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Mechanical Engineering Design: Going over the Analysis-Synthesis Mountain to Seed Creativity

Kant Kanyarusoke

Abstract

This chapter advocates and exemplifies a change in delivering mechanical engineering design (MED) to undergraduate students. It looks at, and critiques the current delivery mode which treats MED as an extension of Natural and Engineering Science, through its bias for analysis of existing systems. It is argued that even though students' innovativeness might be getting slightly enhanced, their creativity is stunted by the mode. So, is their understanding of how machines evolve from human needs, and of how non science related issues affect the evolution. A new teaching approach which attempts to align student thinking and learning activities with what exists in industrial MED is suggested. In this approach, human needs drive engineering problem formulation, which in turn, precipitates a synthesis of machines, mechanisms and constituent elements to satisfy the needs in a regulated environment. The regulation obeys laws of science but is mostly, 'Humanities'—constrained. Creativity and innovation case studies are given, and it is shown how new machines can come into existence in the course of learning MED. This would be difficult in the current delivery mode. The new mode, of synthesis followed by iterative analysis, helps students build self-confidence and prepares them better for industry.

Keywords: analysis, creativity, innovation, mechanical engineering design, synthesis

1. Introduction

Mechanical engineering design (MED) deals with conceptualising, planning, optimising and communicating mechanical systems to do specific tasks [1]. The tasks are meant to satisfy specific needs as desired by Man. In a most general form therefore, human needs satisfaction, requiring tasks to be done in a mechanised way, are the primary drivers of MED [2]. These needs could be anything from physical, such as moving between places 'X' and 'Y', to thermal comfort as in air-conditioning, to egoistic and futuristic as in imagining being part of a generation that sends human species out of the solar system, etc. It is evident that these need-drivers can be diverse and very complex: sometimes, they may neither be directly related to ordinary science, nor to normal expressions of art. Yet, the systems which have to do the tasks are physical. They are regulated by laws of Physics and Mathematics—whether known, or yet to be discovered. Moreover, they are expressed in artistic form to appeal to potential users and handlers. This marks the first hurdle in MED: to relate the obscure needs to as yet, inexistent systems. At engineering student level, this is perhaps the greatest challenge. We shall shortly see why this chapter symbolically refers to it as a 'mountain'.

Physically, mechanical systems consist of materials—shaped, sized and connected in such a way that energy can be input at certain points to cause desirable changes at other points within the system [3]. ‘Desirable’ here, means the ‘changes’ at those other points positively contribute to satisfaction of needs. The simplest identifiable material in the system is called a machine element. The contribution in most systems is through several groups of connections of elements, called mechanisms, which in turn are also interconnected to form the total system, or machine. Therefore, MED has to consider selection of materials for the elements, sources of input energy, and transformations of this energy within the machines being designed. Prior education and training of mechanical engineering students tends to prepare them quite well for this part of MED. This is especially so, because MED, as a subject, is normally taught later in their studies, after they have done a fair amount of engineering science subject modules. Hence, many undergraduate MED curricula tend to focus on design of individual machine elements, as typified in Refs. [4–6], and in text books [7–9]. Necessary and convenient as this may be, it creates a mental comfort zone for students that tends to further disable them from connecting the obscure human needs to the very machine elements they may be studying. They are in one valley of comfort, while the needs are in another. An invisible mountain separates the two valleys. How do we make that mountain visible—and how do we help students ascend, and then descend it? Those are the two questions addressed in this chapter.

MED is not simply the identification of needs, and inventing or conceptualising machines to satisfy those needs. In a world of ever increasing scarcity of both materials and readily exploitable energy resources, and where many other engineering designers are competing to satisfy the same needs—possibly in different ways, MED has to include a consideration of alternative and/or complementary designs. The alternatives have to be compared with, and contrasted against, each other on well-defined criteria. Complementary designs may be necessary to extend market outreach. To the extent that these comparisons and contrasts can be modelled mathematically, and analytical optimisation procedures carried out, engineering students have little difficulty in this area. However, careful consideration of needs, gives rise to two questions. One is on extents to which the needs are likely to be met; the other is on how infrequently and for how long in a given period, they are not likely to be met. The first of these concerns, contributes to quality of the design. The second leads to reliability. These two areas are probabilistic and are less familiar to students than the physical or ‘functionality’ part of MED. Along with them, come others characterised by chaos. These include marketability, effects on and by the environment, etc. All these issues (Functionality, Quality, Reliability, Marketability, Safety and Environmental, etc.) have to be planned for in the design. Finally, the design has to be persuasively communicated.

The endpoint of MED has traditionally been sets of detailed engineering drawings [10]. Today however, it may, in addition include: a set of simulations and their results, a working physical model, a working prototype and a series of oral and written presentations. This author considers that as much as possible, mechanical engineering students should not be let to end designs at drawings alone. This is because at their stage of professional development, they have not yet mustered sufficient insights on manufacturing and assembly processes to give error-free manufacturing drawings for workshop personnel to make and assemble satisfactory machines. The author finds that—requiring and guiding them to translate their drawings into models or working prototypes, greatly helps them improve their overall design and manufacturing abilities. More importantly, drawings, and simulations, do not produce the same level of satisfaction and self-confidence building as a finished working model or a prototype. One case in this chapter illustrates the principle of ending with a working prototype while the other, builds on a similarly finished student project.

The remainder of the chapter is therefore arranged as follows: we begin with a quick description of engineering analysis, to which, most MED students and practitioners are used, and in which, they easily find a comfort zone. Then, as a point of departure, we present a sample of industry design processes as reported in the literature. In Section 3, we present two cases: one is by the author, on design evolution of a hydro mechanism he invented in 2015. The second is by a physically challenged student, building on previous work. The originality and contribution of this chapter is in demonstrating an alternative method of delivering MED courses in order to quicken nurturing of innovation and creativity among mechanical engineering undergraduates. In the conclusion section, we summarise the differences between the two delivery approaches.

2. A brief on engineering design processes and methods

In this section, we first present the current state of handling MED at undergraduate level. We show it as being biased towards engineering analysis, rather than to the more desirable engineering synthesis. In the second and third subsections, we turn to how engineers in industry do MED. In one, we debrief the reader on processes, while in the other, we describe recorded methods.

2.1 Engineering analysis

Engineering analysis works on an existing system, which may be real or virtual in form. It applies already known laws of science and engineering to check both functionality and feasibility—if virtual. By functionality is meant, a ‘YES’ to the question: does this system do what it is intended to do? Feasibility means—a high (acceptable—in the circumstances) probability that the imagined system can be made and that, after then, it will be functional. The applicable laws of science consist of the virtually ‘inviolable’ and universal principles (within limits of present knowledge) of Physics and Chemistry, usually, but not always, as explained by Mathematics. In mechanical and chemical engineering, for example, laws of motion and of thermodynamics are good examples [11, 12]. So are those of electric and magnetic circuitry, and of logic systems in electrical and electronic engineering [13], etc. The second group—i.e., of engineering—however, are not necessarily inviolable. Nor do they have to be universal. They are practice—based. These engineering practice principles distinguish the engineering professional from the physical scientist in ways similar to how a medical doctor is different from a biologist, or an agriculturalist from a botanist. In mechanical engineering, such principles include those of making parts of the system; joining and assembling into subsystems, and finally into the finished system. Then, there are principles related to system usage, e.g., legality, cost, safety, security and environmental impacts, etc. It is clear that both the making and usage principles can vary from place to place and with era, depending on levels of development and acceptability in the societies where the systems are to be made or used.

In countries like South Africa, Botswana and Kenya, where pre-university education consists of 12 years at ‘primary’ and ‘secondary’ levels [14–16], University engineering curricula tend to start off with a consolidation of physical science and mathematical principles, and are then, in mechanical engineering, followed by an introduction to ‘making’ principles. In others like Nigeria, Uganda and Zimbabwe, the consolidation starts before admission to university in a so called ‘Advanced’ level of education [17–19]. Here, the mechanical engineering student starts off at a slightly higher level, is introduced to engineering communication, and to other essential branches like electrical and materials engineering in addition to some of the ‘making’ principles. MED in either case is introduced later, with analysis of virtual systems.

Even when real systems like engines, motor vehicles, home use machines, etc. are available, they are rarely analysed as whole systems because universities tend to compartmentalise knowledge. For example, in the case of a car engine, the student would have to draw on learnings from ‘experts’ in Thermodynamics, Mechanics of Machines, Fluid Mechanics, Materials & Manufacturing Engineering, Environmental Science, Electrical/Electronics, etc. These ‘experts’ would have taught the respective ‘knowledge compartments’ most generally, often, not even mentioning the engine. For the average student, integration of these ‘compartments’ in MED can be a very difficult first step to make, up the symbolic mountain mentioned earlier.

The usage principles occasionally come superficially in some final year projects. Even then however, the current approach to MED fails to motivate creativity in part, because it deals with already existing systems, whether imaginary or not. We can accept that it can lead to innovation as when an existing system is modified substantially to perform the same function ‘better’ or to perform others it originally was not intended for. We still note however, that limitations can be imposed by an insufficient grasp of the usage principles. To summarise therefore: to the extent that current treatment of MED at universities is theoretical analysis—driven, relying on existing systems and with limited concern for usage, it stunts both innovation and creativity. The intent of this chapter is to advocate and demonstrate a reversal of that approach, and align it with the practice in industry so that on one hand, students appreciate MED better, and on the other, they can find it easier to settle in industrial practice after they leave campus. **Figure 1** shows the two approaches, side by side.

2.2 Engineering design processes

In industrial practice, design approaches have been formalised to ensure as much detail on user requirements and on limiting constraints are taken care of, to get as cost effective (or profitable) a safe and marketable product as can be achieved. **Figure 2** shows some of the recommended processes in the literature. They all have the following characteristics [20–26]:

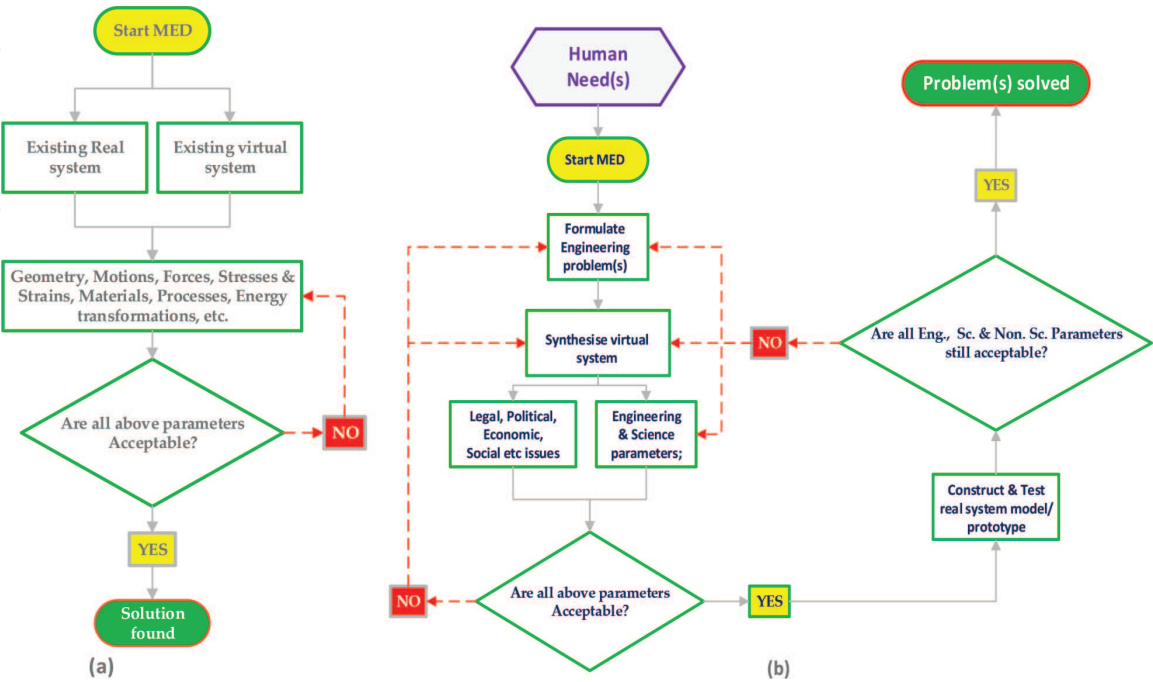


Figure 1.
(a) Current and (b) proposed teaching and learning MED approaches.

- They start with a ‘needs’ identification, followed by problem formulation. This means: ‘needs’, and hence usage principles—but not analysis, drive the process.
- They involve many solutions to the same problem. This means: in different circumstances, any other solution could be appropriate—much unlike in the current class room analysis driven approach.
- They are highly iterative. This indicates incorporation of a trial and error methodology, quite unfamiliar to, and unappreciated by engineering students.
- In the cyclic processes, there is no definite endpoint. The working product at step 8 is to be continuously improved upon, depending on emerging constraints and needs.

2.3 Engineering design methods

Nigel Cross [21] classifies engineering design methods used in the processes of **Figure 2** into two major complementary groups: the creative, and the rational ones. The former are characterised by their ability to stimulate thought processes, removing mental blockages and widening areas of search for solutions to the design problem. The latter on the other hand, systematically examine different issues at each stage of the processes in Section 2.2, also eventually solving the same problem. It is reported that some creative people detest the latter approaches because of their apparent prescriptive nature. Many others however, find the rational approaches most helpful, even complementary to the creative ones. **Tables 1** and **2** summarise methods in these two groups of approaches.

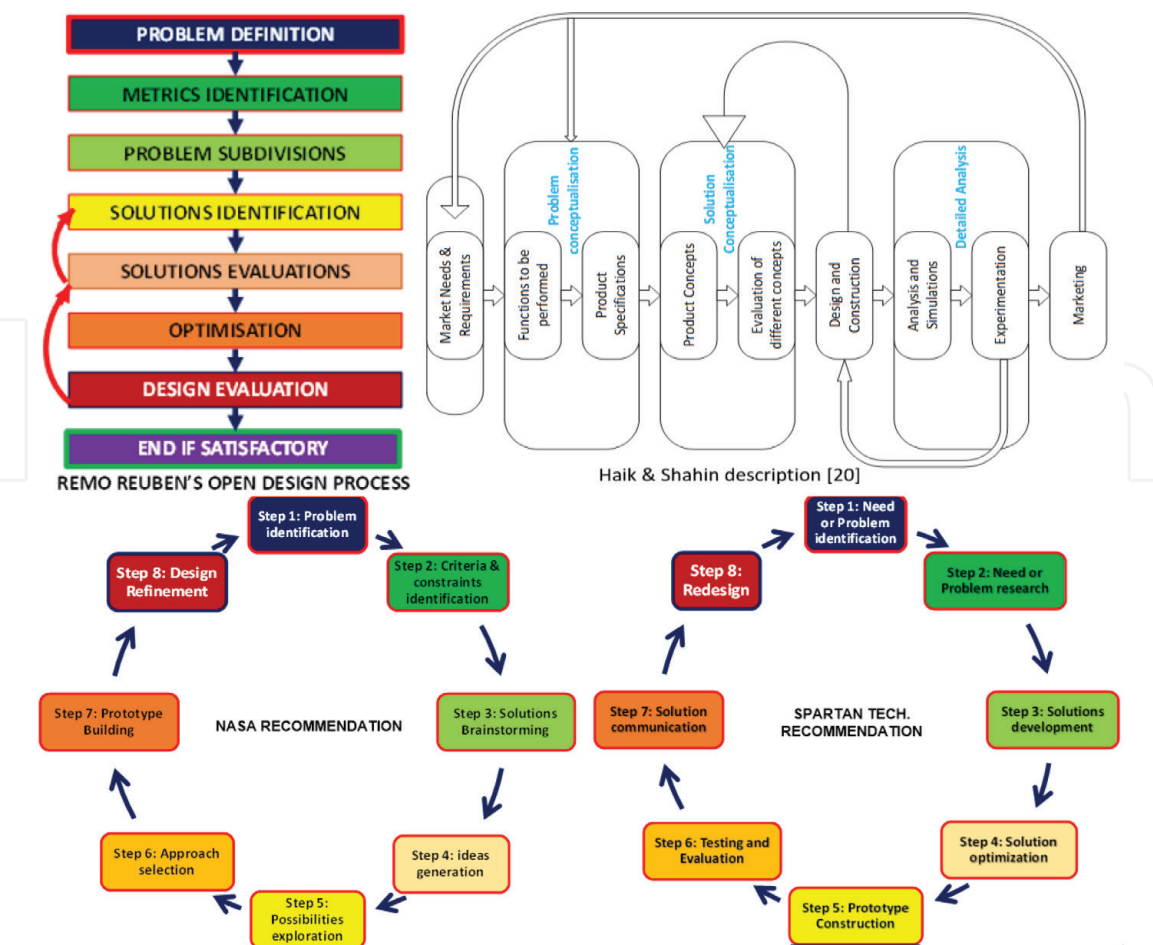


Figure 2.
Four examples of formal MED processes in industry.

Method	Comments
Brain storming	Best in a group, where each individual can make as many suggestions as quickly come to mind, irrespective of their apparent merits/demerits.
Synectics	Requires drawing parallels between quite unrelated events or things, preferably by people in a group discussion, to open up brain cells interconnection channels that can more easily lead to a solution.
Search space enlargement	Redefines the spectrum in which solution is sought. This can be assisted by: questioning the basis of the problem; random actions and making parallels of their effects to the problem on hand; dialectical reasoning, etc.
Spark of moment	Needs individual to have been thinking about the problem for some time—as in solution of plastic-latex jointing in Section 3.1 below.

Table 1.
Summary of creative engineering design methods.

Process	Methods	Comments
Identifying market needs	Market research and analysis	Build product objectives tree as ordered sets of targets to be achieved, in order to satisfy market needs in the prevailing circumstances.
Formulating product functions	Function analysis	Looks at the objectives tree, then determines overall function of the product to meet the objectives. The function is further decomposed into sub functions and then, possible mechanical components are identified to do, and, to integrate these sub functions. Limits on what can be done are imposed in form of a system boundary.
Specifying product attributes	Performance specification	Determined from functions, independent of possible solutions—considering that different products, types and features could provide the same functions. Pahl and Beitz [27] checklist can be used to define attributes that should preferably be quantified in range form, to give a specification.
Synthesizing alternative concepts	Brain storming	As in creative engineering methods.
	Morphological charting	Components for each sub-function in function analysis are tabulated and then, different combinations of these tried, to give different products having the same overall functionality.
Evaluating alternative solutions	Weighted objectives	Each feasible concept is considered for its relative position on each objective. Then summation of weighted scores guides selection. The problem however, is that ordinal scaling can result. This must be changed to interval value scaling.
	Pugh's evaluation matrix [28]	A benchmark concept is chosen. The others are compared with it in turn for each objective on a −1, 0, +1 scale. Totals for each objective, are multiplied by a weighting factor, and then sums of scores for each concept, computed. The bench mark concept scores zero while the best one is that, scoring highest.
Detail design and construction	Drawings	This step involves sketches of layouts for different concepts; assembly and detailed drawings of components of the selected concept.
	Prototyping	May exist in four forms [20]: Mock-ups, Models, Prototypes, and Virtual—CAD generated systems. Experimentation is done on the first three while simulations are done on virtual ones.
Improving the optimized solution	Value engineering	Re-examines the selected concept with intent of either reducing delivery cost—without losing functionality, or increasing value and utility to the customer, or both.

Table 2.
Summary of rational engineering design methods.

3. Case studies

We will now illustrate two cases of using some of the above approaches in an academic—rather than—an industrial environment. The first case is by the author himself. It exemplifies the creative design approach, and addresses an issue in solar energy engineering, of maximising useful energy yields from a flat-surfaced solar energy harnessing device. The second case shows a rational design approach, as taught to students in attempt to change MED from an analysis driven course, to a synthesis driven one. It builds on student knowledge gained from designing and constructing a multispeed fluid mixing vessel. The student designs a system for essential oils extraction from African herbs.

3.1 Case 1: invention of a new hydro mechanism for sun tracking

A new hydro-mechanism for interconverting linear and rotary motion was invented—and is described in a South African patent by the Cape Peninsula University of Technology (CPUT) [29]. The primary motive of the invention was to create a mechanism that would be deployed in a novel single axis sun tracking device that relied on mechanical energy to turn a domestic home solar energy collecting surface during the day, and return it to a morning position any time before daybreak. **Figure 3** shows the mechanism being used in conjunction with a photovoltaic panel.

3.1.1 Design processes

The approach used was a slight modification of the Remo Reuben open process in **Figure 2**. There was branching at the stage of evaluating alternative concepts, which led to other, very different products altogether—discussed in Refs. [30, 31].

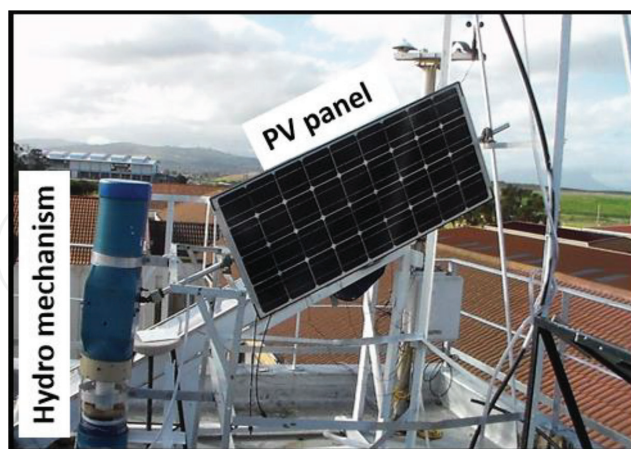


Figure 3.
The hydro mechanism driving a sun tracking PV panel (watch online video at: https://www.youtube.com/watch?v=79CKBxt_h-I).

3.1.2 Identification of need and formulation of engineering problems

A need for a new single axis sun tracking device, suitable for sub-Saharan Africa conditions of bi-hemispherical location, low credit and disposable incomes, and an inadequate technical skill base had been established in Ref. [32].

The product design problem and its sub problems were defined as: “Design a single axis sun tracking mechanism and its coupling means to a domestic home flat solar collector, so that the latter will be able to receive more energy from the sun, and therefore through the appropriate conversion process, yield more output than when in a fixed orientation.”

The sub problems, imposed by constraints discovered during identification of the ‘Need’ were:

- What would be the source(s) of energy in the mechanism?
- What motion transformations would the mechanism have to effect—and by which machine elements?
- How would the motion transformation be controlled, and how much energy would be required for both transformation and control?
- Which materials and manufacturing/assembly methods would be used to make and install the mechanism?
- What operational and maintenance tasks would be expected of the owner/user?

3.1.3 Solutions: evolution of the gravity driven hydro-mechanical tracker

Many solutions were investigated. Some were tried up to manufacture stage, and then discarded. Here, only significant ones are described in chronological order up to the prototype milestone. The reasons for discarding or modifying them are given.

3.1.3.1 The initial concept: solar-thermal hydraulic (STH) system with mechanical clock control of valves

A STH powered, spring controlled system was envisaged as in **Figure 4**. A hydraulic head h_{\max} was to be provided by a liquid in shaded tank ‘A’, connected to spring bank k through a one way valve **V1** and a cylinder-piston assembly. The piston rod would be a cylindrical rack, which energises the compression spring at the other end. The rack would drive a gear train to which, the frame holding the solar collector would have been coupled. At the end of the cylinder, was to be a one way valve **V2**, leading to an un-shaded small tank ‘B’. In late evening, with **V2** closed, and the piston at extreme western position, the panel would be facing west. **V1** would be actuated to open by the closure of **V2**. Liquid would flow into the cylinder, and compress the spring bank to the maximum (at which point a head h_{\min} would act on the piston) while reorienting the panel to face eastward for the next day. In the morning, valve **V2** would be actuated by a clock signal to open. Valve **V1** would simultaneously close. During the day, the **V1-V2** link would be automatically deactivated to enable independent operation of **V2** without opening **V1**. Then, a clock mechanism would intermittently open **V2** allowing a precise liquid weight to flow into un-shaded tank ‘B’ and then close for a definite period. This would relieve the spring bank a distance x , and in turn rotate the solar collector a definite angle westward—hence tracking the sun in this direction.

In due course, the liquid in tank ‘B’ would vaporise and condense in shaded tank ‘A’ so that the hydraulic head in ‘A’ gradually rose during the day in preparation for a night

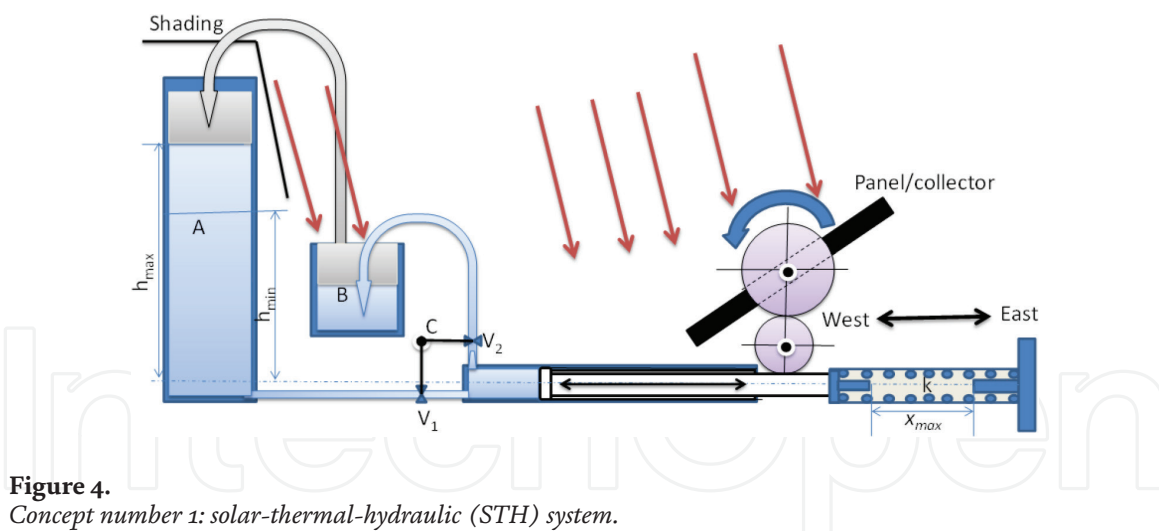


Figure 4.
 Concept number 1: solar-thermal-hydraulic (STH) system.

return action. The panel tracking axis could be rotated about the piston-cylinder axis for correct installation at different latitudes by graduated scales in a plane perpendicular to the figure.

This concept required use of a low boiling point, low enthalpy of evaporation but high density liquid. The low enthalpy would give sufficient daily solar assisted evaporation rates while the high density would enable storage of enough mechanical energy to compress the spring and turn a collector whose centre of gravity would most likely be offset from the axis of rotation. Such a liquid was actually identified among the refrigerants (R140a) but it was expensive in Cape Town. Being a chloro-hydro-carbon ($\text{CH}_3\text{-CCl}_3$), it was banned in some African countries. Although there were other issues, this alone was sufficient to disqualify the concept. However, many of its elements were carried to the next concept.

3.1.3.2 Concept 2: solar-thermal hydraulics (STH): water replaces R140a

After discarding the concept of using a chloro-hydrocarbon, water was considered. The immediate problem however, was that it was less dense and had a much lower vapour pressure at the envisaged working temperatures. Most importantly, its enthalpy of evaporation was an order of magnitude higher than that of R140a. These limitations were to be overcome in a series of solutions—still using STH principles (i.e., evaporate the liquid, raise it to some height and condense it there to provide a head that will reset the mechanism at the end of the day). A summary of the salient ‘solutions’ up to the time the STH system was discarded is given below.

- Evacuation of the system so that the boiling point could be lowered significantly to say, below 60°C . This was in attempt to raise the vapour pressure at a working temperature of between 30 and 40°C in the evaporator tank ‘B’ of Figure 4.
- A redesign of the evaporator ‘B’ to a flat plate solar collector, possibly able to evaporate at least 5 kg of water on a ‘typical’ Cape Town winter day. This was to be supplemented by provision of hybrid heating using say, biomass below the evaporator—in case the day was very cloudy.
- A redesign of the condenser tank ‘A’ and its condensation means to use evaporative cooling so that a smaller unit could be used. This was followed by elevating the tank to an appropriate height and by design of a vapour evacuation and piping system from the evaporator.

- A redesign of the mechanical linear to rotary motion inter-conversion system. A light weight semi cylindrical rack was to be in rectilinear motion, atop a rigid stem. The stem was to be attached to the spring loaded piston. The rack would then drive a fixed axis spur gear, mounted on the solar collector's axis of rotation (**Figure 5**). For locations say in the southern hemisphere, one side of the rack would be used. The other half would be used in the northern hemisphere, where the orientation of the axis and relative position of evaporator would have to be switched to still enable east to west day tracking. In this way, no internal readjustments would be necessary, if the device was moved across the equator.

Figure 5 illustrates the mechanism at this stage. The mechanical valves have also been replaced with solenoid valves by now.

STH systems had been attractive mainly because they looked novel and relied entirely on 'free' solar energy for their operation most of the time. They had a simple backup plan of burning biomass in case of cloudy days. The evaporator, the vapour evacuation system, the cylinder-piston-spring assembly were designed and constructed. A 200 mm × 200 mm × 100 mm aluminium block for manufacture of the semi cylindrical rack was also purchased. Meanwhile, a separate experiment to verify findings of a theoretical analysis on water evaporation rate yields in an evacuated collector gave 'unwanted' results. Whereas water seemed to evaporate fast enough at the low pressures, most of the vapour re-condensed on the collector glazing and in the evacuation piping before reaching the condenser. It was clear that a more elaborate evacuation system would have to be used if STH were to progress further.

A second 'unwanted' result came from the workshop. Machining of the cylindrical rack in the CNC workshop encountered problems when the purchased block was being resized for actual machining (it had not been exactly 200 mm × 200 mm × 100 mm). These problems forced a re-examination of the 'needs' of Section 3.1.2. It became apparent that the manufacturing problems being encountered, together with the possibility of vacuum leaks in the field would make the product not only 'too expensive', but would also affect its reliability. Moreover, as seen in **Figure 5**, the mechanism would be bulky, and perhaps less marketable than substitutes which could come on the scene later. Thus, STH on this product was discarded. Use was however to be made of almost all components and learnings from it in this and other off shoot products.

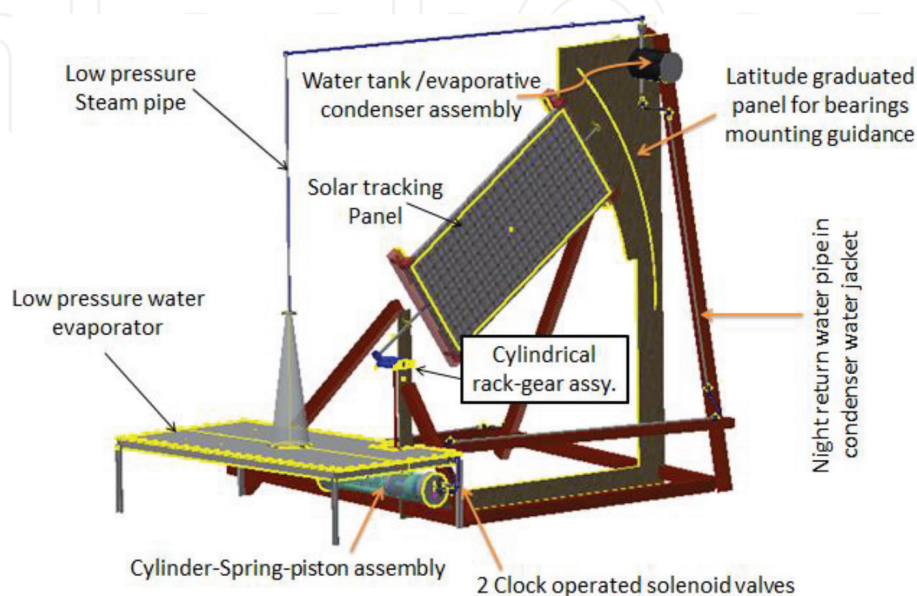


Figure 5.
The last of the STH concepts.

3.1.3.3 Other concepts: genesis of the hydro-mechanism

Although STH was now out of the question, the idea of a hydraulic head provided by an oversized 100 L condenser in **Figure 5** still remained attractive. The condenser had intentionally been oversized to provide sufficient heat transfer area, and also to hold reserve water in case of bad weather and inability to light a fire under the evaporator for whatever reason. The piston-cylinder assembly had been designed to discharge about 5 L a day—which would have easily been evaporated by energy incident on a 1.8 m × 1.2 m collection surface. It was therefore reasoned that with 100 L initially filled into the condenser tank (by whatever means), there could be a 20 day pumping head capacity to reset the mechanism at night. The 50 L tank of **Figure 4** was also revisited to hold daily discharges from the mechanism. This would therefore hold slightly more than a week's discharge (as it could not be filled to capacity). This, at last seemed to settle the hydraulics part—if only the cylindrical rack could be made. It was not made.

3.1.3.4 The double rack replaces the cylindrical rack: a Hooke joint appears; the cylinder orientation changes

Because of manufacturing difficulties mentioned above, the aluminium rack design was reconsidered. Moreover, in absence of the evaporator, the stem sticking out of part of the cylinder looked neither a safe nor an aesthetically 'correct' design. Therefore, it was decided to use an ordinary straight rack-gear set completely housed within the cylinder. The rack would now be part of the piston rod, while the gear shaft axis would be fixed. The gear shaft would protrude slightly out of the cylinder to connect to the collector shaft. Minding about the 'Needs' in Section 3.1.2 on deployment anywhere in sub-Saharan Africa and the now user-inaccessible gearing, the gear shaft was to be standardized as horizontal, normal to the cylinder axis. Variable slope collector shaft axes for different locations were to be joined to this horizontal shaft with a Hooke coupling. Bi-hemispherical installation was to be facilitated by a double rack-gear set such as shown in **Figure 6**.

This selection of elements would affect the geometry of the mechanism-collector connection of **Figure 5**. Either the collector would have to be lowered, or a horizontally oriented spring-piston-cylinder assembly would need to be raised. The former was considered impractical because a collector-ground clearance must be maintained

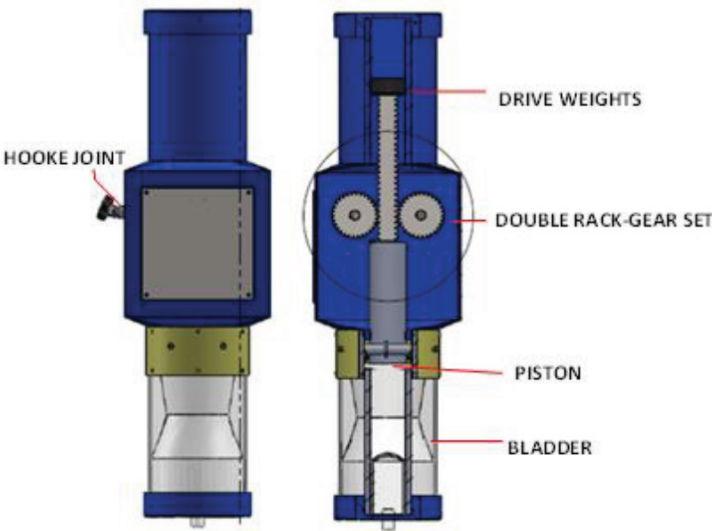


Figure 6.
Reorientation of the hydro-mechanism.

during all phases of rotation of the collector. The latter was considered aesthetically unsound and required more ground space to effect. Therefore, the orientation of the cylinder was now changed to vertical as in **Figure 6**.

3.1.3.5 A pump is introduced: the raised tank is temporarily ignored

At this stage, it was supposed that the 3.5+ m high tank could be installed either on a roof or on a stand provided with properly constructed ladders for filling and inspections. In rural Africa, once about 20 days, the owner or her/his agent would have to climb up and refill it. At the university however, experimentation in the project required a safer and smarter way of filling the tank. The 'Needs' constraints of Section 3.1.2 specified a 'negligible' energy consumption by operation of the mechanism. Since tank filling would be occasional, a small 12 V DC 4 m peak head pump was acquired. Then for experiments, only one tank ('B' of **Figure 6**) would be necessary. The pump would be used to transfer water from this tank to the mechanism. In addition to being safe, this would conserve water since it could be recycled on daily basis.

3.1.3.6 The piston-cylinder part fails: bellows appear: and also fail

The mechanism was now ready for prototyping. The machine elements and components were assembled. First attempts to run it were made in March 2015. Water leaked past the piston. To properly seal the leakage, it would be necessary to reduce clearances. A new piston with an elastomer O-ring was made. Sealing was achieved but friction was excessive. A lot of pump energy went into overcoming this friction. Then in one re assembly, a forceful push onto the piston burst the cylinder. **Figure 7** shows the broken piece. It was now evident that the engineering necessary to produce an efficient and reliable piston-cylinder assembly would easily 'violate' the 'cost effectiveness' constraint in Section 3.1.2, and probably consume more than 'negligible' energy in operation. The assembly had to be redesigned.

Friction between the cylinder and the piston was the main problem in the assembly. It was therefore decided to eliminate direct contact between the piston and the cylinder. Bellows were introduced. One end of the bellow was fixed to the lower base of the cylinder while the other was fixed to a smaller diameter piston. It was supposed that water would progressively fill the bellow segments starting with the lowest, and in so doing, gradually lift the piston-spring ensemble without any significant friction with the cylinder. The first bellow tried was made from

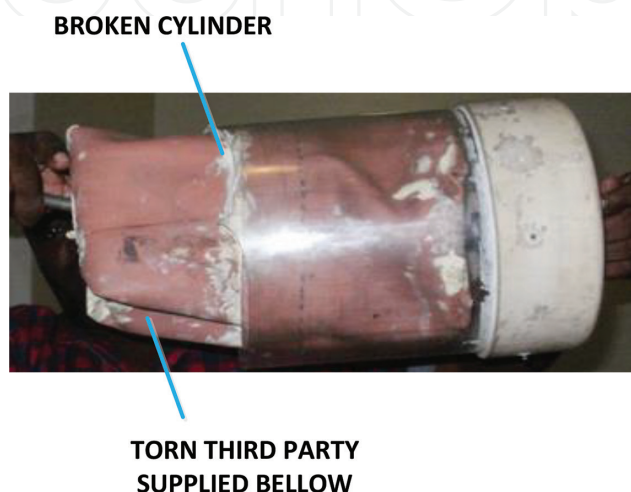


Figure 7.
Example of failure during the project.

a 150 mm diameter heli-steel PVC hose. It was readily available and ‘reasonably’ priced at just below the equivalent of US\$ 5.00 a meter length. It however, failed on trial. When water filled the first segments, they expanded radially before attempting to lift the piston. Even after lift-off, the expansion continued until the steel was beginning to tear out. Attempts were made on using a thicker and stronger rubber bellow made by a local rubber products moulder. It also failed. It was clear that for the bellows to be of use in this project, they would have to be restrained radially—which in the circumstances, was not feasible. They were abandoned, but lessons on need for radial restraint were to serve a breakthrough purpose soon.

3.1.3.7 The bladder is born: the spring works but it is retired; gravity takes over

Bellows failed because they were not restrained radially. Even if they had not failed, it was difficult to tell what would happen to the joints at the base in rural Africa over a prolonged period of intermittent pressurization. It was therefore decided to contain the mechanism water in a flexible liquid sac or bladder that would be completely restrained and protected by a much stiffer, though flexible covering. The active part of the bladder would be an inverted cone frustum grown on a lower normal frustum which in turn, would have grown on a cylindrical portion matching the internal surface and base of the mechanism cylinder. The cylindrical and lower cone frustum would always be with water. Pumping would only affect the upper frustum which would be closed by a permanently joined and sealed piston. The piston would carry a small bleed pipe as shown in **Figure 8**. The primary purpose of this pipe would be to help expel air from the system on first fill.

The bladder and its protective covers were constructed and assembled in the mechanism. The system was then test run. At long last, it was able to reach its design peak compression on 2nd July 2015. But the time to reach maximum displacement was in excess of 2 min. Also, towards that endpoint, the 10.8 W pump was drawing maximum current. The top mechanism end cap was removed so that the mechanism could be filled with water against the spring and piston weights only. It took about 20 s to reach the top dead centre position. On opening valve V2 of **Figure 4** to simulate a day time operation (i.e., rotate the collector East to West), the collector turned the full 180°, but there was difficulty in traversing the mid position. This meant the spring weight (30.2 N) was barely enough to drive the mechanism. However, it had been established that spring force (kx) was not necessary to run the mechanism—and therefore the spring could be discarded to give way to gravity weights. A gravity driven, bladder-flow regulated hydro mechanism for sun tracking had just been invented.

3.2 Case 2: design of a herbal oil extractor for small scale industries

This case study is about a project which started off as one of the many group projects in normal class time, intended to overcome the familiar

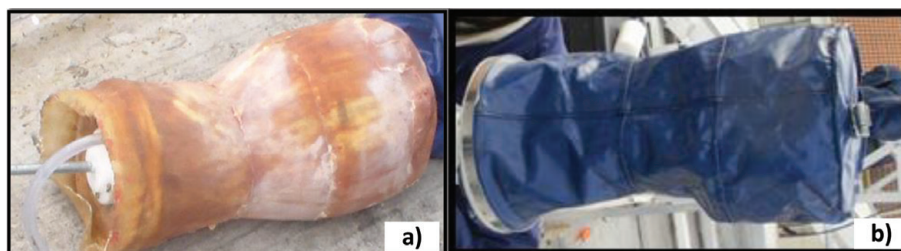


Figure 8.
The prototype bladder: (a) un-protected and (b) when protected.



Figure 9.
A home cottage industry ‘Two speed’ fluids mixer—as designed by MED students left—the assembled unit. Right—the counter-rotating slow speed mechanism (Watch online video at: <https://www.youtube.com/watch?v=VymLqK9DDeo>).

‘analysis-synthesis’ barrier in undergraduate MED. A group of six students had initially been tasked and guided to design and construct a variable temperature and viscosity fluids mixer for a home-cottage cosmetics factory within a period of 6 weeks. The mixer is shown in **Figure 9**. After the project, one of the students was involved in a serious road accident which disabled him, and prevented him from doing the normal pre graduation industrial attachment. To enable him graduate however, he was assigned a new individual design project under supervision of the author at the university. He was to use his experience in the class project, to design (not construct) a herbal oil extractor, again for a home cottage factory. Below is a summary of his design approach.

3.2.1 Identification of needs and formulation of engineering problem(s)

A machine needed to be designed for use in extraction of essential oils from African herbs. A full design with drawings (mechanical, electrical and hydraulic) was to be completed so that students could manufacture and test the machine.

3.2.1.1 Requirements and constraints

- Handles 200 L with 30% spare capacity.
- Filtered liquid product must be extracted separately from the spent herbs.
- The extraction temperature must be between 70 and 80°C.
- Operates on domestic single phase 220–240 V AC power supply.
- Feed herbs are received cut into pieces smaller than 10 mm in length.
- Professional and pleasing appearance
- Students must be able to manufacture all custom designed parts in the CPUT mechanical engineering workshop.

3.2.2 Concepts development and selection

The student considered five concepts as shown in **Figure 10**. He settled for concept number 3 on account of ease of manufacture, minimal heating element corrosion risks, and maximum heat transfer area, thereby reducing heating time.

3.2.3 Detailed design and specifications

Having selected the mode of heating for the herbs, the student laid out the design as in **Figure 11**. Then he did a detailed analysis of the chosen concept in virtual form to give specifications in **Table 3**, followed by detailed engineering drawings of each machine element in the system.

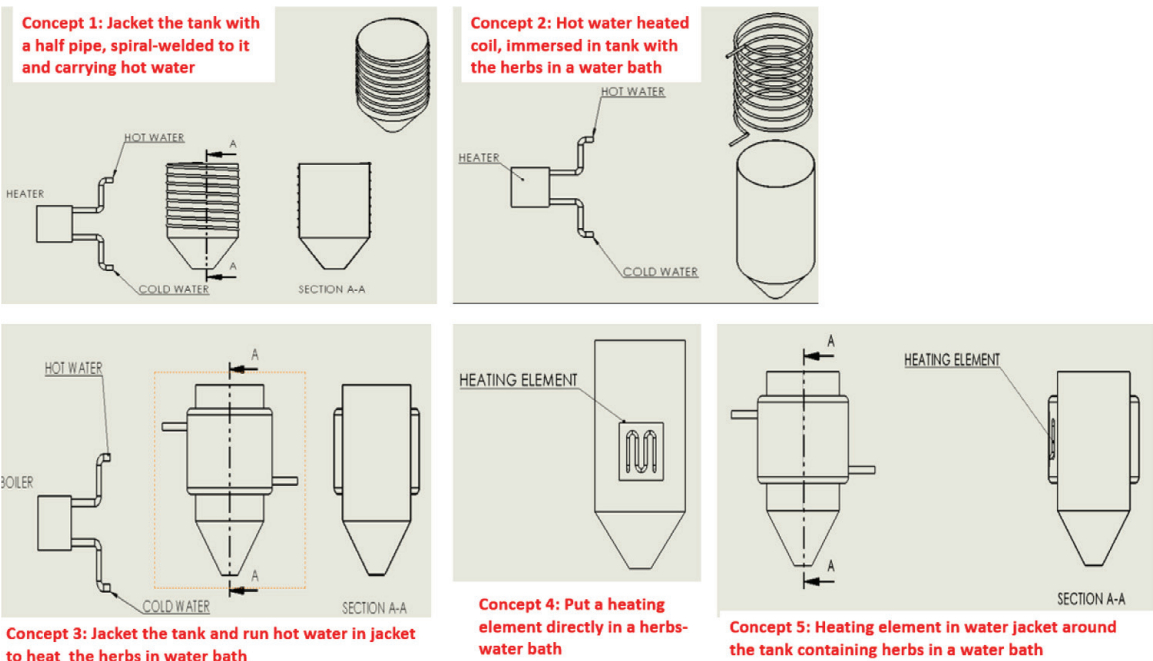


Figure 10.
Herbal oil extraction: different heating concepts [33].

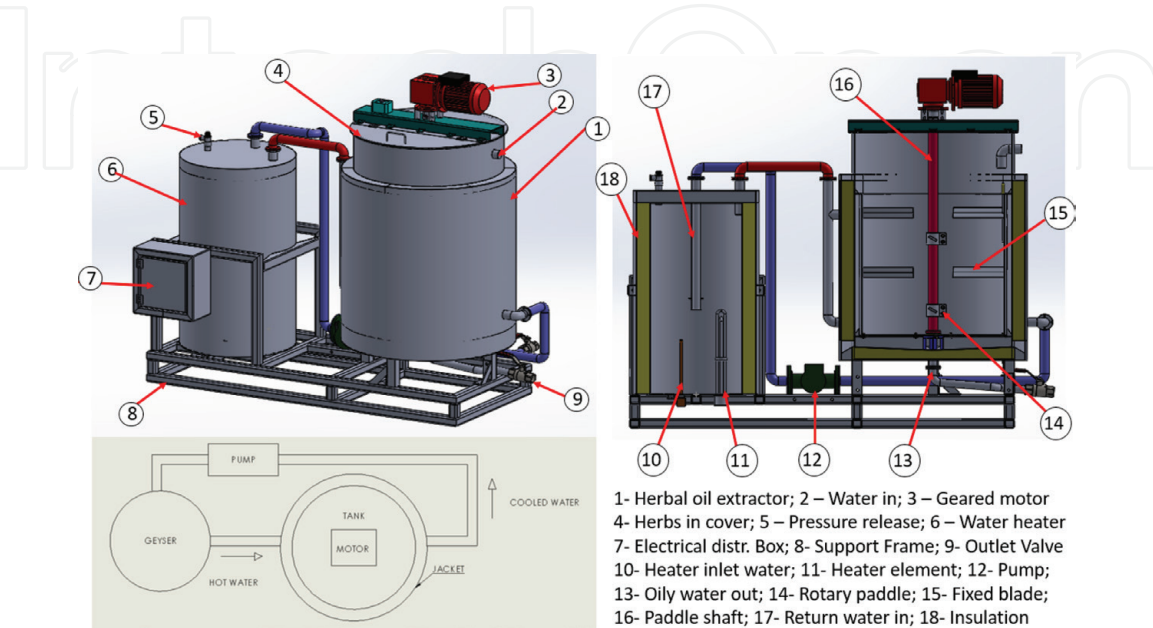


Figure 11.
System layout for a small scale herbal oil extractor.

Overall dimensions (mm)	Height	Length	Width	Power at 240 V AC (W)	Heater	Motor	Pump	Total
	1478	1660	930		4000	180	260	4400
Motor Specs	Type	Manufacturer	Code	Power (W)	Torque (Nm)	Speed (rpm)	Output speed (rpm)	
	Worm geared	SEF	SF37DRK7154	180	70	1450	15	
Heater	Power (W)	Manufacturer	Code	Pump	Head (m)	Power (W)	Max flow (L/s)	
	4000	Thermon	UHRBC14K00350N1		2.75	260	2	
Temperatures (°C)	Heater max.	Vessel max	Materials	Heater	Vessel	Insulation	Frame	
	90	70		SS316	SS316	Thermalite Glass wool	MS	

Table 3.
Key specifications of components for a 200 L herbal oil extractor for a home cottage factory.

4. Summary and conclusion

In this chapter, we have described and illustrated MED from both a classroom perspective and from an industrial one. In undergraduate MED, emphasis is on ability to analyse existing systems. The student is taught MED on a machine element by element basis—and most contact hours are spent that way. There is little room and time to integrate the elements in one worked example or problem. Moreover, those elements from other areas of mechanical engineering, such as in Thermo-Fluids, are normally assumed to be well covered in those subjects. They are rarely given consideration in normal MED class rooms. This is not to mention the even more critical considerations of non-science related issues which, in the first place, are often, the source of problems to be solved by engineering. It has been argued in this chapter that this treatment acclimatises the student to always be expectant of readymade systems to analyse. Even then, understanding how the systems came into being, as answers to specific human needs, can be problematic. This is a disservice to the student and to industry, because the main purpose of MED is supposed to be synthesis of mechanical systems, speaking to the needs of society.

Industry on the other hand, has no choice but to face the design challenge from a problem solution perspective. All areas of knowledge, be they from science, art, or even heuristic and intuition, are brought to bear on the problem. Market, economic, political, legal, social, aesthetic and ordinary engineering constraints are imposed on an inexistent system that is supposed to be created and made. Two largely complementary approaches of doing so were reviewed: the creative, and the rational. It was seen that the rational approach formalises the design process and tends to take care of more constraints a design may be encountering. It is thus advisable, even of creative designers to embrace it. In engineering classrooms, it is without a doubt, the recommended approach.

Two design examples were described in a university setting environment. One was primarily of creative nature, leading to an invention over a long period of time. However, whether consciously or otherwise, it was still tempered with some formality in form of a structured approach between different design stages. The main advantage of this approach seemed to be the generation of other offshoot products arising from apparent failures within the creative process. In essence, therefore, creativity can lead to many other originally unintended, but useful products. The second example was focused on the rational approach—as taught to the author's students. A physically handicapped student was able to demonstrate that he had learned the methodology by designing a product quite related to what he had learnt—and participated in building in class, while still physically fit. Importantly, he demonstrated good understanding of the integrative nature of MED, calling on subject content from diverse areas like Fluid Mechanics, Heat transfer, Electrical Technology, Economics, etc. Moreover, the problem to be solved required him to appreciate compositions of some naturally occurring plants and means of getting useful extracts from them. Such extensive exposure is not normal in MED as commonly taught/learnt.

To conclude the chapter, it could be said that—although the traditional approach of handling MED is helpful in so far as it breaks up the subject matter into smaller, easier to learn, topics, it makes it more difficult for students, and possibly academics, to apply that knowledge to solve real life engineering design problems. This author recommends a mixed approach whereby, early on in the study of MED, the current topic-based system is used but a formalised needs-driven design approach is gradually introduced until it becomes the dominant approach by the time the student is finishing her/his MED subjects. **Table 4** summarises the salient differences in approach.

It is to be understood here, that we are not talking about the final year design project, typical in many engineering schools and faculties. No—it is the timetabled MED we are referring to. The new approach not only works, but it produces tangible results as demonstrated in this chapter. It should therefore, as much as possible, be adopted.

	Traditional	Proposed
Content	MED as extension of Engineering Science Low involvement of issues in Humanities	MED as new body of knowledge, using GEPs*, Design codes, catalogues, standards, etc. Elements from Humanities primarily drive most of MED and even, regulate it
Modelling	Simplified mathematical models and physical science phenomena	Mathematical and non-math models to deal with science and non-science constraints in design optimization
Learning	Study of independent machine elements	Less time on independent elements, but more on their interdependence in an assembly
Design process	Element to assembly design approach (down-up)	Assembly to element design approach (top-down)
Emphasis	Engineering and scientific novelty	Problem solution as simply, safely and economically as possible
Outputs	Engineering drawings	Working models and/or prototypes

*Good engineering practice principles

Table 4.
Summary of differences between the current and proposed MED teaching approaches.

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Conflict of interest

The author’s interest in this, and other related work, is driven by an insatiable desire to make students realise that by their last year of undergraduate study, they can already have an inner ability to start contributing to make their societies live better now, and not wait for tomorrow.

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