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Transformative Teaching of Engineering in Sub-Saharan Africa

Kant Kanyarusoke

Abstract

This chapter advocates transformative teaching in later stages of sub-Saharan Africa's engineering students' study periods. The teaching is meant to help them discover their potential in direct solution of the region's engineering problems. Student attention can be drawn to many of these problems through transformative teaching. Two illustrative case studies are presented. They demonstrate how students at one South African University of Technology were enabled to address common, authentic and 'real world' problems in the course of their learning. A review of theory of teaching modes is given first, with more focus on transformative teaching. The cases follow. The first case seeds a maintenance and continuous improvement culture among successive student cohorts, eventually producing an evolved new product ready for the market in a period of about 5 years. The second case uses multi-level, multi-national students, deploying multi-sourced funds and working at multi-premises in difficult campus study circumstances, to develop completely new products that are field-tested at two sites about 6000 km apart. Benefits, limitations and challenges of the teaching and how to navigate the latter, are given. Following its substantial benefits and the ways to overcome its challenges, transformative teaching is recommended to all engineering academics in the region.

Keywords: continuous improvement, engineering education, sub-Saharan Africa, transactional teaching, transformative teaching, transmission teaching

1. Introduction

As an adult transformative learner and educator, I will introduce this chapter through some questioning. Is it right, that in a region with one billion people [1], 619 million of them [2], should in this 21st century, be in total darkness at night? And that over 300 million [3] should be sharing watering holes with both domestic and wild animals? That is rural sub-Saharan Africa. Now, let us leave the rural areas—from where many urban people, including this author, originate, and still have relatives and homes. Is it nature-ordained that people can live in filthy, crowded and 'man-made' disease prone areas [4–6] without any local educated person doing something about it—either out of philanthropy or out of pure business sense? We go on: Why should a country of 40 million people claim to find substantial crude oil or other mineral deposits, and yet, take a generation or two [7] to get the first extract from underground? Let us come to engineering faculties: **Figure 1** shows part of a 2-year-old engineering faculty building at one of the region's leading universities. They teach Maintenance Engineering at this university. Why should the building look as shown?

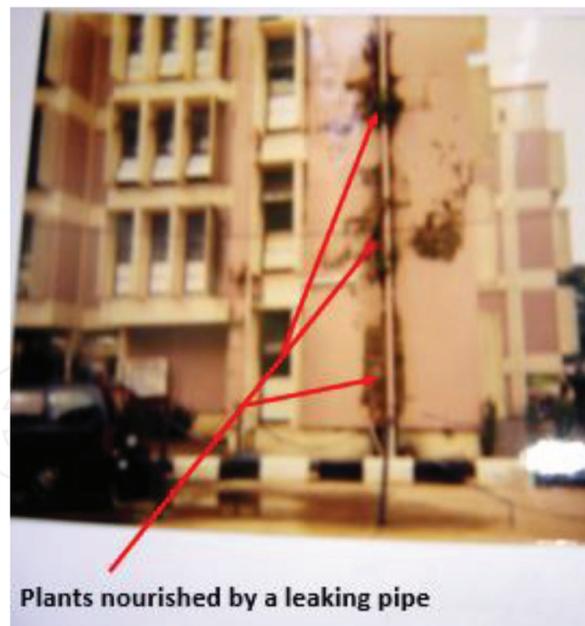


Figure 1.

Part of a 2-year-old engineering faculty building at one sub-Saharan Africa's university (author).

Different explanations for these rather awkward questions have been presented by different people and interests at different forums (e.g. [8–11]). They have included malaria, poverty, slavery, colonialism, dependency syndrome, lack of technology and knowhow, poor governance, etc. Almost anyone can come up with an explanation—provided that explanation excludes her or himself. It is not the intention of this chapter to take that route of exclusion. Nor is it that we should delve on the explanations much longer. Rather, as an engineering educator, I take a pragmatic approach and advocate owning up part of the responsibility to change the status-quo. This is because, whichever cause, or combination of explanations others give, nothing will change, unless some people with engineering knowledge and skills get up and try to do something. It has been said—rightly or wrongly—that Africa is not short of good or bad analysts, advisers, and even policy makers. In only 3 publications [12–14], for example, one can identify not less than 27 advisers and analysts. What the continent is most short of, are thoughtful doers that can transform its resources locally, to benefit its residents first, and others, next.

Therefore, this chapter on transformative teaching is about practice change in sub-Saharan Africa's engineering schools and faculties. It draws on a literature survey and experiential work in 4 universities in Eastern, Western and Southern African countries to show that the current dominant mode of teaching in the region's engineering faculties and colleges is not transformative. For reasons ranging from faculty expertise, to facilities, to student and national politics and economies [15], current higher engineering education practice in the region still heavily relies on transmission teaching. This chapter suggests changes to this practice, particularly during later semesters of students' studies. It illustrates the changes with detailed descriptions of two examples from the author's practices over the last 8 years. The examples tackle some of the questions posed above in a more direct way. Specifically, it illustrates how transformative teaching is being used to address 'real-world' authentic problems. The main thrust of the chapter is that even within limited resources and in relatively difficult environments, a thoughtful engineering educator can enable students to think and act proactively on problems faced by their societies and which are initially thought of, as intractable.

It is acknowledged that most African students coming into engineering faculties and colleges have, in their high school days, been conditioned to

non-transformative learning. This is because many schools' interests are more on percentage pass rates than on deep understanding (e.g. see [16–18]). One of the first steps for an engineering educator, therefore, is to transform the thought and attitudinal processes of the students in regard to learning itself. Secondly, these students have usually not had much practical work, either in Physics laboratories or in engineering workshops. A result of this is that they come to engineering with a bias towards theoretical analysis. Also, they have a deficit of practical and of 3-dimensional visualisation skills [19, 20]. The second stage in their minds-transformation, therefore, is to be nurtured into engineering as a practice—based, tangible results oriented activity, needing multidimensional thinking. Accomplishment of these two stages is not transformative teaching yet. It is a prerequisite though. We discuss transformative teaching in Section 2 and tailor it to the need for physical engineering changes in the region. This prepares the ground for illustrative case practices in Section 3. One case addresses the maintenance question. The second one, tackles multiple issues using potable water and energy sourcing as a two in one example. We discuss key results of the case studies and show opportunities and challenges to effecting changes in Section 4. Finally in Section 5, we summarise the chapter and conclude with a recommendation for implementation of transformative teaching in the region's engineering classes. The originality and value of this chapter is that it illustrates how an engineering educator on the continent could use meagre resources to make a start in transforming both the students' learning and the continent's engineering approaches to solve its problems.

2. Transmission, transactional and transformational teaching

In this section, we make a brief review of the three modes of teaching commonly listed in the literature. The purpose is partly to give a theoretical basis for the case studies in the next section, but more importantly, to create a clear understanding of where the students in the cases are coming from.

2.1 Transmission teaching

In Transmission teaching, the teacher acts as an 'all knowing' individual, passing knowledge and/or skills to attentive, receiving students [21]. Typically, the teacher sources delivery content from a prescribed textbook, often with help of an instructor's manual, and then talks or writes or demonstrates to the students what the source says. Ref. [22] points out, transmission teaching is rigid and mechanistic, bordering on being robotic. This means, the quality and real value of a human-teacher in this mode is badly degraded, and therefore, that it matters less, what kind of teacher is available to handle the class. On the learner side, according to [23], it encourages passive learning, with the students, thinking all there is to learn is what the teacher has transmitted.

Yet, transmission is the simplest and most convenient mode of handling large classes say, of 100 or more students. And through its amenability to use of standardised teaching and learning materials it has been the choice mode of teaching at primary, secondary and high school levels in sub-Saharan Africa (e.g. [24–26]). In almost all countries, this period is up to age 17–19 for a non-repeating learner. The mode is convenient at these levels partly because of age, but mainly because of the national examinations held at ends of each of these levels. In countries like Uganda [27], Ghana [28], Gabon [29], DRC [30], etc., pupils must first 'pass' these exams satisfactorily before going to the next level. In those countries attempting universal and compulsory primary and secondary education like South Africa, Botswana,

Uganda, etc., government financing pressures are forcing an emphasis on fast throughputs, and thus, both schools and pupils are exploiting the weaknesses of a transmission system through what is commonly called ‘spoon feeding’ and ‘spotting’ to pass, and eventually come to university. ‘Spoon feeding’ means the teacher literally tries to do whatever is possible for the pupil, leaving almost nothing for the latter to develop her/his thinking and study faculties. Spotting means the teacher tries to make intelligent guesses of what the national examiners will ask, and then focuses teaching effort only on that.

To summarise, many students coming to university or to engineering colleges, have had almost all their learning times subjected to a transmission type of teaching. A majority have been silent listeners in class, and it should not surprise us that this silence and passivity should be carried forward to our engineering classes. Likewise, the other habits of expectations to be spoon fed and to be told of scopes of assessments are brought to our classes. It is the calling of a conscientious engineering educator to wean them off those expectations and nurture them into a new world of self-driven enquiry, innovation and creativity. Particularly, for the region in question, this is critical because of its level of underdevelopment, limited financial resources, and scarcity of technical personnel at all levels of engineering in each country [30]. Transformative teaching, as described in this chapter’s case studies, is intended to demonstrate this nurturing and its potential effects on the wider society outside the universities. However, it requires that the students have matured a bit in their engineering thought and practices so that they can have something to reflect on and challenge. This necessitates a transition through transactional teaching, which we briefly describe next.

2.2 Transactional teaching

Transactional teaching deviates from transmission in sense that, the students are more engaged in physical activities that enhance their exploration of knowledge. They are exposed to experiences that enable them to learn through direct discovery and through sharing of these experiences among themselves and with the teacher. The teacher’s principle role in this mode is to manage the learning. Ref. [31] advises and demonstrates through a case study on a class of teacher educators, that this mode of teaching is highly reflective: starting with the planning of activities the teacher will get the students involved in, availing the resources, space and support during the activities and report backs, and finally in interpreting the outcomes of the activities and how they may have been evidence of achievement of the desired learning outcomes. The basis of enhancing learning through this mode is according to Dewey, extensively cited, in [32], similar to Darwin’s evolution theory, in which constant interactions with an environment causes organisms to develop features that sustain survival in that environment [33]. In other words, student constant exposure to carefully planned and executed practical experiences will tend to lead to natural adaptation for learning and retaining lessons from those experiences longer.

For the kind of student received in many African engineering faculties, i.e., one who has not been exposed to much engineering, or even, to normal physics practical work previously, and who, during most of the past study time, has been used to transmission teaching, the reflective part of the teacher, should help design activities to wean this student. Therefore, transactional teaching in the region’s engineering faculties could be looked at as a first step in reorienting the study styles of the students. But as this chapter is about transformative teaching, and as the students in the cases of Section 3 are towards the ends of their studies, we will not pursue transactional teaching beyond this point. Interested readers can refer to the works in Refs. [34–38] on the mode.

2.3 Transformative teaching and learning

In the first part of this section, we will describe and relate transformative teaching to the case studies described later. Then, in the second subsection, we will outline methods of using it.

2.3.1 *What is transformative teaching?*

In the literature, many writers (e.g. [39–45]) present transformative teaching as directed to adults or to people who have had previous experiences that shape their current viewpoints and outlooks on existing situations and issues. It then seeks to help them change those viewpoints presumably, for improvement of their understanding of the issues and situations. It was best championed by Jack Mezirow in late 1980s [46, 47], but two other thinkers, Robert Boyd [48] and Paulo Freire [49] made useful circumstantial contributions. Mezirow postulated what is called a perspective model of transformative learning. Here, the learner confronts a dilemma which requires her/him to critically examine and question pre-existing assumptions and beliefs. These assumptions are typically stereotypical and embedded in either culture or norms of a society. In most of sub-Saharan Africa engineering faculties, an example could be that ‘engineering is a male’s profession’ or ‘women are better off in industrial and chemical engineering than in mechanical and civil engineering’. Both case studies demonstrate that female students in Mechanical Engineering can be enabled not only to find the area interesting, but that they can also be very useful and motivational members of engineering teams. An even more striking belief the author had to confront among his industrial workers in Uganda, East Africa at the close of the last century, was: ‘new production machinery needs blood sacrifice to be installed properly’. Here, the belief was turned upside down to motivate peak performance during installation by promise of a big celebratory ‘bull roasting’ after—*not before*—successful installation. A similar approach of promises for, and actualisation of, celebrating engineering project successes, has since been used in student projects to motivate maximum learning effort.

Boyd introduced the analytical model of transformative learning. Rather than focus on society beliefs, this model pushes the learner to re-examine her/his inner self to seek personality changes that will enable solution of the problem on hand. The learner tries to identify traits, personal behaviours or previous own long term effect experiences that may be impeding understanding or performing the current task. In the case of the author for example, three entire household item losses in his childhood due to fires in grass-thatched homes, had left a semi-permanent impression on him by the time he came to study engineering. So, when it came to materials selection in Machine Design courses, wood/timber and many other easily combustible materials were treated as off limit. That is—till he had to supervise an undergraduate student who could only cost effectively accomplish his final year project using timber, as a machine frame material [50]. May be, as we will see later in the chapter, this impression mildly lingers on, because the decision to focus his research on solar energy engineering, and use solar energy systems in his current non grass thatched village home(s) was partly to do with their safety.

For the intellectual class in Africa, perhaps the most appealing mode of transformative learning is the so called ‘Emancipatory’ model, introduced by a radical Brazilian intellectual, Paulo Freire. The model looks not just at individuals, but at whole societies and socio-political-economic systems that keep some of these societies less developed than others. The teaching is then meant to help learners to critically examine these systems and change attitudes, approaches and actions so that they may work for a more equitable society. In the opinion of this

author, while some of this may look extreme, there is merit in questioning the current world economic order and the so called laws that regulate it. For example, the 'law' of comparative advantage [51]: each country or society producing what it does best, and buying everything else from countries that produce those other goods better. What if—as happens in Africa—a country's best output is of low value: how will it ever raise money to buy the other goods of higher value? The answer is partly in Engineering, and partly in rejecting that comparative advantage law. Countries need engineering to convert resources within their borders into useful products for their people and for others outside who may need them. But development of engineering skills and of top quality products is a dynamic process requiring time. In that intervening time, it is absolutely essential to identify, or even to create, local and external captive markets that can take the evolving products at the prices the captive markets can afford. In Section 4 of this chapter, we will find that this is one of the main things the author tries to sensitise his students about.

2.3.2 Elements and methods of transformative teaching

Mezirow listed 10 stages of transformative learning as in [52, 53]. Briefly, they convey three themes: a recall of past experiences; an unbiased critique of those experiences in light of the present situation; and a rational change of course of action in a new dispensation. To facilitate these, Christie et al. [54] advise that transformative teaching involves doing the following:

- Creation of targeted experiences for students, so that they can reflect on the past
- Melding the art and science of a problem, so that all its features can come to the fore
- Creating an enabling environment so that students care and take charge of their learning
- Modelling symphonic thinking so that students can create a more holistic and balanced solution
- Facilitating productive struggle, so that the students will appreciate and value the solutions and learning better.

How are these actions done? Slavich and Zimbardo [55] outline a method the author prefers to use for the reasons given in each step as:

- First, communicate and share the vision of the course with the students. This creates a shared mission, and common objectives, making the students feel you regard their eventual success as yours too.
- Then, provide unquestionable mastery experiences in what you are teaching. This creates authenticity.
- Give intellectually challenging assignments and motivate the students along the way. This helps them to learn deeper.
- Personalise attention and feedback. This makes each student feel noticed and valued.

- Provide experiential work outside the formal class room and times. This creates some realism on what is being done.
- In all these steps, encourage students to reflect on the work so far, and perreflect (i.e. imagine what final solution they envisage). Particularly at the one on one feedback interaction, let them share their learning experiences. This provides an opportunity to redirect the learning if there is need.

In summary, transformative teaching should enable students master the particular topic/assignment to the extent that the knowledge and skills so gained, are irreversible. We will not go into the details of the theories behind this irreversibility but they are listed in [55] as: Piaget's constructivism [56]; Vygotsky's social constructivism [57]; McGregor's Transformative learning [58]; Bandura's social cognitivist [59]; Boyatzis' intentional change [60]; and Bass' transformational leadership theory [61]. We will now turn to the case studies demonstrating this transformative teaching.

3. Case studies

We started this chapter with a set of questions. Although any other question could randomly have been asked, these particular ones were not. They do reflect some of the issues the author tries to address with his students. In this section, we will illustrate two different cases: evolution of water purifying system case study that addresses both energy sourcing and clean water generation at rural home level; and development of a maintenance culture as early as possible in the students' engineering professional journey. The latter case is entirely at undergraduate mechanical engineering level, but it includes research and action elements in non-engineering areas. This is to help the students uncover the totality of the project assignment because the system they work on must in the end be saleable or actionable. The water-energy project is more complex. It is a multi-level project by mechanical engineering students. National diploma, Bachelors, Masters and a Doctoral student are involved. In addition, it is intentionally made pan Africanist in sense that the post graduate students are required to consider elements that would be helpful in their countries of origin. The countries represented are: Angola, DRC, Gabon, Lesotho, Libya, Mozambique, Namibia, South Africa and Tanzania. The lecturer, who in this case, is the overall project manager, is from Uganda, East Africa. We will start with the relatively easier one.

3.1 Case 1: maintenance of engineering systems

This case study illustrates an approach the author uses to inculcate a maintenance conscience and activism among his students, even though he does not teach 'Maintenance Engineering' as a subject. First, a brief background and rationale for the approach is given; then, the approach is explained and illustrated. Some results of the approach are given at the end. The discussion on challenges and opportunities from this approach is left to Section 4, where it is handled with those from the second case study.

3.1.1 Background and rationale

Engineering systems have a life cycle, almost similar to that of natural living things: they are created to perform specific functions; they need energy, other utilities, and physical and mental inputs to operate; they need to be cared for because

they also can ‘die’. After ‘death’, their constituent parts can be recycled for use elsewhere, like for any natural living thing. However, they are incapable of reproducing themselves in ways that normal living things do. In Africa, the problems about these systems start with inadequate understanding of their very nature, through their creation, operation, all the way to, neglect of their recycling possibilities. For example, while Africa’s modern infrastructure systems were initially designed and constructed by Europeans [62], today those roles are increasingly being taken over by Chinese and Indians [63]. It is only bits of operation and maintenance which are in hands of the few, yet, inadequately trained and underfinanced African engineers and technicians [64]. Against this background, is an engineering education system that:

- Is rooted, and is still stuck in old Europe: uses old Europeanised syllabi, European textbooks and is taught by Europe/America trained academics, usually without any form of industrial practice exposure [65, 66]. This may seem to be partly fine—until one realises the following: one—new Europe/America are changing their curricula to emphasise more practical work to match demands of the times (in Europe/America/rest of developed world) [67, 68]; two—European text books are expensive, well beyond the means of most students in Africa. Besides, they lack examples, literature and data, which African students can easily relate to for ease of understanding [69].
- Is elitist and theoretical. It influences students and graduates to expect only white collar office jobs in industry. They hope to find industry, full of artisans and craftsmen, whom they can supervise and direct to do manual, blue collar work. Yet, industry is in shortest supply of these [70], because by nature of national reward systems, it pays non artisanal work better [71]. This has direct impact on maintenance of systems because they require hands-on people.

The effect of the above two points at universities and colleges, is that the ‘Maintenance Engineering’ syllabi are designed to emphasise the theoretical aspects only. **Table 1** is an example of one semester course content(s) at two different universities on the continent.

It is seen from the table that the contents at these universities are biased towards management and analysis. In a situation of insufficient numbers of technicians, fitters, electricians, painters, etc., as happens in the region, it can be asked: whom will the technologists and engineers trained at these universities manage—to do the actual physical maintenance? Needless to say, this negatively impacts on the lives of engineering assets and increases the cost of products and services in the region.

Topic number	University no. 1	University no. 2
1	Business strategy	Maintenance structure
2	Theory of management	Maintenance management
3	Maintenance planning	Statistics
4	Maintenance management	Reliability centred maintenance
5	Maintenance costing and economics	Investment decisions
		Computer methods
		Tribology

Table 1.
Course contents of maintenance engineering at two universities in sub-Saharan Africa.

The rationale and originality of this case study therefore, was to nurture students into a hands-on maintenance approach which, for some, complements the theoretical grounding they receive in ‘Maintenance Engineering’ courses. I say ‘some’ because at many universities—including the above two, this subject is taken as an elective at undergraduate level. The other objective was to sensitise students about financial and non-financial costs either of not maintaining or of outsourcing maintenance work that could be done in-house. An offshoot objective was to enlighten them on opportunities available in taking maintenance as a business proposition for serving those members of society who, for one reason or other, do not do their own in-house maintenance.

3.1.2 Methodology

Basically, the students are assigned team projects during their final semester as part of either their Applied Thermodynamics or of their Mechanical Engineering Design courses, handled by the author. The former, deals with thermodynamic devices such as Boilers, Compressors, Engines, Refrigeration systems, Heat Exchangers, etc. The latter deals with design of machinery through choices of appropriate materials, manufacturing processes, machine elements and devices to make safe and functional complete mechanical systems that do a specific task. Here, we illustrate a case of solar water heaters, in which, different teams of students in both subjects have been involved over the years, since 2011. The project started off like that described in Case No. 2 below, as a design one. It has since, evolved as an on-going maintenance and reengineering project in the compound at entry to Mechanical Engineering building of the author’s university. Its organisation, conduct and assessment are similar to all others used by the author and are fully described in [72]. We shall now show the successive major steps it has gone through since inception in 2011.

Inception: The start was by a survey of available solar water heating systems in Cape Town and their corresponding prices.

Subsequent work: The lecturer discussed the above students’ report with subsequent teams of Machine Design students. Then, he instructed the teams to design and construct 1 m² solar collectors, their stands and tanks. They were also to compare the manufacturing materials costs with 30% of sale prices reported in the previous report. If found to exceed this level, they were to suggest changes in design that could be done to keep costs within target.

Figure 2 shows the students at work, and their initial finished products.

Reengineering of the initial designs: subsequent teams of both Thermodynamics and Machine Design were guided to refine these initial designs every semester, as part of an on-going maintenance program. At one stage for example, two Thermodynamics teams were assigned to change the sun tracking system from manual to electro-mechanical, and test their design changes for a period of 1 week. In addition, they were to make presentations to Mechanical Engineering academic staff at the end of the semester.

The students reengineered the systems successfully, changing from wooden frames to weather resistant aluminium ones. They also incorporated mechanised sun tracking in the systems. Thus, by doing so, they had been guided to learn that maintenance is not simply a ‘repair’ or a ‘prevent failure’ activity. But that it could also be a ‘continuous design improvement’ activity. This is an extremely important lesson for present day Africa, where most engineering systems are originating elsewhere.

Emergency repair maintenance: one morning in early winter of 2015, the polar tracking collector was found blown over by a night storm, unlike its counterpart azimuthal tracking unit. **Figure 3** shows a photograph of what we found in the morning. Students had not yet been assigned the semester’s projects. Immediately, however, a team of 8



Figure 2.
Students in the workshop and their finished products in the Mech. Eng. Dept. compound.



Figure 3.
The blown-over solar collector (left) and the author inspecting the repaired system (right).

Machine Design students requested to repair the installation as their semester project. They were assigned the repair project, but with additional instructions to consider whether, in light of longer term weather data, available at the department's weather station, it was necessary to re-examine the designs of both systems. Additionally, they were to cost their repair work, including their labour at assigned hourly rates. They successfully repaired the system, as in the second part of **Figure 3**. Costing was correctly done and useful observations on the installations were made.

3.1.3 Illustrative results of the case study

There have been many good outcomes of this particular case study and of others, related to in-house maintenance of systems. Those to do with student performance evaluation and team workmanship were described in [72, 73]. We will not repeat them here. We shall mention three others as follows:

- Student learning—the students were exposed to, and did use, different areas of knowledge and skills to supplement their normal mechanical engineering knowledge base. In particular, they learnt to: cost materials and labour; use and program electromechanical and electronic circuits to obtain desired mechanical motions. This was a result of the purposeful attempt to 'meld art and science' and of 'modelling symphonic thinking' mentioned earlier in Section 2.3.2.

Such width of exposure on one specific problem in engineering classes is better facilitated by transformative teaching than by any of the other types.

- Development of entirely new ways of installing and using solar syphon systems. To the limits of the author's knowledge and research, nowhere else in the history of solar water heating, have we had such a concerted approach to sun tracking of these passive heating systems. Ref. [74] gives a more detailed account of effects of these efforts. Again, we see that transformative teaching, through its requirement of 'productive struggle', when consistently applied to solar siphons, was responsible for development of innovative installation methods, which could not ordinarily be achieved using the other types of teaching.
- Industry-faculty cooperation: the routine (semi-annual) sending of student teams to industry during academic term time for consultations and/or assignments as opposed to during scheduled experiential training, has developed good will and cooperation between industry and faculty.

3.2 Case 2: solar water purification using multi-level, multi-nationality teams

This case study is primarily about sensitising students to address the water and energy twin problems of rural and semi urban sub-Saharan Africa. But it was designed to do a lot more than that. Recognising the shortage of artisans in the region, and knowing that it is impossible for engineers to transform natural resources for service of society without artisanal and technician skill support, the case illustrates efforts at imparting some of these skills among all students irrespective of level. That notwithstanding, it also simulates a real workplace environment in which administrative hierarchy is generally structured. This is easiest at a University of Technology, educating and training most of the categories of the engineering profession. Hence, in this section of the chapter, we first give a brief justification of the approach. Then, we explain and illustrate it. Finally, we give some results from using it so far.

3.2.1 Why multi-levels, multi-nationalities on one 'student' project?

In industry, every challenging engineering project involves the following activities: Abstract thinking—i.e. visualising, contextualising, interrogating a specific need for society or for individuals, and formulating (an) engineering problem(s) from that need. This is normally best handled by long experienced senior engineers who are able to seamlessly interact with other engineering and non-engineering professionals or leaders to fully comprehend the—often non-technical—need and reformulate it into a solvable engineering problem. After problem formulation in engineering terms, other engineers, including specialists, apply their knowledge, skills and competencies to work out (an) appropriate engineering solution(s). Technicians are then assigned to implement the solutions through the artisans they supervise. Each solution normally requires multiple crafts. Worldwide, in non-highly automated establishments, the generally expected ratios of these professionals to accomplish a large scale, transformative project are of the order of 1 engineer to 4 or 5 technicians to 20 artisans [75]. **Figure 4** is a graphical representation of this pyramidal line organisation.

It has already been said that many engineering students expect, and do want, to work near the apex of this structure, without realising that their real world pyramid base is very narrow, or even that they need time to build competencies and change attitudes to work near the apex effectively. Therefore, one of the necessary steps in transformative teaching of these students ought to be an involvement in a real life project for which they can be held directly accountable. This forms a key feature of transformative

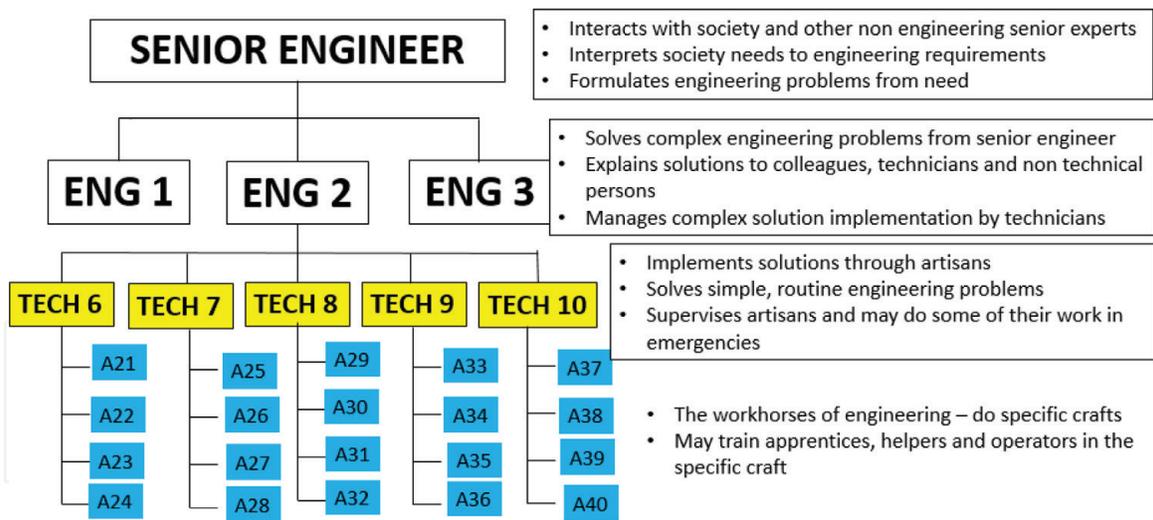


Figure 4. Typical organisation and roles in an engineering assignment: A—artisan; tech—technician; Eng—engineer.

learning: that of encountering, and being required to solve a problem they would never ordinarily meet in class, because of difficulty, time and other resources limitations. As pointed out in [72], failure to accomplish the project cannot be an option. As mentioned earlier in Section 2.3, other factors to facilitate transformative teaching include: creation by the teacher of an atmosphere of learners safety, open-mindedness and mutual trust both among themselves and with the teacher. The teacher needs to behave as part of the team but in a leadership and “provocateur” role, providing direction, where there seem to develop a gridlock. This is especially important in engineering design practice problems, where apart from functionality of products, consideration of conflicting requirements on costs, quality and safety are almost of equal importance. This means, all necessary knowledge, skills, competencies and attitudes have to be marshalled and deployed in the projects. It is the reason why projects like that about to be described in Section 3.2.2, are necessarily, multilevel; i.e. they involve: a senior engineer (the lecturer), engineers to be (post graduate students), technologists and technicians (bachelors and diploma students), and artisans (all the above 4).

A typical university of Technology in South Africa outputs all but one of the 4 levels of engineering professionals. This is why the author’s projects demand that the artisan level be infused into all levels. The second reason for the infusion is that after graduation, the students will find no sufficient artisans in the field, and therefore, will on certain occasions have to do the artisanal work themselves.

The projects use multinational, multicultural teams, partly for the simple fact that the particular university has students from many countries, especially those in the southern half of the African continent. More importantly, different nationalities and cultures can bring new dimensions and solutions to the problem on hand. For example, the fact that in some African cultures and countries, women are the ones expected to fetch both water and firewood, and still prepare meals for the family [76], brings passion and urgency to solving the water-energy problem in a team containing students from such backgrounds. The other factor necessitating a mix of nationalities is that the fundamental problems needing most attention are virtually universal across the continent. They are not specific to particular peoples or areas. For a continent where racism, xenophobia, tribalism and other man-imposed divisions are still factors that can bar access to social, economic and political opportunities [77], transformative teaching needs to bring this fact to the fore: that as humans living anywhere on the continent, largely not by choice, our fundamental existential interests are the same, and therefore, we need to cooperate across these artificial barriers to satisfy the common interests.

3.2.2 The approach

We will now describe the rest of the approach in this case study.

Inception: the water purification project is one of two projects which started as an off shoot of a failed solution in the author's 2012 solar-thermal-hydraulics design of a mechanical sun tracking mechanism invention [78, 79]. The other, was solar crop drying [73, 80]. One of the first motivational pieces of advice all students on these two projects receive, is that: 'in engineering design practice, even a tried and tested failure is a success'. This is meant to transform their attitudes on fears of taking initiative to transit from being analytical theoretician designers, to reflective pragmatic designer-doers, needed by the continent, as pointed out earlier, in Section 1.

An evacuated water evaporative chamber had been required. It was actually designed and constructed. Water was supposed to boil at very low pressure so that steam could rise up and be routed into a raised, shaded condensation tank. Yes, boiling was achieved, but two practical problems had arisen. One was that steam began condensing way before entry into the tank and therefore, water was dripping back to the evaporation chamber. Secondly, it proved impractical that the high vacuum necessary for low temperature boiling could cost-effectively be maintained by users in the field. The designed, constructed, and tested unit was therefore abandoned. As other completely different approaches were being tried, the issue was what to do with the materials of the abandoned unit.

First designs: meanwhile, the observation of rapid evaporation using solar energy in the unit and a recollection of rural Africa's potable water needs led to formulation of a new problem as:

"Design and construct a solar water purifier for rural areas".

This was passed on to a Master of Technology student from Gabon, Central Africa, with the proviso that initially, she would have to work with a team of 6 diploma students for one semester. She designed a model, passed the design to diploma students, and together as their leader, constructed and tested the model. The diploma students left. She used the results to make a fresh prototype design, which she had computed to be big enough to serve a small African home of 4 people with drinking water only. She now worked with one student doing in-service training under the author's overall supervision in the university workshop. They constructed the prototype, which she tested again, and mathematically modelled to complete writing her thesis in November 2014. Details of her work are available in [81].

Reengineering amidst problems: the pioneer prototype was not producing water at design output levels. It was bulky and heavy at 42 kg. The designer, in her thesis, had made recommendations on improvements. These were tried out by a subsequent MEng. student, also from Gabon. Together with another group of 6 diploma students in first semester of 2017, they managed to reduce the weight to 28 kg. Performance was increased by 13% on a per m² basis, but by over 20% in actual output due to a bigger size. Both lecturer and student thought, more could be done. But there was a student strike at the university in the second semester of 2017. To press the point that as a targets-driven engineer to be, the student should always endeavour to push on, amidst difficulties, Design and Production were shifted to an outside campus workshop, where the student now had to work with an intern from DRC on experiential training and with other people of varied nationalities. Eventually, two completely new designs were developed, with one weighing 9.8 kg and the other, 15.6 kg. Full-fledged scientific tests were done at the university in semester 1 of 2018 during late summer and winter seasons. Most of this work is reported in [82, 83].

3.2.3 Interim results

As far as this particular case study is concerned, the following are the key, previously unreported results of transformative teaching:

- *New products*: functional, and value for money solar water purifiers can now be made available in a region where they originally were not. This is a major achievement, although, more still needs to be done.
- *Continuous improvement*: as already implied in Section 2, at the heart of transformative teaching is a cultivation of a constant urge among learners to seek improvements of a current situation by questioning premises that may have led to it. One of the two designs developed above, was made to larger commercial size and in April 2018, transported from Cape Town to the author's rural home in Uganda, East Africa for field consumer tests in an equatorial climate. **Figure 5** shows the installation. By July 2018, this unit's daily output had not yet reached the design 5 L (which it was achieving in Cape Town) owing to daily cloud cover. Therefore, at the time of writing this chapter, one Doctorate student has been identified, assigned and started not only to solve this cloud cover problem, but also to extend production deep into, if not across the night.
- *Student interest in postgraduate work*: there has been an unprecedented rise in numbers of students wishing to undertake postgraduate studies with the particular lecturer. From an average of 2 MTech students a year in the early half of the decade, to a current 10 Masters and 2 doctoral, with others being channelled to other academics because of capacity limitations.



Figure 5.
One of the new solar water purifier designs deployed in Uganda for consumer trials.

4. Discussion: opportunities and challenges

In this penultimate section of the chapter, we will briefly discuss the results of Section 3 and follow on with opportunities and challenges of transformative teaching of engineering in the region—as encountered in the author's practice of the same.

4.1 Brief discussion

As a way of discussing the 6 listed results in Sections 3.1.3 and 3.2.3, we ask: are these demonstrated outputs beneficial to student learning and society or not? Would they have been achieved in equal or greater measure by means other than transformative teaching? The first question need not take space and time to answer. The fact that student numbers wanting to do postgraduate studies under supervision of the lecturer using this approach, had multiplied by a factor in excess of 5 in just 5 years, is proof enough that they found the approach beneficial. This is especially so when it is noted that most of those wanting to do these studies prefer to pursue what they had been involved in at diploma or at Bachelor degree levels. For society, it could be debated whether the resulting industry-faculty cooperation could not have been achieved otherwise. But here, the focus is on student learning. And in the situation of the author, he found use of student projects as the easiest and most cost effective way of reaching out to many industry players in the Cape Town area.

On development of new products, subsequent maintenance and continuous improvement culture among students: again it might perhaps have been possible to do so without transformative teaching. For example, the experiential training they receive outside campus could probably help in this direction. However, that training is largely outside the control of engineering academics, and is non-uniform across the student cohort. Moreover, we could argue that there is nothing to lose, but everything to gain if that training was simply an addition to what is obtained at campus through transformational teaching. In any case, the author has not witnessed or found recorded efforts on the African continent which produce the same outputs at a rate exceeding that demonstrated and not demonstrated in this chapter (because there are at least six other areas not discussed here).

4.2 Opportunities offered by transformative teaching as practiced in the case studies

Here, we will share some opportunities as first-hand experienced in the practice of transformative teaching. The aim is to persuade those engineering academics on the continent, who may not already be practicing it, to give it a try.

- Rapid development of products touching every day needs of a majority of the African peoples, using locally available materials and resources. Involvement of students helps bring vigour and variety to this process.
- Accelerating human capital development through the motivating effects of successful implementation of a project within the time and cost allocated (recall that failure in these projects is not allowed and cannot be submitted to).
- A great opportunity to increase the academic's publication record (and its attendant rewards) through multiple openings addressing engineering and non-engineering aspects of the projects.
- Easiest method to develop patentable products and consequent raising of third stream incomes for both university, and lecturer.

4.3 Challenges encountered by transformative teaching as practiced in the case studies and how they could be overcome

Major challenges to be encountered can include:

- Disruptive strikes, leading to destruction of facilities, project materials and loss of teaching and learning time. This can partially be overcome by arrangement with willing and secure, off campus workshops, preferably, under partial control of the academic.
- Projects funding limitations and financing micro-controls, leading to stunting creativity and stifling innovation respectively. Both of these could be partially overcome by careful choice of initial start-up projects and material selections followed by seeking alternative less formally controlled funds, including own, and participating students' contributions.
- For purely academic research-based universities, without complements of technician and artisan training, a lack of sufficient lower level engineering skills to accomplish the projects in time and cost-effectively. Perhaps, in the short term, the easiest way out is to cooperate with universities of Technology or even, with technical colleges on joint projects. Another short term, but perhaps more difficult option, is to search for industries or workshops willing to commit extra training resources for joint Research and Development projects. The longer term solution is to question the rationale of continuing as a purely basic research engineering faculty in a continent, severely deficient of lower level skills, and then, change course. In other words these universities need to transform in order to facilitate 'transformative teaching' in a form exemplified by the above case studies.
- All said, perhaps the greatest challenge could be insensitive, irresponsible, and rigid university management systems and their managers. For, it is these that hire and fire, motivate and demotivate staff; admit students and discontinue them; plan, and fail to plan revenue generation; allocate and misallocate funds. As in financing above, a partial solution to this is to seek less controlled funding, even sometimes operate in alternative environments. In the extreme case, the concerned transformative lecturer is best advised to seek satisfaction elsewhere.

5. Summary and conclusion

We have come to the end of this chapter on transformative teaching of engineering in sub-Saharan Africa. Its discussion was premised on the observation that many students in the region come to study engineering after having been subjected to a transmission mode of teaching during most of their school time. A transactional mode, which enables positive interaction among themselves and with the teacher as they learnt new material, was recommended as the initial weaning approach. However, as they matured and gained more knowledge, it was suggested that they should be encouraged to adopt a critical look at the past, the present, and imagine a future they would want to have. A transformative teacher brings them to this state, and then, tips them over into working for that dreamed future. At the very least, this teacher would use the following principles in assignments for the students:

- Provide intellectually challenging assignments, which for engineering, take the form of real life projects tackling problems that on first thought, seem intractable in the prevailing circumstances.

- While giving students latitude to freely make independent decisions, retain the authority and use the capacity to provide expert guidance when achievement of critical project milestones is at stake.
- Though students would be working in teams, pay attention to each individual's specific concerns, and provide appropriate counselling where needed.

The above narrative formed the foundation of the two illustrated case studies that have been run by the author since 2011. One case tackled Africa's maintenance culture problem, where once assets are acquired, their maintenance is not taken seriously. The case also highlighted the accompanying design evolution work in which, totally new kinds of solar syphon installations were eventually introduced on the scene. The second case illustrated how multi-level, multi-national teams were enabled to use multi funding sources to develop a series of completely new products on multi premises for the African market, even in times of severe campus crises. In the author's opinion, this was transformative teaching at its best.

There were several benefits of transformative teaching illustrated in these case studies. The more important ones included:

- Getting students to develop products they never ever thought they were capable of making in the circumstances and at costs they did.
- Increasing the publication record of the concerned academic both in Engineering Education and in Solar Energy Engineering areas
- Increasing several fold interest by students in postgraduate work

The benefits notwithstanding, limitations of the teaching include:

- When there are many students, a corresponding big number of projects is required if each team is not to be too big. The author has usually overcome this problem by creating competitive teams on variants of similar projects as in the solar syphon case of Section 3.1.
- Real life projects involve real time, expenses, quality, and safety pressures. These factors do not normally get encountered to the same intensity in normal educational processes. There can therefore be initial resistance not only by students but by their sponsors and even by some university administrators. Persuasiveness, Professionalism, Persistence and Resilience are the key success factors in such situations.

Finally, a brief attempt to persuade all engineering academics to adopt the teaching approach through highlighting the key benefits, and then, showing the most critical challenges to expect along the way, and how to possibly navigate through them, was made. In conclusion therefore, we should have by now shown that: transformative teaching of engineering in sub-Saharan Africa is not only desirable, but it is possible too.

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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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Author details

Kant Kanyarusoke
Cape Peninsula University of Technology, Cape Town, South Africa

*Address all correspondence to: kanyarusokek@cput.ac.za

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