Engineering Science and Technology, an International Journal 23 (2020) 345–356

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Contents lists available at ScienceDirect

Engineering Science and Technology, an International Journal

journal homepage: www.elsevier.com/locate/jestch

Full Length Article

Problems of engineering entrepreneurship in Africa: A design optimization example in solar thermal engineering

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A R T I C L E I N F O

Article history:
Received 3 January 2019
Revised 17 April 2019
Accepted 1 May 2019
Available online 16 May 2019

Keywords:
Africa
Design optimization
Engineering entrepreneurship
PESTLE analysis
Solar water heating

A B S T R A C T

This paper addresses Africa's challenges and opportunities to engineering entrepreneurs. A business environmental scan is done in line with the standard PESTLE analysis, identifying at least twenty generic problems across the continent. Focus is directed to an opportunity in solar water heating, where inadequate electricity supply combines with a plentiful solar resource amidst environmental protection awareness, to make investments potentially worthwhile. Three home level market segments are identified. Key issues in the PESTLE scan are linked with available materials to formulate and solve a design optimization model for these segments. A competition-less product emerges for rural homes. Another – for small urban homes – can be retailed at 50% of current equivalent system prices, and yet, still make profits for the entrepreneur. Both these systems attain average temperatures in excess of 57 °C, the fatal level for most pathogenic bacteria. The 3rd and larger system for rich urban homes incorporates a supplementary electric heater that is programmable to kick in half an hour before water withdrawal if solar energy has failed to maintain water temperature above 60 °C. The entrepreneur can still make profit if the product retails at 52% of the equivalent competition price.

1. Introduction

Africa, the earth's second largest continent by both area and population [1] is the least technologically developed human-occupied continent [2]. With riches in form of raw material and diverse bio resources, a full range of geographic features and a plentiful supply of both renewable and fossil energy resources [3–5], it would seem paradoxical that a continent with a young population [6] is also, the most labor intensive in carrying out its daily chores. From basic life maintenance activities like food sourcing (farming), water, energy, and medicine sourcing – through shelter construction – to the relatively more luxurious activities of travelling, formal education and entertainment, many Africans still use manual labor. Not that they necessarily like it that way, but rather, the opportunities and means to live better are limited, and constrained by a raft of challenges in their societies. This is both a challenge and an opportunity to engineers because engineering knowledge, skills and competencies are required to transform the abundant natural resources into products and services these societies urgently need. Engineers are required to create and multiply tangible wealth that government leaderships can hopefully tax to improve the lives of a majority of the people.

But there are challenges. Which ones are they – and what can be done about them? This paper first surveys the generic ones as related to engineering enterprise formation and sustenance on the continent. It then assumes that 'Resourcefulness' in form of innovation and creativity are required to navigate them, and solve the underdevelopment problems. If resourcefulness is combined with management and leadership skills, the engineer could turn it into entrepreneurship, making the original problems and their solutions a business opportunity. This hypothesis is illustrated in Fig. 1.

As a second step, the paper presupposes the above hypothesis to be applicable in the area of solar water heating. We note that the solar resource for most of the continent is abundant, exceeding 1500 kWh/m^2.year on a horizontal plane [7]. Also observed, is the fact that nascent efforts to harness it have tended to focus on electricity generation for lighting [8–10]. Yet, there are more efficient uses for it in heating, and which could help alleviate the wood fuel and environmental degradation problems on the continent [11–13]. Accordingly, the significance of engineering in the hypothesis leads to a literature search of factors affecting engineering entrepreneurship development on the continent in form of a Political, Economic, Social, Technical, Legal and Environmental (PESTLE) scan. Those to play a more significant role in later sections of this paper are expounded upon while the lesser ones are only cited.

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https://doi.org/10.1016/j.jestch.2019.05.002
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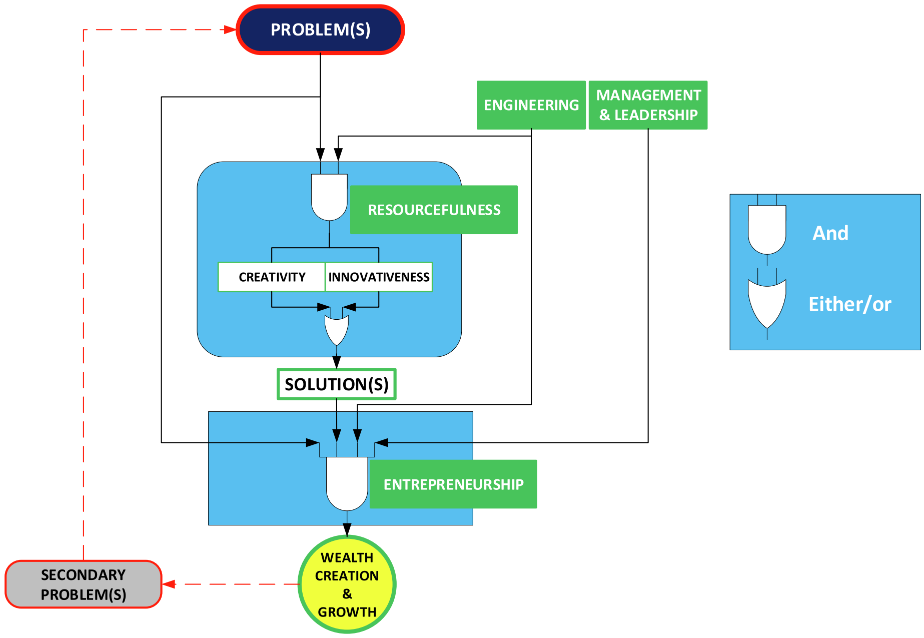

Fig. 1. The hypothesis: Engineering, Resourcefulness, and Entrepreneurship and how they drive technology-based wealth creation.

This is followed in Section 3 by solar water heating design optimization modeling which takes care of key issues from the scan. After solving the optimization, prototypes of design solutions are constructed and tested. Section 4 gives sample performance test results of one of them. The originality of this work is in its connection of 'soft' issues such as social capital, political disaggregation, etc., to the 'hard' scientific variables as temperature, product mass, etc., to make a reasonable business case. The greatest value of the work is a synthesis of a product that competition had as yet, not done – perhaps because their focus was on the more readily accessible urban market segments. Even in these latter segments, the paper's design approach yields highly competitive products relative to what currently exists. The totality of this work therefore, is to underpin the importance of matching new products/services with objective conditions in a given market.

2. PESTLE analysis for African engineering entrepreneurship

PESTLE analysis is a survey of a business environment, external to an organization. Basically, this environment is scanned in the 6 key areas of Politics, Economics, Sociology, Technology, Law and Environment. Hence, the acronym: 'PESTLE'. There are many problems with starting and running any business in Africa: even more so, for engineering based ones. Fig. 2 shows only 20 of such problems in respective scan categories. Details of these can be found in the literature indicated. The remainder of this section focuses only

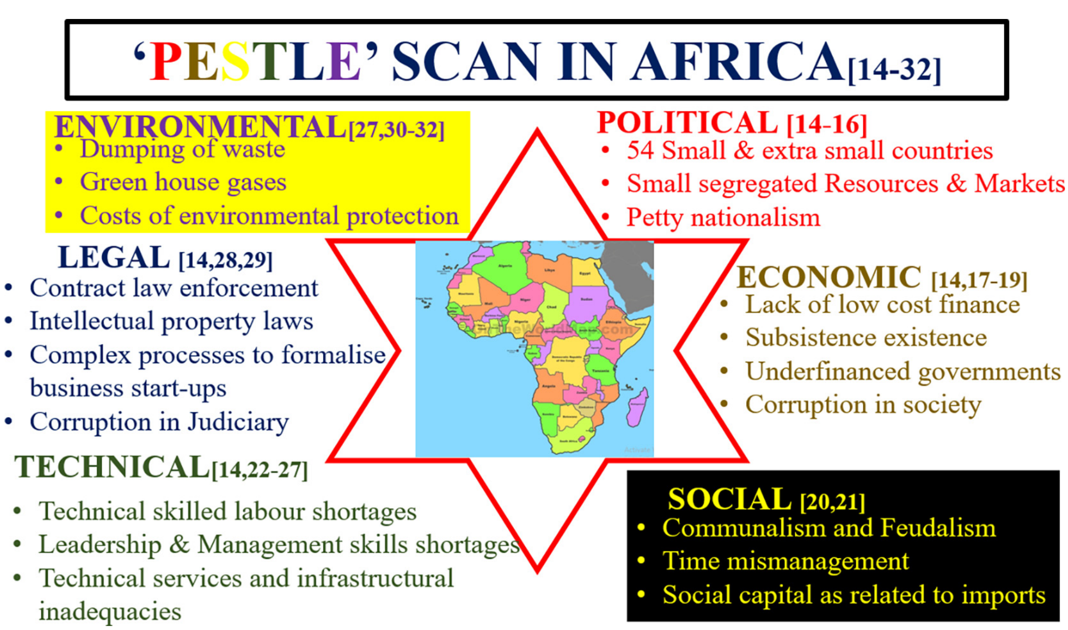

Fig. 2. Some of Africa's generic Engineering Entrepreneurship problems. [14–32].

on those areas more directly affecting the optimization model of Section 3.

2.1. Political scan

As is evident in Fig. 2, Africa is fragmented into 54 political states, ranging in size from very small to medium areas. Populations also vary from as small as below 2 Million people for countries like Gabon, Lesotho, Swaziland etc., to as high as nearly 200 Million for Nigeria. This means some countries are necessarily starved of critical masses of entrepreneurial engineers, as illustrated by Magagula for Swaziland [18], while others like North Sudan, DRC, etc., require long distance transportation of products to access internal markets due to sparse distribution of population. It does not help that colonial linguistic and education system differences hamper market integration in many cases. For example, Swati/English – speaking Swaziland is surrounded by Portuguese speaking Mozambique and multi-lingual South Africa. Newly curbed South Sudan borders Arabic speaking Sudan in the north, Francophone DRC in the west, Amharic Ethiopia in the east and Anglophone Uganda in the south. These and other factors pose political barriers to engineering entrepreneurship in most of Africa. The challenge therefore is to seek to produce in some country but ultimately market in several others without violating any regulatory or social-cultural mores of any one community.

2.2. Economic scan

Economically, each African country is characterized by isolated islands of commercial activity amidst a prevalence of subsistence existence. It is only South Africa and the extreme Northern countries which have substantial urban population components at 66%. But even then, the urban centers – like in other African countries – are dominated in population by rural migrants in satellite settlements surrounding central business districts. Wages and other incomes are very low for these migrants. This creates a market growth problem for engineering entrepreneurs looking at products and services for these people. In rural areas, where up to 85% of the population live in most countries, social-cultural issues described below combine with subsistence living to constrain engineering entrepreneurship.

Whether in rural or in urban areas, the biggest economic hurdle is lack of low cost finance [14,17,18]. Low incomes and savings, limited banking facilities, lack of bankable collateral, high inflation and interest rates, unstable currencies, etc. – all combine to limit both investment and working capital of would be – engineering entrepreneurs. The challenges here are: gain the courage to 'start small' but aim big; be frugal, without being 'mean'; be 'cost conscious' without compromising quality and service.

2.3. Social-cultural scan

Traditionally, the African was closely tied to the culture and customs of her/his people, in form of a tribe. Land and any other natural resources were communally owned by the tribe. In slightly more organized cases, feudalism under one overall ruler-ship in form of a king or a chief resulted. Remnants of this mixture of communalism and feudalism have persisted in rural areas even in this modern era, dominated by individualistic capitalism.

Engineering entrepreneurship on the other hand, is closely linked to capitalism. One of the first hurdles therefore in rural areas, is to overcome resistance to capitalism as a social-economic system. Many cultural practices and norms do not easily blend with those for commercial competitiveness and efficiency. For example, time management in a typical traditional setting is at variance with requirements of modern high productivity. Many traditional ceremonies (e.g. birth of twins, marriage and burials/funerals in a village) tend to be carried out by societies as if nothing else mattered. For an engineering entrepreneur, this creates problems on management of labor, on social responsibility and on public relations, ultimately, leading to a preference to operate in the more cosmopolitan environments of urban areas. But then, the following entry barriers and operational problems manifest themselves: Higher cost of industrial land and rates in urban areas; a more sophisticated and demanding market than that in rural areas; greater competition, including from imports, oligopolies and copycats, facilitated by weak intellectual property laws as explained in 2.5 below. These social-cultural issues combine to stifle Africa's engineering entrepreneurship, and complicate engineering-based business learning curves.

2.4. Technical scan

A myriad of technical and technological challenges have to be contended with by engineering entrepreneurs on the continent. In fact, it can be argued that navigating some of these is easily the greatest call on the entrepreneurs. This particular paper's work on solar water heating is such contribution on energy challenges. They can be grouped under subheadings of Materials, Technology, Services and Management.

2.4.1. Materials

Most materials for economic transformation only exist in their rawest forms on the continent. They need extraction and processing before use by most engineering entrepreneurs. Thus, many start-ups require imports of already processed intermediate materials, a problem well illustrated in [23].

2.4.2. Technology

If we look at technology as a way of doing things requiring scientific knowledge, then three sub-problems present themselves: the things to be done (entrepreneurial technical activities), the tools and equipment required to do them, and the skills of people to use those tools. Solar thermal technical activities include solar water heating as in this paper, solar cooking, solar water purification, solar crop and meat drying, etc. The challenge to the entrepreneur in rural areas is to convince a largely conservative market to leave their traditional methods and adopt the newer ones being introduced at a cost to them. The same holds true in urban areas, but this time, with the additional complication of presence of other technologies giving similar benefits using imported, and possibly better looking products. On 'Tools and equipment', the challenge is to resolve the fundamental debate of selection along a mechanization continuum scale from pure manual, using simple tools to fully automated systems using minimal, but highly skilled labor. In case of solar thermal engineering entrepreneurship, Fig. 3 shows examples of the continuums from both manufacturing and customer service viewpoints – which viewpoints must be contended with.

Perhaps the biggest engineering entrepreneurial problem on the continent is that of skill gaps. To begin with, outside South Africa and Egypt, availability of engineers is approximately 1 for every 6000 of population. This compares most unfavorably with 1: 200, 1:221, 1: 543 and 1: 3166 for China, Brazil, Malaysia and South Africa respectively [27]. This means there is an extremely small pool of people from whom well-informed engineering enterprises can arise. Further, for reasons given in [22], the relative gaps at technician and artisan levels are even bigger. The challenges to the few engineering entrepreneurs on the continent therefore are two-fold. One – is to act as pioneer reference persons to society, who must not fail in whatever project they venture in; and two – is to seek skilled staff and/or retrain them, and then retain them

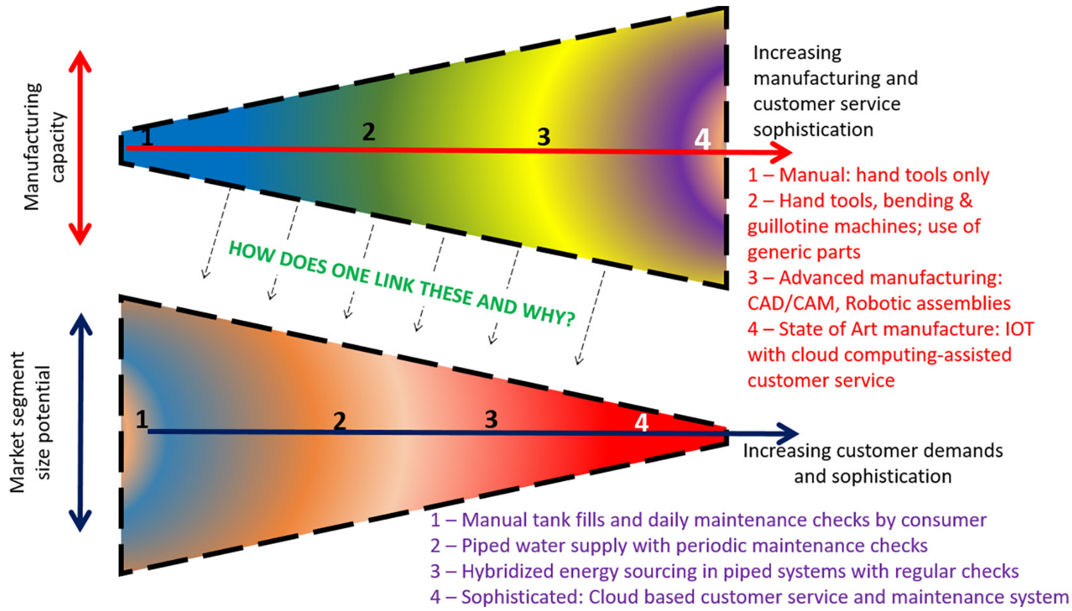

Fig. 3. Engineering entrepreneur solar thermal manufacturing – marketing challenge in Africa: To manufacture simply and serve a bottom of pyramid segment? – OR – To automate systems in order to serve a small discerning top of pyramid consumer segment?

against attractions from many other competing and non-competing enterprises.

2.4.3. Infrastructural services

Energy, Transport, Telecommunication and Water services are among the infrastructural services lacking in many African countries. Even when available, they are either inadequate or unreliable or costly to use, making locally availed products and services expensive relative to imports, while also making them inaccessible/out of reach to a majority of people in the countries. The challenge to an engineering entrepreneur here is to introduce products/services whose total supply chain costs, delivery times and customer service, can best cope with these limitations.

2.4.4. Management and leadership

The challenges of Section 2.4.2 require a combination of leadership and Human Resource/Relations management skills in the entrepreneurs themselves. But current African university and college engineering curricula do little to develop and impart these skills [26]. Those of 2.4.3 require adept financial and operational management skills. Again, many engineering curricula tend to treat these as optional modules. The challenge to engineering entrepreneurs therefore, is to seek these skills after graduation – as a life-long learning activity. It is one of the reasons many would have to go into entrepreneurship only after having worked for someone else.

2.5. Legal scan

The biggest reported legal problem seems to be an inadequate enforcement of contract laws in many African countries [14]. Weak institutional capacities lead to defaults in meeting contractual obligations at small business levels, which tend to go unpunished. Along with weak contract law enforcement mechanisms, are the weak intellectual property laws [27,33,29]. Product counterfeiting by fellow local business persons is common. This makes starting up a long-lasting business difficult, with the result that upward of 90% start-ups fail in their first year of operation. In engineering entrepreneurship, the challenge therefore, is to raise entry barriers by introducing bits of sophistication (e.g. artificial intelligence) in the basic product, without driving product costs and complexity beyond the reach of intended market segments.

2.6. Environmental scan

Engineering entrepreneurship development tends to cause environmental degradation through dumping of solid and liquid waste – such as in [30–32] and generation of greenhouse, acidic and ozone depleting gases. In solar thermal engineering, the challenge is to keep solid waste generation low by minimizing offcuts of raw materials, and yet maintain the weight of the finished product low.

3. Solar water heating design optimization for the African home market

This section exemplifies navigation of some of the above engineering entrepreneurship problems for the case of solar thermal water heating. First, we show the essential parts of the heating and storage system. Detailed heat transfer and fluid flow modeling are covered in earlier publications [34,35]. Here, focus is on entrepreneurial mechanical design decision making and its optimization modeling as constrained by the PESTLE scan. The section ends with illustrative optimal solutions for different market segments.

3.1. Basics of solar water heating and its optimization

Fig. 4 shows the simplest solar water heating system, in which radiation received at the collector is transformed to thermal energy of the circulating water, which transfers it to the water stored in the tank.

The issue in this section is to model selection of parts shown in Fig. 4 for optimal design to serve different market segments subject to both technical and PESTLE – imposed constraints.

3.1.1. Design decision variables in optimization

Engineering design decision making is constrained by the market segments intended to be served and by available materials and processes that can be used to make the solar water heating sys-

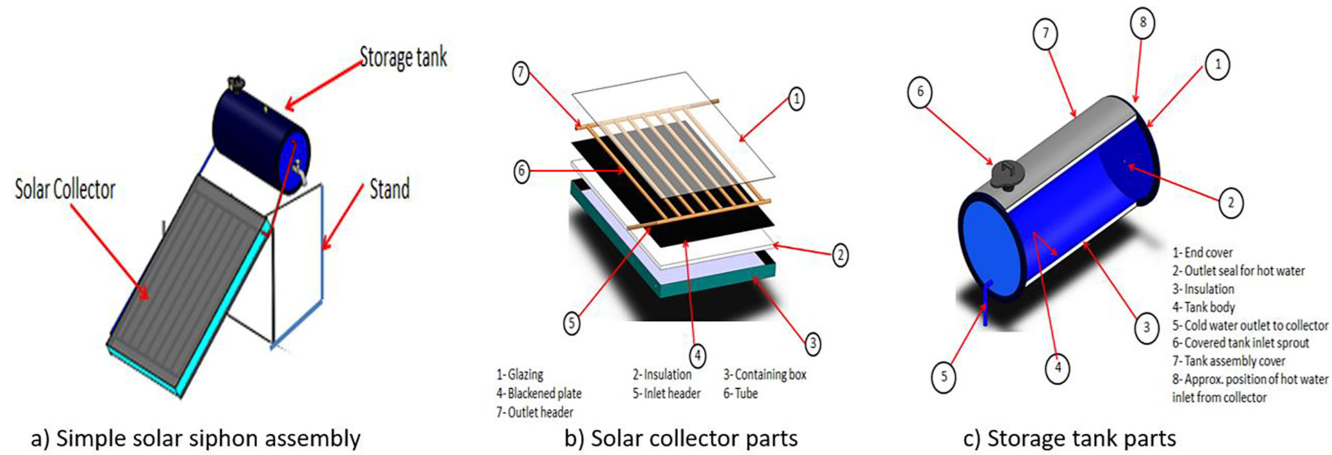

Fig. 4. The simple solar siphon system.

tems. The decisions could be grouped into 4 areas as: Sizes and shapes; Materials; Manufacturing Processes; and General issues. Fig. 5 summarizes these variables.

3.1.2. Examples of available 'values' of some design variables in South Africa

Here, we present examples of ranges of identifying characteristics for the variables, as can be sourced within South Africa. Table 1 gives the most important variables for collectors and tanks respectively.

3.1.3. Other constraints

Apart from available materials, Manufacturing methods and costs, desired Temperature and Energy gains are the other important technical constraints to be considered in the optimization. Manufacturing is influenced by the materials selected, while collector geometry determines energy and temperature gains [35,45,46].

3.2. Optimization objective function

The optimization problem is a multi-objective one, considering key elements in the PESTLE scan and constraints of Sections 3.1.2 and 3.1.3. A unit product cost penalty function combining the multiple objectives into a single cost objective function is formulated for minimization, as in Eq. (1).

$$C = c_pC_p + c_eC_e + c_sC_s + c_tC_t + c_lC_l + c_{en}C_{en} \tag{1a}$$

where the coefficients total to 1:

$$c_p + c_e + c_s + c_t + c_l + c_{en} = 1 \tag{1b}$$

The PESTLE penalty cost objectives (C_p, C_e, C_s, ---), described in Table 2, are non-linear. The key issue in using this approach is to be able to determine the relative weights of linear coefficients c_p, c_e, -- as realistically as possible for a given product. For new products and/or market segments, these can be determined either heuristically using intuition or from a preliminary market research targeting the segment. For others, either the 'Survey' or the 'Delphi' method as suggested by Kumar and Murthy [47] would be appropriate.

3.2.1. Estimations of cost penalties of individual objectives C_p, C_e, –

The cost penalties of an option or product are in this paper, defined as material cost deviations from those of the least cost option that fully satisfies the particular objective. Hence, the

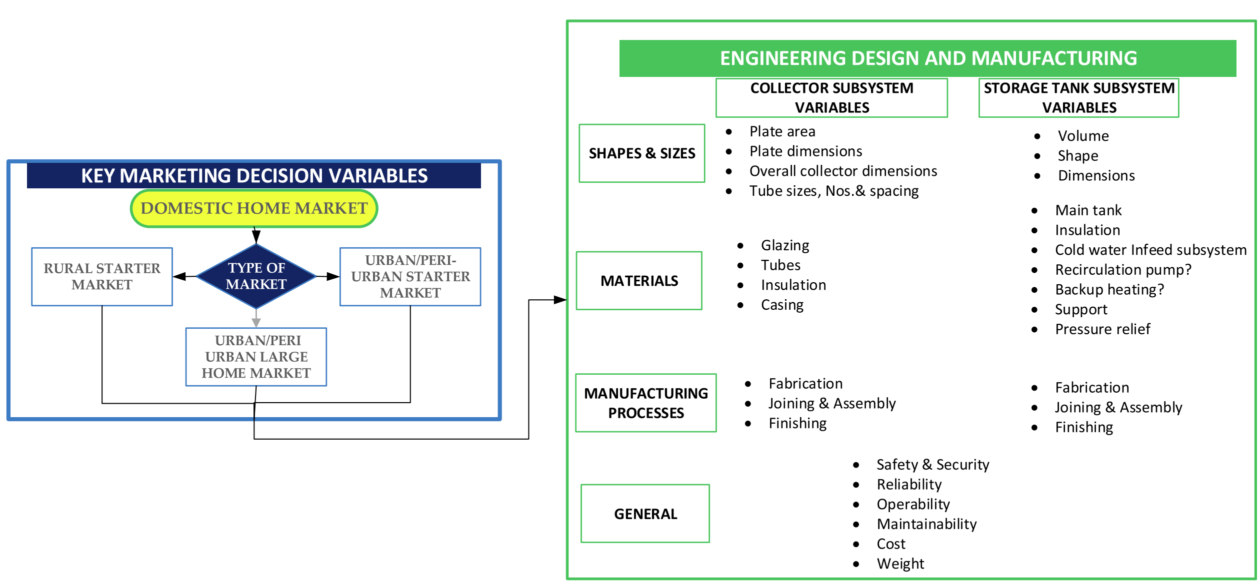

Fig. 5. Decision variables for optimization of domestic home solar water heating.

Table 1
Some 'values' for solar water heating collector design variables in South Africa.

Part	'Value'	Sizes (mm)	Cost US$/unit	Typical source
Glazing	Solar glass	2000 × 1000 × 3	85.71	PG Glass – (by arrangement)
	Poly Carbonate	3050 × 2050 × 1.5	92.85	Maizey Plastics [36]
	Perspex	3050 × 2050 × 1.5	74.28	Maizey Plastics
	Normal glass	2000 × 1000 × 3	26.67	PG Glass [37]
Tubes	Copper	15F × 5500 × 0.5	11.87	Copper Tubing Africa [38]
		22F × 5500 × 0.6	20.20	
	Aluminium	16F × 6000 × 1.22	6.67	Euro Steel [39]
		19F × 6000 × 1.22	9.41	
	Galvanized Steel	15.8F × 6000 × 1.6	10.63	Tubecon [40]
		20F × 6000 × 1.6	27.04	
	HDPE	16F × 6000 × 2	8.47	Marley Pipe Systems [41]
		22F × 6000 × 2.9	23.22	
Insulation	E/Polystyrene	2400 × 1200 × 25	11.90	Isover [42]
	E/Urethane		26.67	
Covering & Plate	Aluminium	2500 × 1250 × 0.9	31.13	Non Ferrous Metals [43]
	Galvanised Steel	2450 × 1200 × 0.5	13	Mac Steel [44]
	PVC	3000 × 76 × 38	12	Maizey Plastics
Main Tank	Welded SS		300	Finished 100 L product
	Welded GS		200	Finished 100 L product
	PVC piping 1	400 × 6000 × 7.90	72	Marley Pipe Systems
	PVC piping 2	315 × 6000 × 6.2	45	Marley Pipe systems
	PVC piping 3	450 × 6000 × 9.6	92	Marley Pipe systems
End plates	PVC	1000 × 2000 × 8	40	Maizey Plastics
Tank Insulation	Glass wool	1200 × 5000 × 50	26.67	Isover
	E/Urethane			

Table 2
Some multi-objectives derived from PESTLE analysis for optimization.

PESTLE Area scan	Key constraint/challenge addressed	Objective
P-Political	Small internal markets due to over fragmentation of the continent and land-locking of many African countries.	Minimize weight and bulk so that product can be land-transported and handled easily across long distances even to areas in neighboring countries.
E-Economic	Small incomes for majority	Minimize unit product manufacturing cost so that prices can be reduced, to enable affordability.
S-Social cultural	Necessity to grow national social and health capital while considering cultural practices of communities in the countries.	Maximize achievable temperatures preferably higher than the cholera bacterium death level of 57 °C to ensure maximum hygiene potential of the product.
T-Technical	Provision of adequate heating using minimal technical labor and services inputs.	Minimize deviation from the Elhabish-Gryzagoridis square collector configuration for maximum energy yield per unit collector area [45]
L-Legal	Necessity to introduce products with unique features, not easy to copy or duplicate	Maximize intellectual property content within the products without compromising technical operation simplicity
En- Environmental	Minimum effect on environment both in manufacture, usage and at decommissioning	Minimize production material waste

optimization procedure for a product targeting a specific market segment, involves three steps: one – determine which objectives C_i are relevant, and their corresponding coefficients, c_i. Two – for each of the relevant objectives, determine the 'ideal' solution that fully satisfies it at lowest cost; and thirdly for any other trial solution, compute the costs deviations for each objective from corresponding least costs of step 2, and substitute these deviations into Eq. (1a) for minimization. The formulation of how to determine the objectives is given below. Penalties for collectors and tanks are worked out separately and added to make system totals. It is these totals to be sub-optimized for the specific objective.

3.2.1.1. Collector penalties -.

- Collector tubes – Let $\boldsymbol{n_t}$, be the number of bought length $\boldsymbol{L_t}$, tubes in one collector with $\boldsymbol{z_t}$ tube lengths of values $\boldsymbol{l_t}$. The material density is $\boldsymbol{\rho_t}$ and the cost per unit length of bought tube is $\boldsymbol{c_{tube}}$.

Then : mass of tubes in collector : $m_t = \rho_t z_t l_t;$ (2a)

cost of tubes : $C_{tube} = c_{tube} n_t L_t$ (2b)

If sizing leads to tube off cuts, cost of waste is:

$$C_{tubewaste} = c_{tube}(L_t n_t - z_t l_t) \tag{2c}$$

- Collector glazing – For $\boldsymbol{z_g}$ collectors of length $\boldsymbol{l_g}$, width $\boldsymbol{w_g}$, made from an available glazing stock size $\boldsymbol{L_g}$ X $\boldsymbol{W_g}$, of density per unit area $\boldsymbol{\rho_g}$ and cost per bought area $\boldsymbol{c_g}$:
- Then: mass of glazing in collector:

$$m_g = \rho_g w_g l_g \tag{3a}$$

Cost of glazing:

$$C_{glazing} = c_g \frac{W_g L_g}{z_g} \tag{3b}$$

- For no waste: Either

$$\frac{L_g}{l_g} \text{ and } \frac{W_g}{w_g} = N \quad \text{or} \frac{L_g}{w_g} \text{ and } \frac{W_g}{l_g} = N, \text{ with } N = 1, 2, 3, - - - \tag{3c}$$

If there were to be glazing off cuts, cost of waste would be:

$$C_{g-waste} = c_g\left(\frac{L_g W_g}{z_g} - l_g w_g\right) \quad (3d)$$

- Collector casing – For a collector depth $\boldsymbol{d}$ and folded flange $\boldsymbol{l_f}$, we can write:

$$\text{Constraints}: L_m \geq l_g + 2d + 2l_f \text{ and } W_m \geq w_g + 2d + 2l_f \quad (4a)$$

$$\text{Mass of casing}: m_{case} = \rho_{case}(l_g + 2d + 2l_f)(w_g + 2d + 2l_f) \quad (4b)$$

$$\text{Cost of casing}: C_{case} = c_{case} L_{case} W_{case} \quad (4c)$$

$$\text{Cost of waste}: C_c = c_m(L_m W_m - (l_g + 2d + 2l_f)(w_g + 2d + 2l_f)) \quad (4d)$$

- Collector plate: constraints-:

$$L_{plate} \geq l_g \text{ and } W_{plate} \geq w_g \quad (5a)$$

$$\text{Plate mass}: m_{plate} = \rho_{plate} l_g w_g; \quad (5b)$$

$$\text{Plate cost}: C_{plate} = c_{plate}\frac{W_{plate} L_{plate}}{z_{plate}} \quad (5c)$$

$$\text{Waste}: C_{plate-waste} = c_{plate}\left(\frac{L_{plate} W_{plate}}{z_{plate}} - l_g w_g\right) \quad (5d)$$

- Insulation waste: Constraints -:

$$L_i \geq l_g + 2d \text{ and } W_i \geq w_g + 2d \quad (6a)$$

$$\text{Insulation mass in collector}: \mathrm{m_i} = \rho_\mathrm{i} \mathrm{l_g w_g} \quad (6b)$$

$$\text{Insulation cost}: \mathrm{C_i} = \mathrm{c_i}\frac{\mathrm{W_i L_i}}{\mathrm{z_i}} \quad (6c)$$

$$\text{Waste}: C_{i-waste} = c_i\left(\frac{L_i W_i}{z_i} - (l_g + 2d)(w_g + 2d)\right) \quad (6d)$$

We can now obtain indicative measures for the total materials, their costs and waste for making a single solar collector so as to work out the respective contribution to the system's objective being considered. If we include the manufacturing process cost $\boldsymbol{C_{coll-man}}$ we can write:

$$\text{Measure of mass(and hence weight)}: m_{collector} = m_t + m_g + m_{case} + m_{plate} + m_i \quad (7a)$$

$$\text{Measure of cost}: C_{collector} = C_{tube} + C_g + C_{case} + C_{plate} + C_i + C_{coll-man} \quad (7b)$$

$$\text{Measure of waste}: C_{coll-waste} = C_{t-waste} + C_{g-waste} + C_c + C_{plate-waste} + C_{i-waste} \quad (7c)$$

3.2.1.2. Tank penalties-. Tank sizing and shaping in this paper are dictated by prevailing market practice in which cylindrical shapes and multiples of 50 L sizes are common. This eases market entry by the entrepreneur.

- Tank body – For a target volume $\boldsymbol{V_{tank}}$,

$$V_{tk} = \frac{\pi(d_{tk} - 2t_{tk})^2}{4} l_{tk} = 0.05N \text{ with } N = 1, 2, 3 - -- \quad (8a)$$

For aesthetics and neat pipe connections, tank length approximates collector width. And if it is one of $\boldsymbol{z_{tk}}$ – made from material sheet of length $\boldsymbol{L_{tk}}$ and width $\boldsymbol{W_{tk}}$, thickness $\boldsymbol{t_{tk}}$, density (kg/m^3) $\boldsymbol{\rho_{tk}}$ at cost of $\boldsymbol{c_{tk}}$ US$ per m^2, then:

$$l_{tk} \leq w_g;\ l_{tk} \leq W_{tk};\ z_{tk}(\pi d_{tk} + 0.02) \leq L_{tk} \quad (8b)$$

$$\text{Tank material mass}: m_{tk} = \frac{\rho_{tk}\pi d_{tk} t_{tk} l_{tk}}{z_{tk}} \quad (8c)$$

$$\text{Tank material cost}: c_{tk} = \frac{c_{tk}\ L_{tk}\ W_{tk}}{z_{tk}} \quad (8d)$$

$$\text{Material waste penalty}: C_{tk-waste} = c_{tk}\left(\frac{L_{tk} W_{tk}}{z_{tk}} - \pi d_{tk} l_{tk}\right) \quad (8e)$$

- Tank ends – Could be purchased as readymade end caps in some materials, but this was found to be more costly than making them. So, If made from suitable sheet $\boldsymbol{L_{end}} \times \boldsymbol{W_{end}}$, we have:

$$\text{Number of tanks from sheet is}: z_{end} = \frac{1}{2} rounddown\left(\frac{L_{end}}{d_{tk}}\right) rounddown\left(\frac{W_{end}}{d_{tk}}\right) \quad (9a)$$

$$\text{Mass of ends}: m_{end} = \frac{\rho_{end}\pi d_{tk}^2 t_{end}}{2z_{end}}; \quad (9b)$$

$$\text{Cost of ends per tank}: C_{end} = \frac{c_{end} L_{end} W_{end}}{z_{end}} \quad (9c)$$

$$\text{Material waste penalty is}: C_{end-waste} = c_{end}\left(\frac{L_{end} W_{end}}{z_{end}} - \frac{\pi d_{tk}^2}{2}\right) \quad (9d)$$

- Insulation – thickness is determined from heat transfer requirements and available sizes. For a given thickness: we have:

$$\text{Either}: L_{ti\,i} \geq z_{ti}\pi d_{tk} l_{tk} \text{ and } W_{ti} \geq l_{tk} \quad (10a)$$

$$\text{Or } W_{ti} \geq \pi d_{tk} \text{ and } L_{ti} \geq z_{ti} l_{tk} \quad (10b)$$

$$\text{Insulation mass}: \mathrm{m_{ti}} = \rho_{ti} t_{ti}\pi d_{tk}\left(l_{tk} + \frac{d_{tk}}{2}\right) \quad (10c)$$

$$\text{Insulation cost}: C_{ti} = c_{ti}\frac{L_{ti} W_{ti}}{z_{ti}} \quad (10d)$$

$$\text{Insulation material waste penalty is then}: C_{ti-waste} = c_{ti}\left(\frac{L_{ti} W_{ti}}{z_{ti}} - \pi d_{tk} l_{tk}\right) \quad (10e)$$

$$\text{Outer tank cover sheet} - \text{constraint}: L_{to} \geq z_{to}\pi(d_{tk} + 2t_{ti}) \quad (11a)$$

$$\text{Mass of tank cover}: m_{to} = \rho_{to} t_{to}\pi(d_{tk} + 2t_{ti})\left(l_{tk} + 2t_{ti} + \frac{d_{tk} + 2t_{ti}}{2}\right) \quad (11b)$$

$$\text{Cost of tank cover}: C_{to} = c_{to}\frac{L_{to} W_{to}}{z_{to}} \quad (11c)$$

$$\text{Material waste penalty}: C_{to-waste} = c_{to}\left(\frac{L_{to}W_{to}}{z} - \pi l_{tk}(d_{tk} + 2t_{ti})\right) \tag{11d}$$

Eqs. (8a)–(8e) are valid only for tanks that are built in-house, from purchased sheet/plate materials. Sometimes, it may make more business sense to source appropriate piping and simply close it, if available. In that case the constraints and penalty simplify to:

$$z_{tk} = rounddown\left(\frac{L_{pipe}}{l_{tk}}\right) \tag{12a}$$

$$\text{Mass of tank body}: m_{tk} = \frac{\rho_{tk}\pi d_{tk}t_{tk}l_{tk}}{z_{tk}}; \tag{12b}$$

$$\text{Cost of tank body}: C_{tk} = \frac{c_{tk}L_{pipe}}{z_{tk}} \tag{12c}$$

$$\text{Material waste penalty}: C_{tk-waste} = c_{pipe}\left(\frac{L_{pipe}}{z_{tk}} - l_{tk}\right) \tag{12d}$$

The total individual tank objective functions can finally be written as:

Measure of mass (and hence weight):

$$m_{tak} = m_{tk} + m_{end} + m_{ti} + m_{to} \tag{13a}$$

$$\text{Measure of cost}: C_{tak} = C_{tk} + C_{end} + C_{ti} + C_{to} + C_{tak-man} \tag{13b}$$

$$\text{Measure of waste}: C_{tak-waste} = C_{tk-waste} + C_{end-waste} + C_{ti-waste} + C_{to-waste} \tag{13c}$$

Referring to Table 2, the above sets of equations respond to the Political, Economic and Environmental scans. This means: In Eq. (1),

$$C_p = C_{p-ideal}\left(\frac{m_{collector} + m_{tak}}{m_{ideal}} - 1\right) \tag{14a}$$

$$C_e = (C_{coll} + C_{tak}) - C_{e-ideal} \tag{14b}$$

$$C_{en} = (C_{coll-waste} + C_{tak-waste}) - C_{en-ideal} \tag{14c}$$

For the other elements of the scan, we can have:

Social-cultural – use temperature achievable in the tank on a sunny day. This acts as an indicator of quality, since 57 °C marks the death point of most pathogenic bacteria [48].

$$C_s = C_{s-ideal}\left(1 - \frac{T^{o}C}{57^{o}C}\right) \tag{14d}$$

Technical: use the Elhabish-Gryzagoridis [45] 'square configuration' criterion of getting maximum energy from a given collector glazing area as:

$$C_t = C_{t-ideal}\left(1 - \frac{w_g}{l_g}\right) \tag{14e}$$

$$\text{Legal}: C_l = \begin{bmatrix} 0 \\ C_e \end{bmatrix} \begin{matrix} \text{if patented} \\ \text{if not} \end{matrix} \tag{14f}$$

This completes the modeling for optimization of the function in Eq. (1). It is to be minimized by appropriate selection of materials in Table 1 and of corresponding manufacturing methods.

3.3. Optimization procedure

Fig. 6 gives a summary of the optimization procedure of the objective function in Eq. (1) when subjected to constraints indicated in Eqs. (2) to (14). It was used to write a MATLAB® program to solve for the three home market segments as in Section 3.4 below.

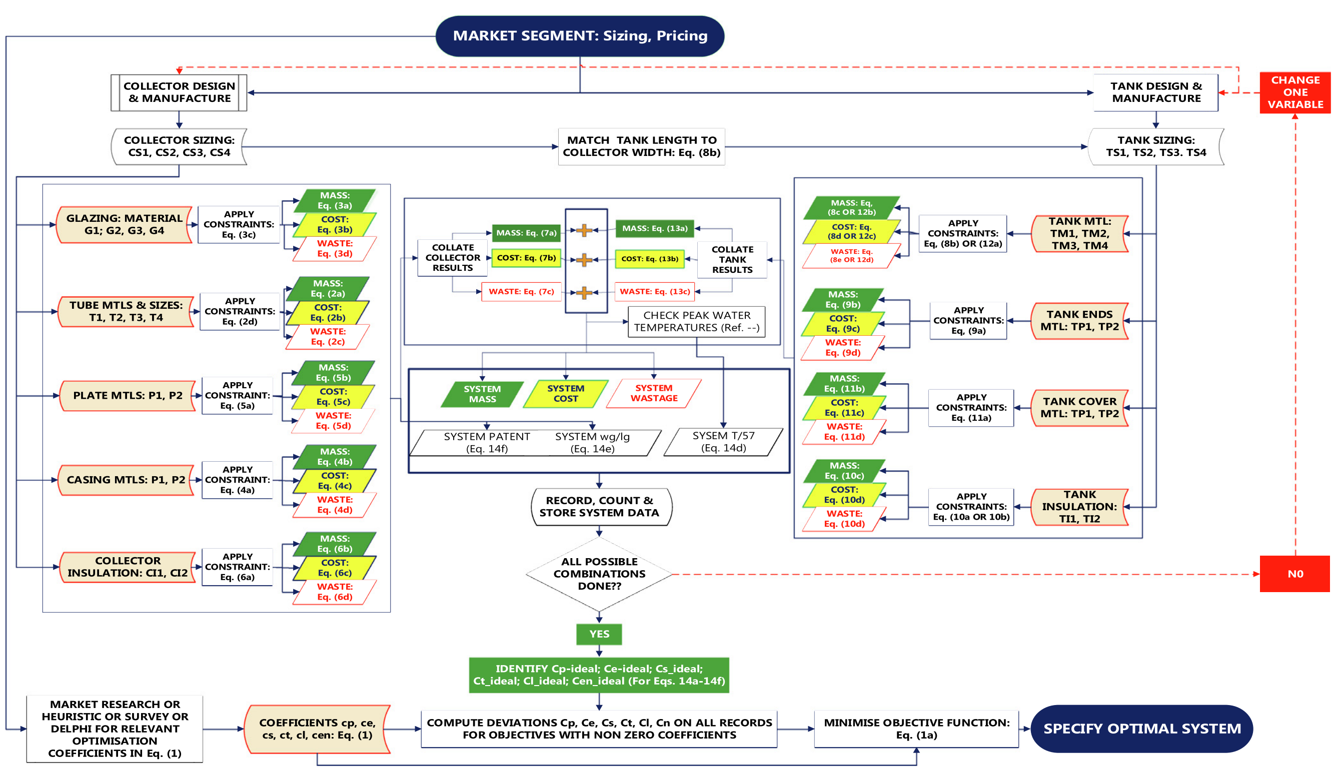

Fig. 6. Home solar siphon system design optimization chart -: Left block – collector design; Right block – Tank design; Middle – optimizing the combination.

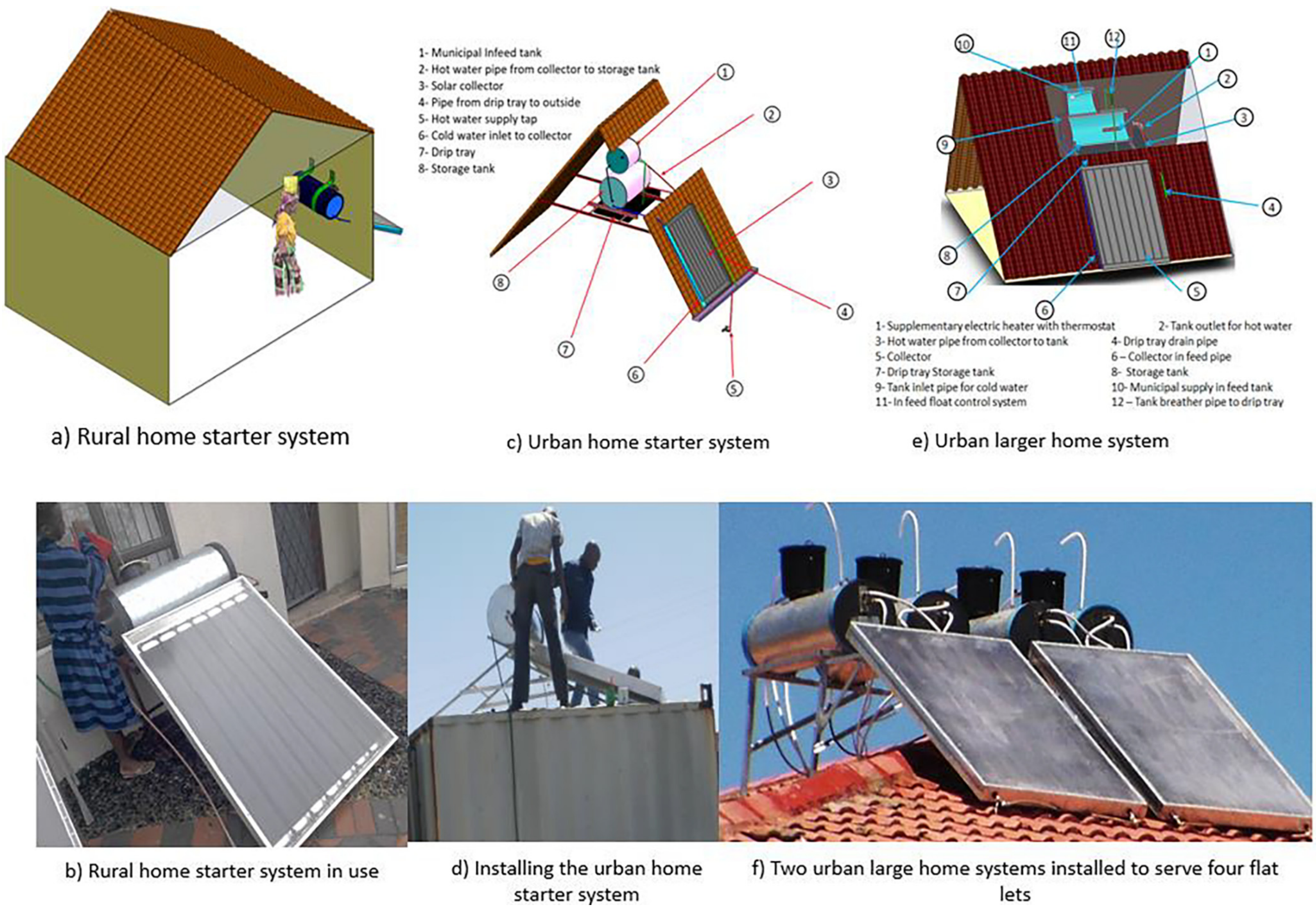

Fig. 7. Illustration of optimal solutions for the 3 market segments: Designs and photos by author.

Table 3
Key specifications of the optimal solutions.

Item	Rural-starter	Urban-starter	Urban – large
Non-zero optimization coefficients	$c_p = 0.1;\ c_e = 0.8;\ c_s = 0.1$	$c_p = 0.1;\ c_e = 0.7;\ c_s = 0.1;\ c_t = 0.1$	$c_p = 0.3;\ c_t = 0.1;\ c_l = 0.3;\ c_{en} = 0.3$
Capacity	50 L	100 L	150 L
Collector size	1 m × 1 m	1.5 m × 1 m	2 m × 1 m
Tubes	8 No. Al 16∅ × 1.22	8 No. Cu 15∅ × 0.5	8 No. Cu 15∅ × 0.5
Glazing	Perspex 1.5 mm	PC 1.5 mm	PC 1.5 mm
Insulation	EPS 25 mm	EPS 25 mm	EPS 25 mm
Plate	Al 0.9 mm	Al 0.9 mm	Al 0.9 mm
Casing	GS 0.5 mm	GS 0.5 mm	GS 0.5 mm
Manufacturing - collector	US$ 20	US$ 10	US$ 10
Subtotal Collector Mtls & Mfg. costs	US$ 72.50	US$98.40	US$ 133.90
Collector weight (kgf)	12.5	17.7	26.5
Main Tank material	PVC pipe 315∅ × 6.2	PVC pipe 400∅ × 7.9	PVC pipe 450∅ × 8.9
Tank ends	PVC 8 mm	PVC 8 mm	PVC 8 mm
Tank insulation	Glass wool 50 mm	Glass wool 50 mm	Glass wool 50 mm
Tank cover plate	GS 0.5 mm	GS 0.5 mm	GS 0.5 mm
Fittings & Manufacturing	US$ 30	US$ 40	US$ 107
Subtotal Tank Mtls & Mfg. costs	US$ 54.40	US$ 82.00	US$ 157.40
Empty tank weight (kgf)	17.7	25.7	34.9
Total system Mtls & Mfg. costs	**US$ 126.90**	**US$ 180.40**	**US$ 291.30**
Total system weight (kgf)	30.2	43.4	61.4
Total weight of materials waste (offcuts) (kgf)	15.2*	14.0*	11.18*
Total cost of wasted raw materials (US$)	22.50**	34.47**	29.80**
Suggested retail price	**US$ 255.00**	**US$ 365.00**	**US$ 585.00**
Present equivalent competitor retail price	**No competitor**	**US$ 733.00*** **	**US$ 1133.00**
Suggested %age price differences	Infinite	51.3	48.4

* The smallest system wastes the most material by weight because of its large offcuts of GS plates in its optimal design. However, by value, it wastes least because the other system sizes waste more Aluminum, which is a lighter, but more expensive material.
** This cost of waste is already included in the total materials and manufacturing costs above. If some offcuts could be used in other products, the total cost could be reduced, with even better prospects for increased profitability.
*** There are fragile evacuated glass tube units retailing at a best price of US$ 367.00, but these are not taken as 'equivalent' in this optimization because of their increased maintenance requirements.

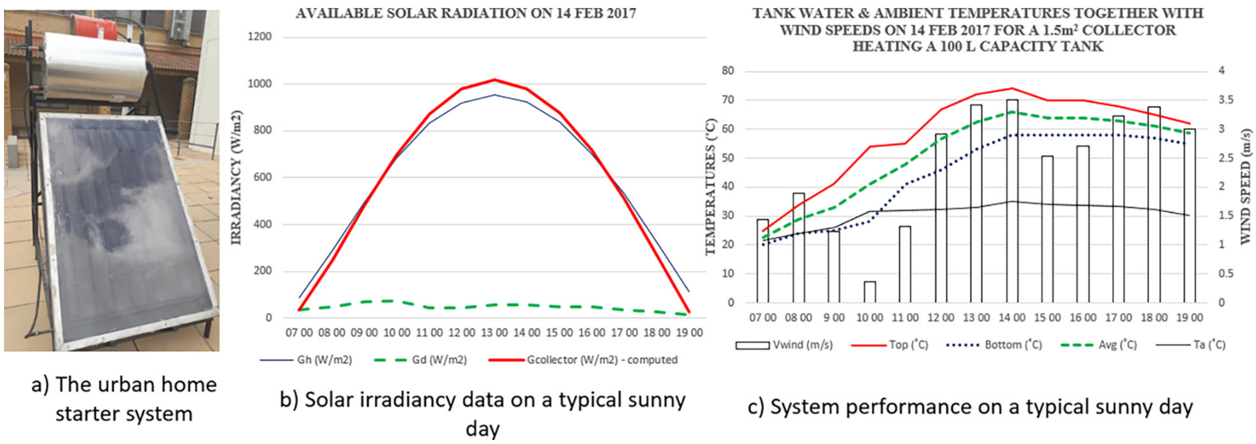

Fig. 8. The urban starter solar water heater system and its test results on a sunny day.

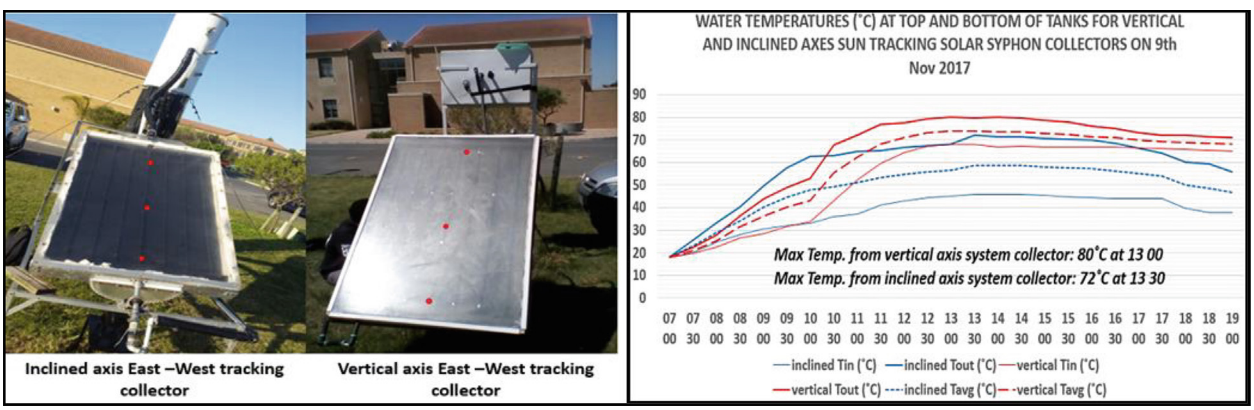

Fig. 9. A later set-up of sun tracking solar siphons and their water temperature variations [35].

3.4. Examples of optimized solar water heating designs based on South African materials

Fig. 7 shows the outcomes of the optimization procedure for the 3 home market segments. Filling of the tank in the rural starter system is manual because of lack of electricity. Therefore, it is ground mounted. The other two are roof mounted. The larger system has a supplementary electric heating and control system to ensure temperatures are always at least 60 °C like in normal electric geyser systems. Table 3 gives the detailed specifications and indicative retail prices of the systems. It also gives total weights and costs of waste generated in the optimal solutions. Additionally, retail prices of equivalent available competition products are given.

4. Performance example

In this section we give one example of system performance to illustrate the general behavior on a sunny day. The system, corresponding to the optimal 1 m × 1.5 m × 100 L urban starter was manufactured in the university workshop and tested like many others (e.g. see Kanyarusoke [35]) in the university compound. The weather data was obtained from the Campbell Scientific weather station on site, while water temperatures were measured by 2 direct immersion thermometers, installed at both ends of the tank.

Results in Fig. 8 show achievement and maintenance of a steady average temperature within the range 61–66 °C between 2 pm and 6 pm on this sunny day. By 7 pm however, average tank temperature had dropped to 58.5 °C. These temperatures are good enough for normal shower/bath conditions – as they are comparable to normal domestic electric geyser outputs of 60 °C. Their trend is also in agreement with later results of sun tracking solar siphons reported in [35] and part-reproduced in Fig. 9. As explained in the cited reference, temperatures peak some time during the day and thereafter, cease to rise because incident radiation levels in late afternoons/evenings cannot sustain natural circulation of the now – hot water – in the collector-tank circuit. The slight tank water temperature drop in this period is due to normal conduction through tank insulation, followed by convective transfer at the tank cover surface.

5. Conclusion

This paper examined Africa's engineering entrepreneurship problems through a PESTLE analysis. It identified 20 generic issues, some of which were incorporated in an optimization model to design solar water heaters for home use. It was pointed out there can be others depending on the country in question. From a Marketing perspective, the PESTLE analysis yielded three home market segments for any one country: the rural home, with no supply of electricity, the urban small starter home, and the larger urban home. The optimization model was solved for these segments, and prototypes constructed and tested at the university campus. There were two major findings from this work. One, that the rural segment did not at this point in time have a suitable solar water heating system. Therefore, an engineering or other entrepreneur has an opportunity to enter a green-field segment with the design in this paper. Two – that existing systems for the urban sector were relatively of high pricing, perhaps owing to them, being based on external designs, even though some may have been manufactured locally. The crucial difference between the work presented and such systems is that the design here is based on objective conditions within the target markets. It was shown that an entrepreneur using this approach could undercut current prices by 50% and still do good business. While these two might be the biggest contributions of this work, the optimization procedure itself could be extended to designing for the commercial and industrial sectors as well. That is work for future investigations.

Acknowledgments

This research was in part funded by Cape Peninsula University of Technology through a research subsidy grant account number RU63.

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