next period, from the 1st century AD through to 1700 AD wind and water streams became popular sources of power. They were also used to power some interesting reciprocating piston well pumps (Agricola, B3-1556; Ramelli, B3-1588; Keller, B3-1964)

Although steam had been employed much earlier by Hero of Alexandria, its first widespread use for ground-water pumping occurred in the eighteenth century in the mine dewatering pumps of Savery, Newcome and Watt. Wood, peat and coal were used as fuels, coal being the most widely used. Coal burning steam pumps were quickly taken up for city water supply in major cities and towns, often from ground-water.

During the 1800s, coal continued to be the major fuel and the steam engine remained virtually unchallenged until the 1870s. About the middle of the century, people started to experiment with ideas that lead eventually to the invention of the internal combustion engine which, in its various forms, was run on coal gas, producer gas, blast furnace gas, paraffin and oil. In the 1850s Ericsson experimented, in Egypt, with a thermal solar pump using solar energy incident on focusing parabolic reflectors as its power source. Grid electrical power was first produced in the late 1800s.

The first production of electrical power by wind turbine generators was in the early 1900s. In the 1930s many American farmers owned small wind turbine generating sets. However the government’s installation of wide-reaching electrical grid networks put an end to this practice.

The next power source relevant to ground water pumps was photovoltaic cells which, after a small but expensive beginning in the 1960s, started to make an impact in the 1980s. By this time the capital cost of photovoltaic power had come down from hundreds of dollars per peak watt to about $10 per peak watt. The downward trend in
cost of photovoltaic cells, which has not so far kept up with predictions, is expected to continue and a target of $2 per peak watt may be achieved by the year 2010.

A7.1.4.1 DESIGN IDEAS RESULTING FROM THIS RESEARCH ON POWER SOURCE

Many power sources have been discovered over the years. Low yield pumps in remote areas would benefit by being designed to readily operate on a wide variety of these sources. The availability, practicality and economics of particular energy sources varies from site to site.

A7.1.5 PRIME MOVER

The history of the prime movers follows a similar pattern to the previous section of power source. It commences in the BC era with human and animal power. There was possibly some primitive use of wind power employed in vertical axis surface water pumping in ancient China.

The wind machines and water wheel powered machines of the Middle Ages made a very significant impact in many countries. Both these prime movers were used to pump water from wells.

The steam engine had a huge impact on the dewatering of mines and marshes, city water supply and eventually sewerage disposal in the eighteenth and nineteenth centuries. In Australia, during the 1800s, steam engines were sometimes employed during wind droughts to pump ground-water at outback cattle stations. This would involve a man camping by the steam pump for a period of perhaps six weeks in order to tend the wood fired steam pump.

The steam engine was eventually challenged by the internal combustion engine in its various forms. The IC engine became popular as a prime mover for jack pumps that used the down-hole components of wind pumps during the first half of the 1900s. These jack pumps were of heavy/bulky cast iron construction.
Submersible AC induction motor drive multi-stage tube well pumps became popular during the mid 1900s. They were not developed for “low yield wells" until the 1980s and had the low efficiency problems mentioned in section 7.2.

The diesel engine was used to surface drive progressive cavity tube well pumps from about the 1930s to the 1980s. These were comparatively cumbersome systems. After this time submersible electric motor driven forms of the progressive cavity pump were developed in order to improve efficiency. This development was driven by the need to eliminate the inefficiency of the well shaft required by the surface driven diesel progressive cavity pumps.

The change to submersible progressive cavity pumps was primarily driven by the high cost of photovoltaic modules and the availability of highly efficient brushless DC motors. The manufacturers designed these motors complete with sophisticated controls that are able to optimize pumping output under varying electrical input conditions and that could temporarily provide the high starting torque required by the progressive cavity pumps.

**A7.1.5.1 DESIGN IDEAS RESULTING FROM THIS RESEARCH ON PRIME MOVER EVOLUTION**

One of the trends has been the reduction in size, mass and complexity of the prime movers. However, “low yield tube wells”, which have been serviced for many years by hand pumps, wind pumps and surface driven jack pumps, have only in about the last 20 years been serviced by submersible electric motor driven and grid powered, photovoltaic and wind-electric powered pumps. These systems, although compact and direct coupled, have not yet demonstrated a satisfactory history of reliability, particularly in wells yielding water containing corrosive or abrasive contaminants.

The trend to reduce the size and mass of systems is universal for engineering products and systems. This often involves increasing the rotational speed of machinery so as to obtain a greater power output or throughput for a given or reduced size. Direct coupling, rather than geared coupling of rotational modules is also universally favoured.
I believe that the universality of the above trends has influenced low yield pump manufacturers to produce direct coupled, submerged electric motor driven pumps and that they have not yet assessed the effect of this decision on other factors such as life, reliability, product adaptability as I have mentioned in section 2.6.

The manufacturers of the submersible electric motor systems mentioned above, have no experience with the surface driven reciprocating systems that I have come to favour. Their systems have been developed in European environments where groundwater is more plentiful and less aggressive than that in the markets that I have noted in section A 7.2.1.

A7.1.6 GEARING, BALANCING AND MATCHING

The ideal water well pumping situation involves a steady head and steady flow rate. This is sometimes approximated in practice. However a number of influences can upset this ideal. Ground water depth may vary from two main causes. The first is pumping rate which causes local draw down of the water table thus increasing the pumping head. The second is seasonal variation of the depth of the water table resulting from the complex balance between rainwater recharge and ground water flow. These influences vary the pumping head to varying degrees that vary both geographically and seasonally.

The maximum inflow rate available from a particular well is usually limited by the surrounding hydrogeology and the well construction. It may vary seasonally or reduce over a period of time due to general depletion of the ground water table. Pumping systems are usually matched to the minimum inflow rate at the set depth of the pump although some users adjust the depth of the pump seasonally so as to avoid the pump running dry during the dry season. This situation causes many currently manufactured pumps to burn out.

The benefits of, and need for balancing would have first become apparent with ancient shadoofs and early piston pumps (see section 4.6), where water and rope (or rods) were lifted on the upstroke. In many reciprocating ground fluid pumps the optimum counterweight for balancing the lifting tackle and fluid is such that the motor works evenly on both up and down stroke. The next detail requiring design is the flywheel. This is necessary to smooth out non steady influences from either the linkages (crank
and connecting rod) or the power source. Both wind and solar power are prone to fluctuate very significantly.

The need for **gearing** as part of the transmission is fundamental with positive displacement pumps. The optimal torque output of the prime mover must be **matched** with the load caused by the fluid pumping head.

Roto-dynamic pumps require **matching** (both head and flow) as well as positive displacement pumps. However the fluid head matching is done by stacking pump stages, each stage providing a relatively small pumping head. This leads to the availability problem mentioned in section 7.2. Well designed piston pumping systems are much more tolerant to varying head over a wide range than other pumping systems, particularly centrifugal systems whose efficiency is near maximum in a limited flow range where fluid entry and exit conditions are smooth.

The need for balancing is a problem that relates to piston (and diaphragm pumps). This need was discovered and investigated in ancient times, as mentioned above, and is still present. The huge Rotaflex oil pumps (Section 5.3.1) employ balancing masses of up to 10 tonnes to balance the weight of the down-hole pump rods. The long stroke reciprocator only needs to apply sufficient force on the upstroke to lift about half the weight of the production crude oil elevated by the swept piston area on each stroke. This technique results in even load on the engine during both up and down stroke.

Engineers’ understanding of the gearing seems to be still evolving as evidenced by all the events noted in the gearing, balancing and matching row of Figure 7.2.

**A7.1.6.1 DESIGN IDEAS RESULTING FROM RESEARCH INTO GEARING, BALANCING AND MATCHING**

A number of ideas emerged from this trend area.

- My first idea from this trend category was to investigate the viability of hydraulic balancing, rather than mass balancing as is common in oil-well artificial lifting and wind-pumps. Hydraulic balancing is not new. Some of the early double acting pumps effectively used hydrostatic upthrust to (part) balance the weight of down-hole driving rods, and indeed early wind pumps employed
the buoyancy of the relatively large cross-section wooden rods to balance the total weight of down-hole lifting equipment. My early idea was to drive the down-hole piston downwards with a moving delivery tube of approximately half the cross-sectional area of the piston instead of the conventional arrangement where the piston is pulled upward by a rod string (Dartnall, 1988, US Pat 4,762,474). All of my company’s pumps to date have employed this feature.

- The next idea that this trend category produced was the use of a very inexpensive way of accommodating a wide range of gear ratios necessary to match one pump model with the wide range of pumping heads and flow rates required in the field. This technique involves using a low ratio multi-vee drive from the motor to the well head long stroke reciprocator (LSWR), with a small drive pulley on the motor. Using drive pulley diameters of say: (1) 20 mm, (2) 25 mm, (3) 35 mm, (4) 50 mm, (5) 80 mm. The driven pulley diameter is of the order of say 300 mm. With this choice, the lowest ratio has four times the torque of the highest ratio – a wide range. The cost of the small pulleys can be low. For electrically powered systems, this torque range may be considerably extended by using an oversized permanent magnet direct current PMDC motor with a wide torque range of high efficiency. Pumping rate may be matched by a combination of pulley ratio selection and voltage selection. Using this line of thinking I have been able to match a wide range of systems with only one standard stocked motor, LSWHR and down-hole pump (DHP).

- Another idea was the use of exceptionally low friction fluid sliding seals in my pumps (Dartnall, 1992, US Pat. 5,152,537; Dartnall & Novak, 1996, US Pat. 5,492,342; Novak, 2000, US Pat. 6,098,986). This has practically eliminated starting friction problems for all installations. This problem plagues progressive cavity pumps and causes many electrical burn-outs and mechanical breakages in these pumps.

- The above ideas have resulted in my pumps being able to be balanced and matched to a wide range of operating heads and flows without the need for fragile short lived electronic matching systems and without the need to manufacture and stock a complex range standard module sizes.
**A7.1.7 TRANSMISSION OF POWER DOWN THE WELL**

Historically, a large number of means of power transmission down the well to the pump have been used.

![Morphological Chart](image)

*Figure A7.1.4: Morphological Chart showing different power source, prime movers, down-hole transmissions and down-hole pumps*
One idea which started with the rope and bucket pump involves *mechanical transportation of the fluid the whole way up the well*. The chain of pots pump was an extension of this idea. Another one is the rag pump and its derivatives. This system has a fluid absorbent media (sometimes a series of rags) attached to a continuous flexible member (rope) with a similar mechanical configuration to the chain of pots pump. The absorbent media soaks up fluid water or crude oil at the bottom of the well and delivers it at the well head with the aid of squeezing rollers or by centrifugal effect.

Other major mechanical ideas included *reciprocating rod* and *rotary shaft* driven systems whereby the fluid is pressurised and pushed in pseudo-continuous manner to the surface and beyond through a delivery pipe.

Further ideas, all of which have been employed at various times, are mentioned in historical context in Figure 7.2 and summarised on Figure A 7.1.4.

Has there been a trend? The trend has been the expected one: increasing compactness, reduction in mass, reduction in number of components, increasing functionality, etc. The electric submersible pump is a direct outcome of this trend.

**A7.1.7.1 DESIGN IDEAS RESULTING FROM RESEARCH INTO TRANSMISSION OF POWER DOWN THE WELL**

The concept of an electric submersible pump is a good one and has demonstrated its worth in the many grid powered “high yield” multi-stage submersible centrifugal pumps in use worldwide. High yield bore-holes tend to have less contaminated water. One reason for this is the flushing effect of higher rainfall and larger water movement.

However in low yield situations such as inland areas where the water quality is such that corrosive and abrasive elements are likely to be present, the life of submersible pumps has so far proved to be limited. They have the following problems and disadvantages.

- Starting friction can cause seizure. (progressive cavity pumps).
- Low operating efficiency (particularly with fluctuating power input such as occurs with solar and wind energy).
- They are not appropriate in systems that favour mechanical transmission from the surface such as wind-pumps, IC engine driven pumps and hand-pumps
- Dry-running breakdown. Electronic level sensing equipment can be installed but this has not proved to have long term reliability due to the quality of water present.
- Early failure due to corrosive and/or abrasive (and sometimes biological) elements in the water.
- Heavy and cumbersome to install and extract from the bore (for maintenance) due to the total weight of pump plus electric cable plus delivery pipe plus safety cable plus level sensing equipment.

The above disadvantages have motivated me to seek a mechanical drive system that is of the form of a cable of sufficiently low weight per unit length, rather than the conventional joinable rods and tubes or cumbersome poly-pipe systems that are currently available.

The apparent convenience of the submersible pump systems has resulted in their recent encroachment into what was traditionally, in the inland farming areas, for about one hundred years, the wind-pump market. This market is now also challenged by the solar pump which has turned out to be essentially an electrically powered pump.

My design idea is that if a sophisticated mechanical cable can be developed, it can be promoted and marketed as having all the advantages of the electric cable whilst at the same time permitting the use of a more appropriate long term total system with the combination of advantages resulting from the rest of this investigation.

### A7.1.8 DOWN-HOLE PUMP

The evolution from bucket to piston pump has been described in Section 4.6 and the introduction of the centrifugal pump described in Section 7.4. Many rotary pump configurations have been invented and numerous specialised systems using air pressure, hydraulic oil pressure, steam pressure and even pressurized drilling mud (important for drilling bores), to drive various pumps, have been employed over the years. The trend
has been towards compact, direct coupled systems, which has led to the submersible electric pump.

**A7.1.8.1 DESIGN IDEAS RESULTING FROM RESEARCH INTO DOWN-HOLE PUMPS**

The general trend of mechanical machines has been towards direct coupled and close coupled systems. The dispensing of reduction and step-up transmissions generally simplifies, reduces size and cost and increases reliability of machines. However it destroys the option of the product having variable or selectable speed and torque matching ability. In the ground water pump industry, the submersible electric motor has been well developed and is universally used for high volume, multi-stage centrifugal pumps operating under steady conditions. However, so far, its extension to low volume (multi-stage centrifugal and rotary) bore-hole pumps has proved to result in low efficiency, has not been able to produce long life adaptable systems.

This line of development and general trend for the low yield applications appears to be misleading. There appears to be an exception to the general trend for this low yield market.

The design idea of this section is to improve the old reciprocating piston pump technology rather than discard it. This positive displacement approach, in my opinion, is proving to be more promising and its prospects will greatly increase as development expenditure even mildly approaches the development expenditure of the competing compact rotary systems.

**A7.1.9 CONTROL SYSTEM**

The necessity for control of the many water well pumping systems that have evolved over the years relates to a large number of matters, some of which are listed below:

1. Variation of water depth, both seasonal and transient.

2. Variation of water requirement at the user end of the system.

3. Variation of wind or solar incoming energy – seasonal, diurnal, geographical.
4. Directional variation of wind machines.

5. Protection against damage from excessive wind.

6. Starting and stopping of IC engine systems and mains electric systems.

7. Managing excessive starting torque.

8. Automatic matching of a new system to the various site requirements.

The wind pump operated for over 100 years by meeting the need for 2, 3, 4 and 5 mechanically. The mechanical control systems have been found to perform with long term reliable operation. A current trend especially with photovoltaic systems is towards increased electronic control, but this seems to be leading to shorter life systems. A further problem with electronic control systems is the unavailability of maintenance or even replacement sub-systems that occurs only a few years after installation. It is worth noting that the windmill manufacturers in Australia are still repairing and maintaining designs that are over 100 years old.

Today, electrical systems such as the multi-staged submersible pump have emerged and along with these technologies, have emerged electronic control and management systems. Most electronic manufacturers have totally changed their designs after 5 years and are simply not available to service their products after 10 years. This lack of service is not what the farming industry needs.

**A7.1.9.1 DESIGN IDEAS RESULTING FROM TREND ANALYSIS OF CONTROL SYSTEM**

Will the electronic control systems eventually become sufficiently robust for the low yield pump market? It seems that, in general, it is possible to make robust electronic control systems to meet the rather complex range of requirements outlined in the previous section. However, the environments in which low yield pumps operate are severe, often involving extremes in temperature and humidity as well as ingress of fine dust caused by severe winds and in the case of submerged pumps, chemically aggressive environments.
Under these conditions, the cost of these systems is prohibitively high. However prohibitive cost is not the only problem. A second problem is the tendency for the systems to become obsolete in only a few years. As mentioned above, not only has an electronic control system become obsolete, but the manufacturer is either nonexistent or no longer interested in servicing it at a reasonable price. This presents a very different maintenance-cost scenario than that of the mechanical systems that have been so well understood and serviced by farmers for so many years.

My design idea derived from the control trend analysis is to persevere with mechanical systems and control systems of robust construction and minimal complexity that can be understood and serviced by people in the areas where the pumps are used. Some submerged pump manufacturers have submerged encapsulated control systems within the electric motor packages. This is leading to serious and expensive early system failures due to ingress of water and aggressive chemicals through the encapsulating material. At present, elimination of this problem seems to be prohibitively expensive.
APPENDIX 7.2

CASE STUDY: MORPHOLOGICAL ANALYSIS OF DOWN-HOLE PUMP

A7.2.1 INTRODUCTION

This appendix relates to the morphological approach (ie. MORPH applied) to subsystems of the pump case study. The section commences with the most recent events related to morphological generation. The most recent of these was the graphical generation of down-hole pump configurations. The most promising of these configurations were solid modelled. In a similar way, MORPH was applied to each of the major sub-systems of the UniPump, leading to system solid models. These solid models are shown after the down-hole pumps. Some detail is given for the column, a direct result of following the TREND-MORPH- PDS process. Finally, some old pump diagrams are included.

A7.2.2 MORPHOLOGICAL APPROACH APPLIED TO THE DOWN – HOLE RECIPROCATING PUMP.

Having decided that some form of reciprocating piston pump is required, this appendix records my processes towards generation of all conceptual designs for down-hole reciprocating piston pumps. This generation/classification commenced with sketches on scrap paper, collection of old books and company catalogues dating back to the 1800’s, searching through all relevant US patent records back to the 1850’s, reviewing various petroleum industry classifications of down-hole pumps. These searches were followed by systematic combinatorial generation involving both spread sheets and graphical manipulation.
### Code for Constructing Down-Hole Pumps

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

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<th>Element</th>
<th>Symbol</th>
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<tbody>
<tr>
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<td>![Cylinder Symbol]</td>
</tr>
<tr>
<td>Rod</td>
<td>![Rod Symbol]</td>
</tr>
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</tr>
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</tr>
<tr>
<td>Caged Valve Element - limited movement</td>
<td>![Caged Valve Symbol]</td>
</tr>
<tr>
<td>Assembled Valve - closed</td>
<td>![Assembled Valve - Closed Symbol]</td>
</tr>
<tr>
<td>Solid item</td>
<td>![Solid Item Symbol]</td>
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<tr>
<td>Fixing (in well casing)</td>
<td>![Fixing Symbol]</td>
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</table>

*Figure A7.2.1: Code for rapid graphical generation of down-hole pump configurations*
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 with stepped rod. This step has a plunger effect. Pumping occurs on both strokes and changing the cylinder on the up stroke.

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

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

Figure A7.2.2: Graphical generation of down-hole pump configurations – continued over.
This is one of the author's configurations. It is a double acting (single volume) tube driven pump. A potential advantage with respect to maintenance is that both valves and the seal are on the drive tube and could be extracted from the well with the tube without removing the cylinder and its casing.

This is one of the author's configurations. It is a single acting tube driven pump having a tube piston. A potential advantage with respect to maintenance is that both valves and the seal are on the drive tube and could be extracted from the well with the tube without removing the cylinder and its casing.

This is one of the author's configurations. It is a double acting (single volume) tube driven pump having a tube piston. A potential advantage with respect to maintenance is that both valves and the seal are on the drive tube and could be extracted from the well with the tube without removing the cylinder and its casing.

Figure A7.2.2 - continued: Graphical generation of down-hole pump configurations. –continued over.
This is the well-known double acting pump. In a down well configuration the pump has been rod driven in early days. It is unsuitable for tube wells because of the manifolds.

This is the well-known double acting (single volume) differential piston pump. In a down well configuration the pump has been rod driven in early days. It is unsuitable for tube wells because of the manifold. This pump delivers on both strokes and intakes only on the up stroke. Its cycle volume is only half of that of a truly double acting pump such

Figure A7.2.2 - continued: Graphical generation of down-hole pump configurations. - continued over.
A Company known as Dando-Ferry produced this double-acting (not quite double volume!) tube well pump. It could fit into a tube well and had the advantage that all components could be extracted for maintenance by pulling the rods.

Figure A7.2.2 - continued: Graphical generation of down-hole pump configurations. - continued over.
This tube well pump was produced as early as the 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.

Deming Co of the United States of America produced this double acting tube well pump as late as the 1940's and possibly later. All down-hole components could be extracted for maintenance on the rod string.

Figure A7.2.2 - continued: Graphical generation of down-hole pump configurations. - continued over.
Figure A7.2.2 - continued: Graphical generation of down-hole pump configurations. - continued over.
This double acting tube well pump was "invented" by the author. It is a conceptual model. It is almost identical to the Deming pump above, 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.

Figure A7.2.2 - continued: Graphical generation of down-hole pump configurations. - continued over.
A7.2.3 NECESSARY TIME CONSUMING DETAIL AND MARCHING EVALUATION

As the designer rapidly (and systematically, but with an open mind) sketches the different configurations, constant evaluations take place. This procedure is described by Ullman (B2-2002) in his paper on designer support ideas in CAD.
**Figure A7.2.3:** Most recent double acting, ganged, retractable, down-hole UniPump. See Figure A7.2.2 [13]

**Figure A7.2.4:** Earlier double acting, ganged, down-hole UniPump. See Figure A7.2.2 [18]
In the configuration of Figure A7.2.5, the drive cable was to be separate from the (off the shelf, polythene) delivery tube. Both could be clipped together as they were fed down the well after attachment to the pump. The down-hole pump of a new system is shown in Figure A7.2.3. It is shown, inserted and sealed inside the bottom of a proposed riser tube/casing. In this configuration which came to mind as a direct result of following TREND, when reading the work of the Pounder rig group at Cranfield University, the pump is lowered on the cable only, inside the dispensable riser tube/casing.

A solid model of this configuration is not included in this report.
Figure A7.2.6: Earlier solid model of double acting, ganged, down-hole UniPump. See Figure A7.2.2 [13]. In this model, DFM, DFA and Design for maintenance are yet to be considered.

### SUMMARY TABLE FOR DOWN- Hole PISTON PUMPS

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<th>Category</th>
<th>Cylinder (C)</th>
<th>Plateau (P)</th>
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<th>Delivery Valve Disc (V)</th>
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<th>Comments</th>
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<td></td>
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<td>1</td>
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</table>

**Table A7.2.1 (a): Summary of some early symbolic models (combinatorial generation) of down-hole pump configurations (morphological analysis.)**
Table A7.2.1 (b): Combinatorial generation of some early symbolic models of down-hole pump configurations (morphological analysis of the first category, 10.00).

Figure A7.2.7: Some early solid models constructed for generation of down-hole pump configurations
A7.2.4 THE HISTORY AND LOGIC OF THE DEVELOPMENT OF THE COLUMN SYSTEM FOR (TUBE-WELL) RECIPROCATING PUMPS

The pump column for mechanically driven ground water pumps, driven from the ground surface, has taken many forms over the past 250 years from the Watt era. There are two important functions normally served by the pump column. These are: (1) to provide the mechanical linkage from the surface engine to the pump at the bottom of the well, usually by means of a drive or pull rod and (2) to conduct the pumped water to the surface, usually by means of a pipe.

In the Watt era the rod and the pipe were often separated. The rod was often required to be both pushed and pulled on alternate strokes by the pump. This was done in order to balance the load on the engine. The weight of the rod assisted the pumping action on the down stroke and provided a load on the upstroke. The pump was often a single acting plunger type whose pumping occurred on the down stroke. The pumps of the Watt era were always installed in open wells of sufficient diameter to include stairwells or ladders for human access to all components of the rod, pipe column and pump for both operation and maintenance. The rods (which were usually of square timber, joined with bolted iron plates) were guided periodically with bushes secured to the walls of the well or to structures secured to the walls of the wells. The pipe structure was separately secured to the well or structure. This type of system grew out of the coal mines and was continued in coal mines until the early 1900’s.

Meanwhile, during the 1800’s bore water for cities, villages and farms was beginning to be supplied from tube-wells of smaller diameter. Human access was not required as it had been for mining. It was discovered that the installation, operation and maintenance functions could be carried out at the surface. This required the pump column and pump to be lowered or removed using lifting equipment at frequencies that allowed the pump to operate for some months between shutdowns. Hand pumps, wind pumps and engine driven city water supply pumps were all reciprocating piston pumps requiring the two functions mentioned above. The concept of a rod actuated bucket pump became
popular. The bucket pump is elegantly simple. The two functions are served by the one column system. A pull rod is installed in the centre of the riser column. The pump is single acting and pumps on the upstroke when the rod is in tension. This type of pump is and has been widely used for farm stock water lifting as well as for oil well pumping from oil wells. It can and often is configured to operate in a double acting manner by making the cross-sectional area of the rod to be approximately half the cross-sectional area of the cylinder. In this configuration the rod displaces fluid up the riser tube on its down-stroke so that the delivery of fluid at the wellhead is approximately equivalent for both up-stroke and down-stroke.

During my early investigations I became interested in the idea of replacing the pull/push rod with a delivery tube having guide bushes fitted at intervals of less than a meter. These guide bushes, of low friction material were guided in a loose clearance guide casing connected to the pump cylinder at the bottom of the well. The bottom of the reciprocating delivery tube was connected to a tube piston. This configuration is illustrated in Figure A7.2.8 if one imagines the central member as a delivery tube. The earlier Supertube pumps very successfully employed this configuration.

**A7.2.4.1 Main functional and specification requirements of the pump column**

- conduct fluid to the surface
- mechanically link the reciprocating actuator to the piston of the down-hole pump
- support the cylinder ideally eliminating elastic deflection
- have minimal overall diameter
- be conveniently installed and removable for maintenance
- resist wear
- resist corrosion
- be convenient for transport to site and for distribution
- be competitively priced
- all components to be available from competing and stable suppliers
"Poly-pipe"—which is universally available and commonly used with submersible pumps.

Diagram illustrating column buckling action of "cable drive" during the down-stroke.

Figure A7.2.8: Total UniPump system including the long stroke, wellhead reciprocator (LSWHR); earlier double acting, ganged, down-hole UniPump (see Figure A7.2.2 [18]); UniPump double acting drive cable and off the shelf delivery pipe. Column buckling illustrated.
A7.2.4.2 Derivation of critical parameters involved in column buckling

**Nomenclature**

- D: internal diameter of guide tube
- d: eternal diameter of tube bush
- d_{g}: external diameter of reciprocating riser tube/rod
- d_{i}: internal diameter of reciprocating riser tube/rod
- C: diametral clearance between D and d
- s: bush center to center spacing
- F_s: rod drive force to pump
- F_{x}: rod force (downward) above n^th bush
- F_{i}: rod force (downward) above i^th bush
- F_{i+1}: rod force (downward) above (i-1)^th bush
- R_i: normal force between i^th bush and internal wall of guide tube
- FF_i: friction force between i^th bush and internal wall of guide tube
- F_I: inertia force of i^th bush and tube/rod segment
- F_I: combined inertia force of all n bush and tube/rod segments
- F_{b}: rod bending stiffness force at the i^th bush and tube/rod segment
- M_{b}: rod bending moment at the i^th bush
- F_{r}: typical rod bending stiffness force at “average” bush and tube/rod segment
- L: Column length
- n: number of guide bushes
- th: angular deflection due to C of (assumed pin jointed) tube/rod segment
- rho: relative density of tube/rod material
- m: mass per unit length of tube/rod
- m_i: mass of i^th tube/rod segment
- g: gravitational constant
- a: maximum acceleration of moving tube/rod system during reversal
- E: elastic modulus of tube/rod material
- I: second moment of area of tube/rod
- mu: coefficient of friction of bush-guide tube combination
- Pcr(s): Force to buckle a single pin ended tube/rod segment using Euler formula
- Pcr(2s): Force to buckle a double length pin ended tube/rod segment using Euler formula
- FF_n: total friction force of all n bushes
- F_{n}: net downward driving force needed at well-head actuator
- R_i: lateral wall-bush force due to knuckling of single pin jointed tube/rod segment
- F_{n,loss}: friction loss (%) of pump driving force
A7.2.4.3 Pump column design diagrams

Fig 1: Model of pin jointed bushed riser tube and guide tube showing forces relevant to the $i^{th}$ element.

Fig 2: Force polygon on pin jointed $i^{th}$ bush.

Fig 3: Equivalent cantilever beam to simulate lateral force due to stiffness of riser tube.

A7.2.4.4 Derivations related to the above figures

Fig 1 illustrates the downhole pump column assembly under a loading condition such that the riser tube deflects as a column which is buckling in such a way that alternate bushes are forced against opposite sides of the guide tube walls as shown. This is idealized as a planar situation for ease of analysis. Theoretically this situation may occur on the downward stroke of the pump and will give rise to forces acting on the $i^{th}$ bush as illustrated. This figure illustrates a second, more conservative idealized situation. In this second situation, the column is assumed to be pin jointed at each bush as well as being planar.

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Fig 2 is a force polygon for the i th bush treating the riser tube as a pin jointed system and hence ignoring its stiffness.

Summing the vertical forces related to the i th bush leads to the following equation:

\[ \Sigma F(\text{vertical}) = 0 : \quad F_i = F_{i-1} + FF_i - m_i \ast (g - a) \]

\[ R_i = 2 \ast F_{i-1} \ast \sin(\theta), \]

\[ FF_i = \mu \ast R_i = 2 \ast \mu \ast F_{i-1} \ast \sin(\theta) \]

\[ F_i = F_{i-1} + 2 \ast \mu \ast F_{i-1} \ast \sin(\theta) - m_i \ast (g - a) \]

\[ \approx F_{i-1} \ast (1 + 2 \ast \mu \ast \theta) - m_i \ast (g - a), \ldots \text{for small } \theta \]

where \( \theta \equiv C / s = (D - d) / s \)

Now evaluate the nth term of the sequence:

Firstly let: \( \phi = 2 \ast \mu \ast \theta \) and \( \beta = m_i \ast (g - a) \)

Substitute:

\[ F_i = F_{i-1} \ast (1 + \phi) - \beta \]

Sequence:

\[ F_0 \]

\[ F_1 = (1 + \phi)F_0 - \beta \]

\[ F_2 = (1 + \phi)^2 \ast F_0 - \beta \ast (1 + \phi) - \beta \]

\[ F_3 = (1 + \phi)^3 F_0 - \beta \ast (1 + \phi)^2 - \beta \ast (1 + \phi) - \beta \]

\[ \vdots \]

\[ F_n = (1 + \phi)^n \ast F_0 - \beta \ast [(1 + \phi)^{n-1} + (1 + \phi)^{n-2} \ldots \ldots \ldots \ldots \ldots \ldots (1 + \phi) + 1] \]

\[ = (1 + \phi)^n \ast F_0 - \beta \ast [n + (n \ast (n - 1) / 2) \ast \phi] \]

\[ = [(1 + \phi)^n \ast F_0 - (n \ast (n - 1) / 2) \ast \beta \ast \phi] - n \ast \beta \]

\[ F_n = [(1 + 2 \ast \mu \ast \theta) \ast \phi \ast F_0 - n \ast (n - 1) \ast (\mu \ast \theta) \ast m_i \ast (g - a)] - [n \ast m_i \ast (g - a)] \]

frictional term  inertial and gravitational term
The standard equation for a cantilever beam shown in Fig 3 is:

\[ \text{deflection} = \frac{W \cdot l^2}{3 \cdot E \cdot I} \]

Substituting the parameters from Fig 3:

\[ C / 2 = \frac{F_s \cdot (s / 2)^2}{3 \cdot E \cdot I} \]
from which...

\[ F_{ei} = 12 \cdot E \cdot I \cdot \theta / s^2 \]

(note: The Euler column buckling formula is \( F_c = \frac{\pi^2 \cdot E \cdot I}{L^2} \). This has a similar form.)

The stiffness force at each bush is:

\[ F_d = 2 \cdot F_{ei} = 24 \cdot E \cdot f \cdot \theta / s^2 \]

**A7.2.4.5 Spreadsheets for design of the column**

The spread sheets of pages 184 to 187 analyse the performance of the proposed double acting cable drive system. A worst case during its operation is considered to be when the central rod is in compression and acts as a column. The spread sheet was originally constructed for analysing the earlier Supertube reciprocating, bushed riser tube in a similar mode.

The continuous central rod in the new system will be of either spring grade stainless steel or a glass reinforced resin matrix pultrusion. The material is noted in the top right corner of the spread sheets. Both of these materials are coilable for transport. The central rods will be regularly bushed with wear resisting, low friction PTFE containing bushes. These will be added to the continuous rod using an automated draw bench.

The design, using the spread sheets involves a trade-off between high bush friction and column buckling action of the rod. More bushes per unit length—more friction, less bushes per unit length—more risk of buckling. I have already gained considerable experience with this trade-off situation with the earlier Supertube pumps, which have performed well in the field, with respect to both buckling and friction as well as wear.
PERFORMANCE OF BUSHED COLUMN FOR DEWELLING WATER PUMP

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<td>393</td>
<td>393</td>
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<td>Net driving force</td>
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</table>

**Effects of Bush Spacing**

- Friction Loss, Fai (%)
- Euler Buckling Force (bush spacing of s), P(0)
- Euler Buckling Force (bush spacing of 2s), P(0/2)
- Driving Force including friction, Po + Fc
- Net Driving Force, Fc
- Knuckling Force, Fc
- Static Force, Ps
- Friction Force, Fc
### Table: Performance of Bushed Column for Dei Water Well Pump

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</table>

### Diagram: Effects of Bush Spacing

- **Friction Loss, %**
- **Euler Buckling Force (bush spacing of s), Per(s)**
- **Driving Force including friction, Fo + FFn**
- **Net Driving Force, Fn**
- **Knuckleing Force, Fk**
- **Stiffness Force, Fsi**
- **FFn**

### Various Parameters (all forces in Newtons)

- **Bush spacing, mm**
- **1.0** to **10.0**
- **100.0**
- **1,000.0**
- **10,000.0**

---

**Material: Stainless Steel Red 19 mm dia**
187
A7.2.5 RARE DIAGRAMS FROM OLD BOOKS AND MANUFACTURERS, CATALOGUES

Figure A7.2.8: Aerotor Windmill manufactured in Australia by W D Moore since early 1900's
Figure A7.2.10: An early Australian attempt at polymer down-hole windmill column and pump
Figure A7.2.11: An early Australian attempt at polymer down-hole windmill column and pump
Figure A7.2.12: A Dando pump – see The War Office, Britain, B2-1936; Military Engineering (Vol. VI): Water Supply
Figure A7.2.13: A Dando-Ferry pump – see The War Office, Britain, B2-1936; Military Engineering (Vol. VI): Water Supply. Principle of operation of down-hole pump as per Figure A7.2.14
Figure A7.2.14: A Dando-Ferry pump – see The War Office, Britain, B2-1936; Military Engineering (Vol. VI): Water Supply. Principle of operation similar to my Figure A7.2.2-[11]
**Double-Acting Deep Well Cylinder**

**With Composition Gum Valves**

*Fig. 2324-S*

These cylinders are recommended for use when the capacity required is greater than can be obtained by the use of a single-acting cylinder.

The upper working barrel is wrought iron with brass lining which permits the use of pipe tongs when screwing the cylinder to the drop pipe; the lower working barrel and casing are seamless brass tubes; the plunger rod is "Everdur" ground and polished.

Plungers and valves may be withdrawn without disturbing the piping.

No water hammer; Space between Lower Plunger and Packing Box is vented to the well.

Pump rods should be made of Extra Strong Iron Pipe cut in 10-foot lengths.

Double-Acting Cylinders should not be located in the well more than 200 feet below the surface. Cipher, CALLA.

**Key to Sectional View 2324-S Shown at Right**

1. Upper Working Barrel
2. Pump Rod Connection
3. Upper Plunger Spring
4. Upper Plunger Valve Plate
5. Upper Plunger Valve Rubber
6. Upper Plunger Valve Seat
7. Upper Plunger Formed Spacing Ring
8. Upper Plunger Cup Leaether

10. Lower Working Barrel Casing
11. Lower Working Barrel
12. Lower Plunger Formed Body
13. Lower Plunger Formed Leaether
14. Lower Plunger Formed Spacing Ring
15. Lower Plunger Formed Lock Nut
16. Lower Plunger Upper Locking Ring
17. Lower Plunger Upper
18. Lower Plunger Upper Locking Nut
19. Lower Plunger Upper
20. Lower Plunger Upper
21. Lower Plunger Upper

Fig. 2324-S Double-Acting Cylinder must be submerged at all times.

Where it is necessary to use a suction pipe below the cylinder, be sure and specify on your order and we will furnish Fig. 2324-A without vent holes.

<table>
<thead>
<tr>
<th>Inside Diameter</th>
<th>Fitted for Drop Pipe Inches</th>
<th>Smallest Size Will Which Will Receive Cylinder</th>
<th>Size of Pipe Tapping in Inches</th>
<th>Size of Extra Strong Pipe Used for Pump Rod Inches</th>
<th>Length of Strokes Inches</th>
<th>Length Overall Inches</th>
<th>Capacity Per Revolution Gallons</th>
<th>Approximate Weight in Pounds</th>
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<td>2</td>
<td>27/6</td>
<td>1 1/4</td>
<td>6</td>
<td>60/5</td>
<td>1.97</td>
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<td>50</td>
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<td>2 3/4</td>
<td>2 1/4</td>
<td>31/4</td>
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<td>12</td>
<td>55/5</td>
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<td>18</td>
<td>60/5</td>
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</table>

* A revolution consists of one stroke up and one stroke down.

**Pump Rod Guide Couplings—Fig. 2325**

These couplings are cast of semi-steel and are so shaped that they cannot catch in the joints of the drop pipe. They are recessed in the ends to fit the extra strong pipe rods snugly, which protects the threads from all side strains. Guide couplings must be used with double-acting cylinders. Cipher, CALLA.

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<th>For Deep Pipe Sizes</th>
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<td>Combined Weight of Coupling and 10 Foot Pipe Rod</td>
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<td>35</td>
<td>35</td>
<td>35</td>
<td>35</td>
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</tr>
</tbody>
</table>

*Guide rod couplings are slightly smaller in diameter than the drop pipe to allow for free travel, but are large enough to prevent rod whip on the down stroke.

Figure A7.2.15: A Demming pump – from a 1934 Demming catalogue. Principle of operation similar to my Figure A7.2.2-[15]
Figure A7.2.16: An Ashley pump – from an early 1900's text book. Principle of operation vaguely similar to my spool pumps. See Figure A7.2.2-[15,17,18]
Figure A7.2.17: An Ashley pump – from an early 1900’s text book. Principle of operation vaguely similar to my spool pumps. See Figure A7.2.2-[15,17,18]
Figure A7.2.18: Possibly a 1500's installation at Augsburg in Germany
A7.2.6 SUMMARY AND COMMENTS

This MORPH section of the case study has detailed the down-hole part of the design process and some of the work that led to the new versatile drive cable.
The full process was much more detailed, and involves applying MORPH to all other areas of the system. It also involves a lot of thinking in between each MORPH analysis in order to consider the interactions between the sub-systems and of course their individual and combined interactions with the larger environments. A complete system review should be done in order to check the system out. This process is well outlined in texts on Systems Engineering.
APPENDIX A7.3

CASE STUDY: EARLY SOLAR THERMAL PUMP PHOTOGRAPHS AND PATENT MATERIAL.

Figure A7.3.1(a): Solar thermal pump called the NH$_3$ pump. This pump employed the Stirling Cycle with a liquid piston.
A discussion about this solar thermal pump arruars in Section 2.4 of this thesis.
Figure A7.3.2: Preliminary circuit for the Solar thermal pump called the NH3 pump. This pump employed the Stirling Cycle with a liquid piston.
Figure A7.3.3: Layout diagram for Solar thermal pump called the NH3 pump. This pump employed the Stirling Cycle with a liquid piston.
Figure A7.3.4(a): Patent diagram for Solar thermal pump called the NH₃ pump. This pump employed the Stirling Cycle with a liquid piston
Figure A7.3.4(b): Patent diagram for the double acting version of the Solar thermal pump called the NH₃ pump. This pump employed the Stirling Cycle with a liquid piston.
Figure A7.3.4(c): Patent diagram for another version (constructed) of the Solar thermal pump called the NH₃ pump. This pump employed the Stirling Cycle with a liquid piston. This version the hydraulic over mechanical matching transmission intended to eliminate the need for the flywheel of Figures A7.3.4(a) and A7.3.4(b).
Bibliography and References

Three separate bibliographies/references are included. They follow as B1, B2 and B3. This categorization was done because research for the thesis fell into three distinct areas:

B3: Historical Research.

B1: Bibliography and References for Engineering Design Process, Methodology and Science


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Zwicky, F., 1971; *Discovery, Invention, Research through the Morphological Approach*, Macmillan, Canada.


B2: Bibliography and References for Pumps, Ground Fluid Technology, Technology and Relevant History

Three separate bibliographies/references are included. They are: B1, B2 and B3. This categorization was done because research for the thesis fell into three distinct areas:

B3: Historical Research.

Addison, H., 1959; A Treatise of Applied Hydraulics, Chapman and Hall.


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