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THEORY DRIVEN DESIGN AND REAL PROTOTYPING OF BIOMASS PYROLITIC STOVE

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ABSTRACT
This article introduces a design approach integrating early design phase and model based engineering in order to develop innovative biomass gasifier system for rural communities in Africa. The need for such a systemic perspective is imposed by the imbrication of technical, ecological and cultural issues that cannot be ignored while designing new technology. The article proposes an integrated generic design theory approaches to discover and rank by order of importance system's variables and to single out most desired design parameters. A pre-design user requirement assessment was carried out to identify detailed stove's functions. Causal-ordering diagrams sketched for system's modelling. System functions were described graphically and synthesized through simple linear algebraic matrices. Contradictions in system functions were solved using Theory of Inventive Thinking (TRIZ 40). And system's optimization was done through simple Taguchi experimentation method. A two level L8 degree of freedom Taguchi table was used in the experimentation and optimization of the pyrolitic stove. The design approach was exemplified using the case of the "AKIBA" biomass stove.

Keywords: design theory, innovation, optimisation, early design phase, systems engineering

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1 INTRODUCTION AND PURPOSE

Biomass still remains the dominant energy source for developing nations. In Kenya for example, it accounts for about 68% of the total energy mix (KNBS, 2008 and GoK, 2006). About 90% of rural dwellers use biomass and its by-products for cooking (Legros et. al, 2009; GoK, 2006) in Kenya. For those living in extreme poverty, the predominant energy conversion method is traditional three stone fires. This form of energy conversion is waste-full (5 -10 % thermal efficiency) and is also a silent killer. About 1.6 million people die annually due to indoor air pollution as reported by World Health Organisation (WHO, 2005 and Legros, 2009). Thus the recent propulsion towards the development of gasifier/pyrolitic stoves and small-scale biomass technologies include inter alia the rising mortality rate amongst women and children, deforestation, climate change and carbon trading. Biomass gasification can be traced back to over 70 years ago (Srithar G. et. al, 2008 and Diaz, 2006). It is defined as thermal-chemical conversion of biomass to gas commonly known as 'producer gas', tar and charcoal. There are two types of gasifier stoves that have been developed, Top lit Updraft (TLUD) and down draft gasifier systems.

Small-scale gasifier system research and development is at infancy stage. Numerous bottlenecks such as, socio-cultural, technical, literacy levels, systems complexity, user environment, affordability amongst others have hindered substantial progress of the technology. Notably, Anderson and Reed (2004) have developed varieties - forced draft and natural draft systems (1985 to 2004). However due to the aforementioned challenges, no gasifier has been identified, that is suitably adaptable to community needs. With the successful delivery of one of the initial small-scale gasifier, Belonio (2005) came up with a bunch of research areas such as: natural draft system for rural access, continuous operation and not batch system, gas storage and control, low-cost and locally available materials preference. Similarly during performance analysis of 14 different solid biomass stoves, Jetter et. al (2009) highlights that stoves with smaller-mass components have better efficiencies but designing similar stoves with acceptable durability, affordable cost and meet user needs is a major challenge. Coupled with other user – system – environment interaction requirement, the existing gasifiers have numerous limitations to penetrate to their target markets – The Bottom of the Pyramid.

Pahl and Beitz (1997) define the general objective of any technical task as, "*the fulfilment of the technical function, attainment of economic feasibility and observance of safety requirement within the environment of influence*". The multi-tool design approach therefore explicitly analyse systems environment and user interaction in the early design activities; A theory driven approach that has been exemplified in the 'Akiba' pyrolitic stove. Small-scale designs have seldom been considered with in-depth systems definition and sub-system's analysis. Estephan (2007) describes model based engineering as a ladder for elevating models in the engineering process to a central and a governing role in the specification, design, integration, validation and operation of a system; whereas early design phase refers to design stage where initial design ideas are being conceptualised in tandem with the formulation of the building project requirements (Lam et al, 2004). The main task in early design stages supporting a later success of the design process consists of being able to understand holistic perspective the interrelation. The designer has to extract from the complexity of functions, the main problems to solve, a set of fundamental interactions that will influence the behaviour of the system.

This paper is proposing tools to support systemic analysis at early design phase. The goals are two fold: providing approach for modelling the stoves environment and selecting a set of most influential and influenced parameters[1], validating the design approach by real prototyping and performance analysis of the stove[2]. The pyrolitic stove, dubbed "Akiba" stove has been developed through integration of multiple design theories and real prototyping. The name Akiba comes from Kiswahili word for 'saving'. The stove has the potential to increase household savings in terms of money, time, health and environment.

2 DESIGN AND METHODS

The design process explored the usage of combined tools towards a design-oriented focus, in the design of the prototype pyrolitic stove. Integrated design theories and linear algebra modelling led to the first ideal Akiba pyrolitic prototype. Early design phase focused on the theoretical relation between User needs, stove design and user environment. This is an intense decision making phase affecting considerably the quality of the final product. Traditional design methods such as LCA are fundamentally incapable of considering systemic effects despite the huge consequences that might

emerge from global interactions.
In the stoves design the following questions were key: what are the dynamic aspects of the stove's environment? What are the flows, stocks and converters in the stoves environment? What are the useful and constraint functions? What interactions exist between the variables? What are the key variables to be considered in system architecture and prototyping? Figure 1 illustrates a V-Model diagram (Forsberg and Mooz, 1999) that was used as the guiding model at every stage of the systems development.

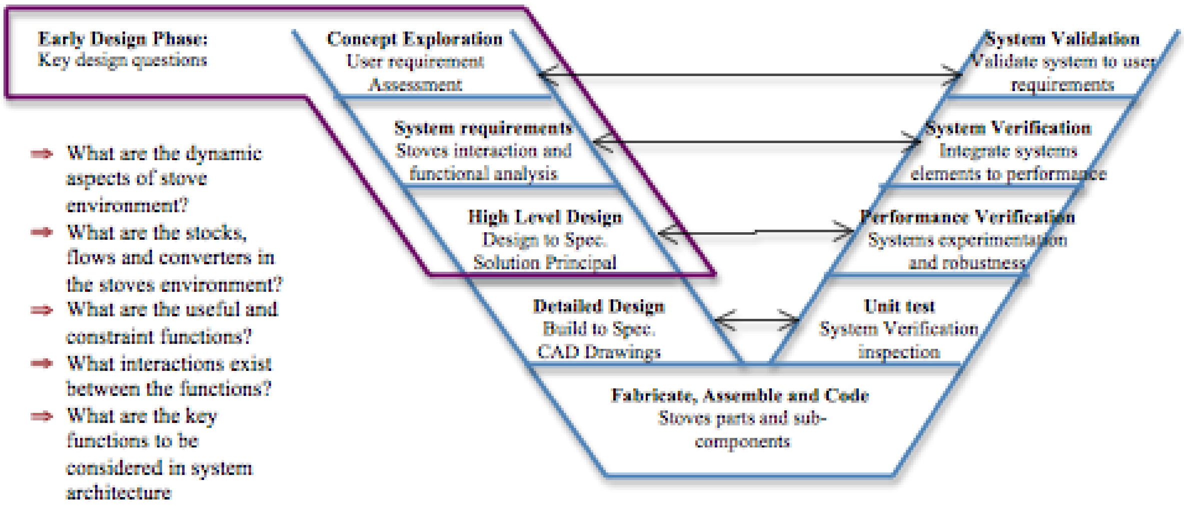

Figure 1. V-Model diagram as applied in the pyrolitic stoves design

2.1 Early Design Stage: The case of biomass pyrolitic stove

2.1.1 Dynamic System Modeling

System dynamic approach was used in this paper due to strategic aspect of decision making process as well as the posibility to study the mapping rules between value analysis modeling approach and systems dynamics modelling language (Boardman, 2008). System thinking paradigm was used for problem discovery and problem solving through the analysis of dynamic aspects of the system. This was achieved by viewing a problem as a conjunction of multiple interacting factors, outcomes or events, all contributing to further development of unintended consequences. There are three different types of causal loops in dynamic system modeling, positive, negative and balanced loop as in figure 2 below. The positive feedback loop indicate that the more the users of pyrolitic stove available, the more the pyrolitic stoves being manufactured, similarly in the negative feedback loop the more adoption of pyrolitic stoves the less the environmental degradation.

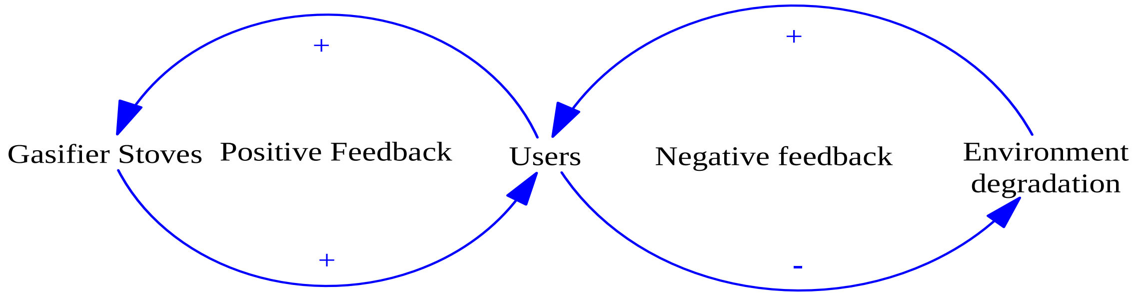

Figure 2. Causal loop diagram

The strength of relationship between two variables was described qualitatively using the polarity signs as in the figure above. Depending on polarity, contradictions emerge. These conflicts or contraditions plays important role in systems development. figure 3 highlights some contradictions as was observed in the analysis of some selected variables.

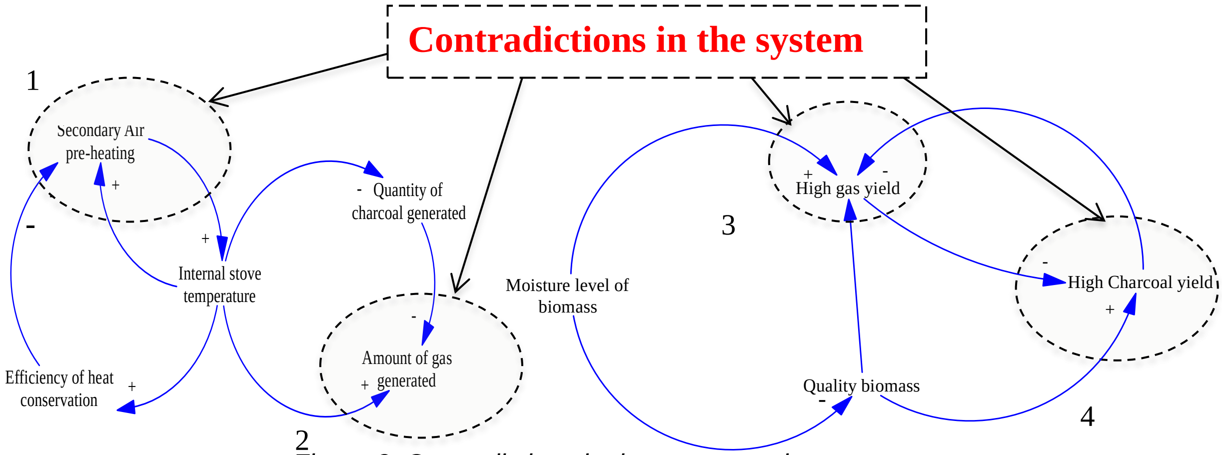

Figure 3. Contradictions in the stoves environment

The authors of this paper hypothesis was that systems dynamics models form an excelent way of locating design contradiction and performing further studies of their influence as in figure 3 above. A contradiction is seen as a non-desired function that comes with the production of a desired function. When a set of contradictions has been discovered then the TRIZ approach was used to solve them. Theory of innovative problem solving (TRIZ) is a Russian inventive design tool. The tool was developed by Genrikh Saulovich Altshuller and is widely used in product development for complex systems. It is a qualitative theory whose formal idea and concepts are like categories patterns and metaphors (Orloff, 2006). TRIZ methodology grasps its positive aspects by integrating past experience into a methodology by describing the underlying design rules of a collection of old successful patents. A systematic discovery of contradiction formed a fundermental tool that supported the design strategy. This is an aspect that was not developed well in the paper but is an area of further research.

2.1.2 Stoves Functional Analysis

Functional, value and cost analysis was arrived at by tree graph method (Apte, 1998; Coatanea, 2005). The diagrams allow the representation of the elements of the environment potentially interacting with the stove as well as different interaction between the stoves and the elements. By listing the functional interaction it was possible to list cost and value inductors for performance evaluation of different functions in experimentation. Table 1 lists service and constraint functions in the stoves environment.

Table 1. Service and constraint funtions in the stoves design

SF	SERVICE FUNCTIONS	CF	CONSTRAINTS FUNCTIONS
1	To transform raw food to cooked food	1	To mitigate on burns by hot surfaces
2	To heat cold water to hot water	2	To be cheap/affordable to local people
3	To transform biomass to syngas	3	To reduce indoor air pollution and to be easily operated and maintained by the users mainly women
4	To combust charcoal to generate heat	4	To reduce the use of wood resource
5	To combust syngas to generate heat	5	To be manufactured by locally available materials and local machineries
6	To transform biomass to generate charcoal/char	6	To be adaptable to peoples cooking habits
7		7	To be able to use variety of biomass feed stocks
8		8	To be used with different size and shapes of cooking pots
9		9	To be easy to operate or use by semi – literate people
10		10	To target X number of people in a household
11		11	To be manufactured by local artisans

The functions were then characterised by set of value and cost inductors describing the properties of the functions for later evaluation of the systems performance. Value inductors measures performance as cost inductors gives a clue on the cost generated by the function. Table 2 below is an extract of a sample list of function, value and cost inductors.

Table 2. Partial function, value and cost inductors

Function	Value inductor	Target	Cost inductor	Target
SF.1 To transform biomass to syngas	H:C ratio of biomass	Target	Concentration of CO	Manimize
	O:C ratio of biomass	Target	Concentration of NO	Minimize
			Smoke emission (PPM)	Minimize
			Volume of stove (m^3)	Minimize
			Heat losses through the surface (^oC)	Minimize
			Moisture level of biomas (%W/W)	Target
			Stove weight (Kg)	Minimize
			Particulate emission (PPM)	Minimize
SF.2 To transform biomass to generate char	Ratio char/kg biomass	Target	Similar to SF 1	Similar to SF 1
	Ratio Ash/kg biomass	Minimize		

2.1.3 Structural analysis

From tables 1 and 2 full list of interacting functions was developed. The complete list was developed taking account of environmental issues, stoves internal variables and service functions. This was then represented in the adjacency matrix partially shown in table 3 below. By rasing the power of the adjascency matrix to an n^{th} level as described by Godet (1994) we are able to select the most important variables to consider when fabricating the stove. Causal graphs can similarly be derived from the matrix below for further simulation using stocks, flows and converters. Godet described structural relationships in a matrix form as direct relation to n^{th} order relationship (Godet, 1994). The matrix relation shows relation between variables as either influencing or influenced. This can be translated graphically for fewer variables however in a complex system synthesis of the relation was done to higher order relationships and represented in chart form.

Figure 4 describes the interrelation between four variables and the corresponding graphical representation. As you move to higher order relations, more interactions are revealed that gives more insight to the most influencing and influenced variables. For-instance, in figure 3 it is not easy to screen out the most important variable in the system as influenced and influencing. However in the forth order relation as shown in figure 4, it comes out clearly that V-B is the highly influencing variable whereas V-A is the highly influenced variable. A plot of a scatter chart as in figure 6, of influenced verses influencing functions gives a chart in which the most influencing and influenced functions can be singled out. The influence-dependence chart is an excellent tool for analysis of product configuration systems.

With the chart we were able to assess the character of the variables. The ideal for every product configuration system is to have a stable system with no relay variables. The presence of relay variables leads to a complex product configuration system; a system with no relay variables would be unambiguous and simple but represents ideality. In the stoves design, figure 6 illustrate a real system with relay variable (quadrant C), highly influencing variable (Quadrant D) and highly influenced variable (Quadrant B).

2.2 Real Prototyping and systems experimentation

The system's design was done taking into consideration the highly influenced and influential variables (Figure 6) and considering the value and cost inductors as highlighted in table 2 above. A 3D model was made and fabricated in the Fablab. The fabricated system underwent actual prototype testing using the value inductors as guiding principal. Taguchi experimentation design was applied for robustness and to ensure optimum experimentation were done.

Table 3. Adjacency Matrix of functional interaction in the stoves environment

MODEL REPRESENTATION USING MATRIX RELATIONSHIP																																									
		STOCKS									CONVERTERS					FUNCTION (Service and Constrain)																									
		Firewood	Gas	Raw. Food	Char/Charcoal	Cooked food	Ash	Tar	Agric. Residues	Forest cover	Air	Agric. Land	Users	Climatic condition	No. Of people in a family	To transform raw food to	To generate heat	To combust gas	To mix air and gas	To generate gas	To transform biomass	To add biomass to the sto	To add heat	To ignite biomass	To channel qty. Of air	To regulate air flow	To adjust inlet air holes	To pre-heat air	To concentrate heat to c	To eliminate fumes	To swirl air	To support cooking pot	To facilitate system's por	To mitigate on surface bu	To conserve heat	To increase reactor temp	To generate char/charco	To dry biomass	To control heat level in p	To stop cooking	To ignite gas	TOTAL
STOCKS	Firewood		1		1	1	-1		-1	-1						1				1	1		-1	-1													1	-1		-1		14
	Gas				-1						1		-1				1	1	1						1																1	8
	Raw. Food	1				1							1			1						1							1			1							1	1		9
	Char/Charcoal		-1	1				-1				1																						-1			1					6
	Cooked food			1											1																											2
	Ash				-1																																					1
	Tar				-1								-1																													2
	Agric. Residues	1	1		1		-1			1						1				1	1		-1	-1													1	-1		-1		13
	Forest cover	-1										-1	1	1																												4
CONVERTERS	Air						-1	1									1		1	1	-1			1		1		-1								1					1	11
	Agric. Land			1					1	-1																																3
	Users	1		1					1	-1	1					1						1	1	1			1					1				1		1	1	1		15
	Climatic condition	-1							-1			-1																										1				4
	No. Of people in a family			1		1						-1																														3
FUNCTIONS	To transform raw food to cooked food	-1		1		1			-1													-1										1		-1						-1		8
	To generate heat			1				1					1			1				1	1	1	1					1	1	1				-1	-1	1	-1		-1			16
	To combust gas		1										1				1					-1								-1										-1		6
	To mix air and gas																	1							1		1														1	4
	To generate gas		1															1	1																		-1					4
	To transform biomass	-1					-1	-1	-1											1		-1															1					7
	To add biomass to the stove	-1	1		1				-1	-1			1																	-1												7
	To add heat																			1	1							1						-1		1	-1	-1				7
	To ignite biomass																1													-1												2
	To channel qty. Of air										1							1	1							1	1	-1			1											7
	To regulate air flow																	1	1						1		1	-1			1								1			7
	To adjust inlet air holes										1								1						1	1																4
	To pre-heat air							-1									1	1								1										1					1	6
	To concentrate heat to cooking pot															1						1												1					1			4
	To eliminate fumes												1																													1
	To swirl air																	1	1							1			1													4
	To support cooking pot												1			1													1				1	1								5
	To facilitate system's portability												1																					1								2
	To mitigate on surface burns												1																													1
	To conserve heat	1						1	1	1						1				1	1	1	1					-1						1			-1					12
	To increase reactor temperature						-1	1			-1						1			1	1													-1			-1					8
	To generate char/charcoal				1		1	-1				1	1							-1																						6
	To dry biomass	1							1											-1	1		-1	1						1						-1						8
	To control heat level in pot															1																	1	1						1		4
	To stop cooking					1										1	1			1	1				1												1		1			8
	To ignite gas		1															1												1												3
	TOTAL	10	7	7	7	5	6	8	9	6	5	5	12	1	1	#	7	8	7	#	9	8	6	5	5	5	4	6	4	6	2	3	2	#	1	6	#	5	6	7	4	

	Influenced				
	V-A	V-B	V-C	V-D	Number of time it is influencing
V-A		1			1
V-B	1		1		2
V-C	1				1
V-D		1			1
Number of time is Influenced	2	2	2	0	

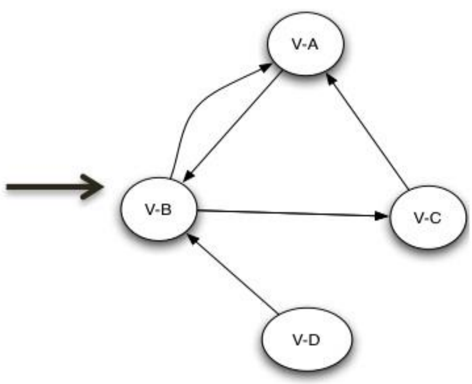

Figure 4. Graphical representation of direct variable relation

	Influenced				
	V-A	V-B	V-C	V-D	Number of time it is influencing
V-A	1	1	1		3
V-B	2	1	1		4
V-C	1	1			2
V-D	1	1	1		3
Number of time is influenced	5	4	3	0	

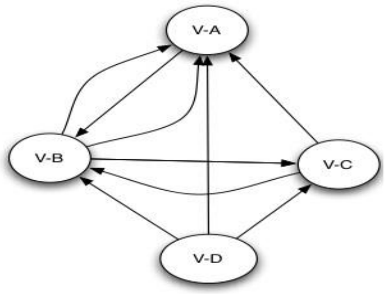

Figure 5. Graphical relation of forth order variable relation

2.2.1 Design of experiment and robustness

Taguchi method uses an orthogonal array to select a limited subset of experiments to run. The orthogonal arrays related to the method are tables showing the configuration of the design variables for each experiment. Otto and Wood (2001) describes the task of robustness as the selection of best set of configuration parameters that satisfies the performance specification with minimal deviations due to manufacture, material or use variations. Table 4 gives key design variables (design features) and experiment level that was applied in the stoves prototype. The four variables done in two levels describe the L8 choice of orthogonal array. The configuration parameters here refer to "inputs" and performance parameters refer to as "outputs" as in table 5 below. A two level L8 orthogonal array was used in systems experimentation and robustness. The systems physical effects were certified with the form design feature of the stove.

Table 4. Definitions of design variables

No.	Variable	Level 1	Level 2
P1	Insulation	Yes	No
P2	Outer shape	Concentric cylinder	Conical cylinder
P3	Air Flow Mechanism	Tangential flow	Axial flow
P4	Chimney effect	Yes	No

The experimental results as highlighted in table 5 were then analysed through a simple algebraic expression of subtracting the general mean "Y" from the resultant output mean for the various test levels. Although the experimentation was more quantitative the level of influence requires further investigation.

Table 5. L8 orthogonal array experimentation result for analysis

No of Experiments	Parameters				Outputs			
	P1 (a)	P2 (b)	P3 (c)	P4 (d)	External Temp. oC	Internal Temp. oC	Start up time (min)	Weight of Char (g)
1	1	1	1	1	84.33	500.0	4	182.0
2	1	1	1	2	50.40	475.0	20	120.0
3	1	2	2	1	42.13	500.0	10	201.0
4	1	2	2	2	28.13	470.0	20	151.0
5	2	1	2	1	164.53	490.0	5	234.0
6	2	1	2	2	37.88	491.0	25	140.0
7	2	2	1	1	96.95	500.0	6	290.0
8	2	2	1	2	77.18	481.0	30	195.0
General Mean (Y)					**72.69**	**488.4**	**15**	**189.1**

2.2.2 Water Boiling Test and Emissions analysis

Using the standard water boiling test procedure version 3.0 of 2007 (Bailis, 2007) three different stoves were tested, Akiba pyrolitic, Kenya Ceramic Jiko and Traditional charcoal stove. The tests were done in the same environment in a span of 3 days period. The data was recorded and analysed.

3 RESULTS

Illustrated as a 3D drawing, 2D and a photographic image in figure 7 below. The design took into consideration the singled out variables from scatter graph in figure 6. From the scatter graph, appearing in quadrant D, heat conservation was the most influencing function whereas biomass type and air (stocks in the system) also presented as the influencing functions. The variables that falls in quadrant C were classified as the relay functions, that when altered affects either results of the system or the influencing variables making its development much complex. They included: to generate heat, to combust gas and users (converter in the system). Both the relay variables and influencing functions were hence key parameters in the stove design. On the other hand Taguchi experimentation studied parametric variations on the form design to optimize the system. The following key variables were established to yield optimised internal temperatures, reduced start-up time and enhanced charcoal production: Insulated, chimney elongation, venturi flow and tangential flow. TRIZ 40 theory was quite useful in complex problem solving in set of contradictory of sub-systems components and variables. In this case the metallic reactor was designed to be internal to the conical ceramic outer insulator. It optimizes heat transfer to heat up secondary air as the ceramic outer that insulates thus enhancing internal temperature of the system and reducing the surface heat losses.

Water boiling test performed in the system gave a positive feedback results however several areas still needs development. The thermal efficiency of the stove was established to be 30% similar to most other modern stoves, however the time required for cooking has been reduced and emission levels drastically reduced as in table 6 below. A survey in India reports that traditional wood stoves report a median concentration of particulate matter (PM) of 1320 µg/m^3 (Johnson et. al, 2011) the Akiba stove PM 209.0 µg/m^3. Research area sited by Belonio (2005) on continuous biomass feeding was made possible with the Akiba pyrolitic, easy to start and made from locally available material. The design sort to reduce on design complexity, 3D and 2D designs were given to a local artisan to fabricate the stove, which he managed to do within six hours. The modular system however expressed user challenges like, stability, components assembly and cultural cooking habits.

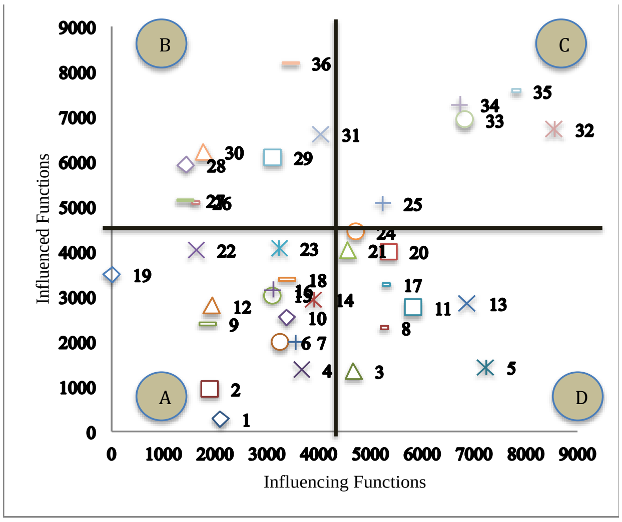

Figure 6. Third order relationship (potential relationship)

Legend.

1. Systems portability	10. Conserve forest	19. Ash	28. Tar
2. Climatic condition	11. Dry biomass	20. Biomass	29. Increase reactor temperature
3. Swirl air	12. Charcoal	21. Increase heat	30. to generate charcoal
4. Cooking pot size	13. Air	22. Control heat level on pot	31. To stop cooking
5. Conserve heat	14. Regulate flow of air	23. Pre-heat air	32. To generate heat
6. Agric. Land	15. To ignite syngas	24. Transform Biomass	33. Gas
7. Adjust inlet air	16. Mix gas and air	25. Channel air	34. Combust gas
8. Start fire	17. To add biomass in stove	26. Eliminate emissions	35. Users
9. Concentrate heat	18. Mitigate on surface burns	27. To cook food	36. Generate gas

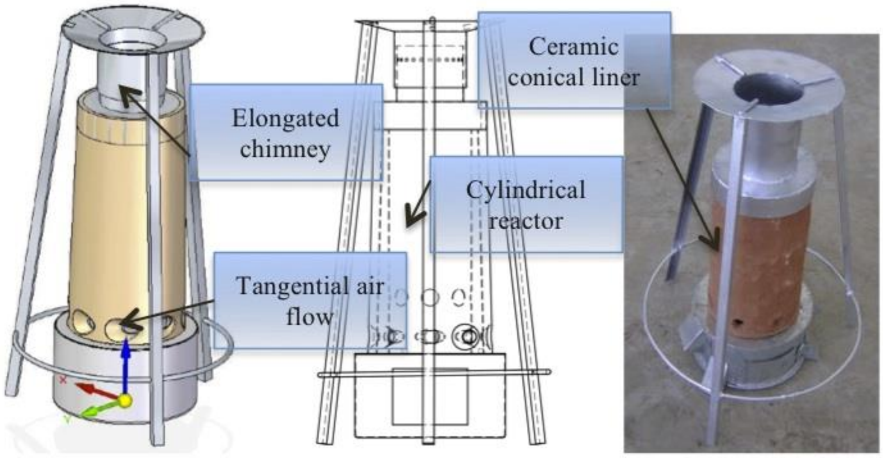

Figure 7. The "Akiba" prototype pyrolitic stove has been developed.

Table 6. Comparative performance analysis of the stove performance as compared to the other stoves

	Kenya Ceramic Jiko (2.5 ltrs)	Metal traditional stove charcoal (2.5ltrs)	Akiba Gasifier Stove (2.5lts)
Specific fuel consumption (g/litre)	85.0	106.9	**76.0**
Thermal efficiency (%)	31%	24%	**30%**
Time to boil water (min)	33.7	26.0	**12.7**
CO (ppm)	78.3	62.5	**33.0**
Particulate (μg/m^3)	140.0	283.3	**209.0**

4 CONCLUSION

The design approach that incorporated theories, models and experimentation logics are great tools in robust systems design and development. The design approach is however a slow and extensively consultative. One main challenge in the design process is the weight of every function interacting in relation to its effect to other functions in adjacency matrix analysis. The research assumed equal weights of a unit; moreover, whether the function affects the system negatively or positively an absolute was assumed. The Taguchi experimentation gave important clues on how to optimise the system towards development of a robust system that is less sensitive to parametric variation. The integrated approach described above, from the case of "Akiba" pyrolitic stove prototype has given a pathway that requires a bit of re-evaluation and refining towards attaining of real robust products for the base of the pyramid. It does not rely on a trial and error concept but utilizes factual theory and easy to understand algebraic expressions in the system engineering.

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