Chapter

Improving Product Quality through Functional Analysis Approach: Case of Dual Axis Solar Tracker

Emmanuel Karabo Mpodi, Zeundjua Tjiparuro and Oduetse Matsebe

Abstract

Product quality determines how well a product meets the customer's requirements. One way of measuring and ensuring that the product's quality is achieved is through incorporating the functional analysis approach in the design process of the product, especially at early stage of lifecycle. A case study involving the design of a dual axis solar tracking system is used to illustrate the approach. In the study, the designed solar tracking concept was compared to existing mechanisms. The designed concept was found to be, generally, less complex than existing models.

Keywords: design, quality, complexity, solar energy, functional analysis

1. Introduction

Since the industrial age, product development has evolved greatly from the primitive craft approach in which design and manufacturing were interlinked to the new enhanced approach in which design and construction are separate. The product development process is often achieved in six (06) steps as illustrated in **Figure 1**. Whereby **Strategic definition** is the identification of the need or a niche in the market, **Research** is the competitive analysis of products related to the one being developed in order to understand the dynamics of the product market and demands, **Product design and manufacturing** transforms ideas into functional objects (physical or virtual). **Production evaluation and selection** is the stage at which the choice of the engineered product is done influenced by factors such as; cost, user preference, product quality, etc. **Use and recycling of product** is the stage at which the product is put to use, encounters tear and wear, it is repaired until it reaches the end of life after which it is disassembled and some parts might be used for other purposes. Finally, **Market feedback** is the input from the market to help improve future generations [1].

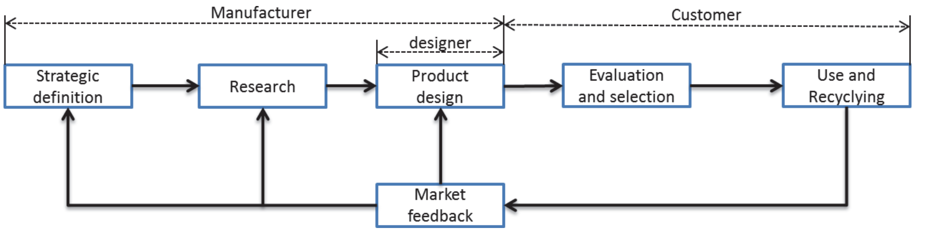

Figure 1.
Product lifecycle [1].

2. Design process model

There are many design models. For instance, French's descriptive model has four stages, namely; a) analysis of problem, b) conceptual design, c) embodiment of schemes, and d) detailing [2]. Cross' model is four staged too. The four stages are; a) Exploration, b) generation, c) evaluation and d) communication [3]. So is Ullman's model consisting of; a) product planning, b) conceptual design, c) product development and d) product support [4]. The stages of all the three models above are nearly similar and apply the general framework given in **Table 1**. Other models comprise of Axiomatic design, the VDI model, quality loss function, and quality-function deployment, and many others [5].

2.1 Design quality

Quality is defined as the ability of the supplier/producer to meet the specified and measurable requirements of the customers. From this definition of quality,

Design stage (descriptive)	Sub-stages (prescriptive)	Relative techniques
Planning	Deriving customer's needs	Questionnaires, usability lab studies, ethnographic field studies, etc.
	Setting design objectives	Checklists, objective and key results (OKR), Specific, measurable, actionable, realistic and time-based (SMART) framework, mind maps, etc.
Generation	Functional analysis	Function-means tree, Becoming-the-flow, Converter-Operator-Transmitter-Control model (COTC) Bond graph model, etc.
	Setting technical specification	Quality function deployment, design for assembly, design for manufacture, theory for inventive problem solving (TRIZ) matrix etc.
	Generating design alternatives	Morphological analysis, brainstorming, biomimetic, design by analogy, 6-3-5, etc.
Evaluation	Testing and validation of product	Simulations, mockup, prototyping, mathematical models, miniaturised models etc.
	Product improvement	Value engineering, Failure mode effect, Fault tree analysis, design for environment, design review, Strength, weakness, opportunities and threads (SWOT) analysis, Pros-cons analysis etc.
Documentation	Detailed design	Technical drawings, designs portfolios, procurement plans etc.
	Design documenting	Design database, patents, product manuals, design report etc.

Table 1.
Summary of theoretical design framework.

design quality is then defined as a practice of ensuring that products developed in a process of design meet the expectation of customer (without imposing any harm to the social and natural environment of society). It is important to control and monitor quality of products in order to minimise cost, resource, time and relative environmental impact of product development.

A five-level hierarchy of design quality was proposed by reference [6]. The attributes outlined in the reference are namely; functionality, reliability, usability, maintainability, and creativity. Functionality of products is considered paramount in controlling, managing, and ensuring that high quality designs are achieved [6].

Simplicity and complexity are also concepts used to define quality of design products. Simplicity is the exact converse of complexity. Simplicity of an artefact is defined as the use of the lowest possible number of lines, shapes, components, etc. without compromising its functional requirements.

2.1.1 Functional analysis

Functional analysis transforms customer's requirements into functional means (physical components). In the approach, the designer surveys the prospective customer's market to develop a product that is suitable for their need. Often, simpler and competitive products than existing ones are realised by this approach [7].

2.1.2 Design complexity

Design complexity is a field in design engineering which focuses on analysing and managing uncertainties of designs (i.e. process and product) due to many interwoven elements and attributes which make an object difficult to understand. Managing complexity in design is important as it reduces effort and resources used when developing products. Design complexity metrics measure a number of design aspects such as; structural complexity: (i.e. physical arrangement and interactions of constituting components), functional complexity: (i.e. number, variety, and interactions of basic and support functions), behavioural complexity: (i.e. predictability and understand-ability of product's behavioural in the field) [8].

Three complexity metrices exist. Bashir and Thompson (1999) developed a design complexity metric system that uses a functional analysis approach [9]. The devices are broken down from basic to advanced functions. This approach considers a linear relationship of functions at each level, but the number of assemblies and components in a device are neglected. Roy et al. (2010)'s complexity metric method was formulated to address the demand of the device with regard to the commonality of components used to construct the device [10]. Whereby product commonality is the number of parts being used for more than one product and is measured for all product family. Keating (2000) developed a complexity metric system which is based on the number of components and their interaction in a device [11]. **Table 2** gives a summary of the metrics and reasons for disregarding some and choosing one.

3. A case study: design and complexity evaluation of dual axis solar tracking concept

To illustrate how the functional analysis technique can be used to remove complexity and ensure that product quality is achieved at the early stages of product development of an engineered system, a design case study for the design of a dual axis solar tracking system is used. **Figure 2** gives the general design framework used.

Reference	Description	Formula	Comments
[9]	Number of functions	$C = \sum_{j=1}^{l} F_j k_j$ Where; C = complexity L = number levels F_j = number of functions at level j K_j = weight of level j; 1,2,	Not selected because only a few of the publications reviewed in this study disclosed the functional analysis of their designs.
[10]	Demand	$C = {}^{d_i}/_{d}$ Where; d_i = demand of part variant d = total demand of product	This approach is based on the availability of product components in the market. Therefore, this method is not relevant for use in this study.
[11]	Number of components and interaction	$C = M^2 + I^2$ Where; M = Module/components I = interactions	Since most publications describe their devices in terms of assemblies, components, and their interactions, this method was found to be the most suitable for this research.

Table 2.
Design complexity metric system.

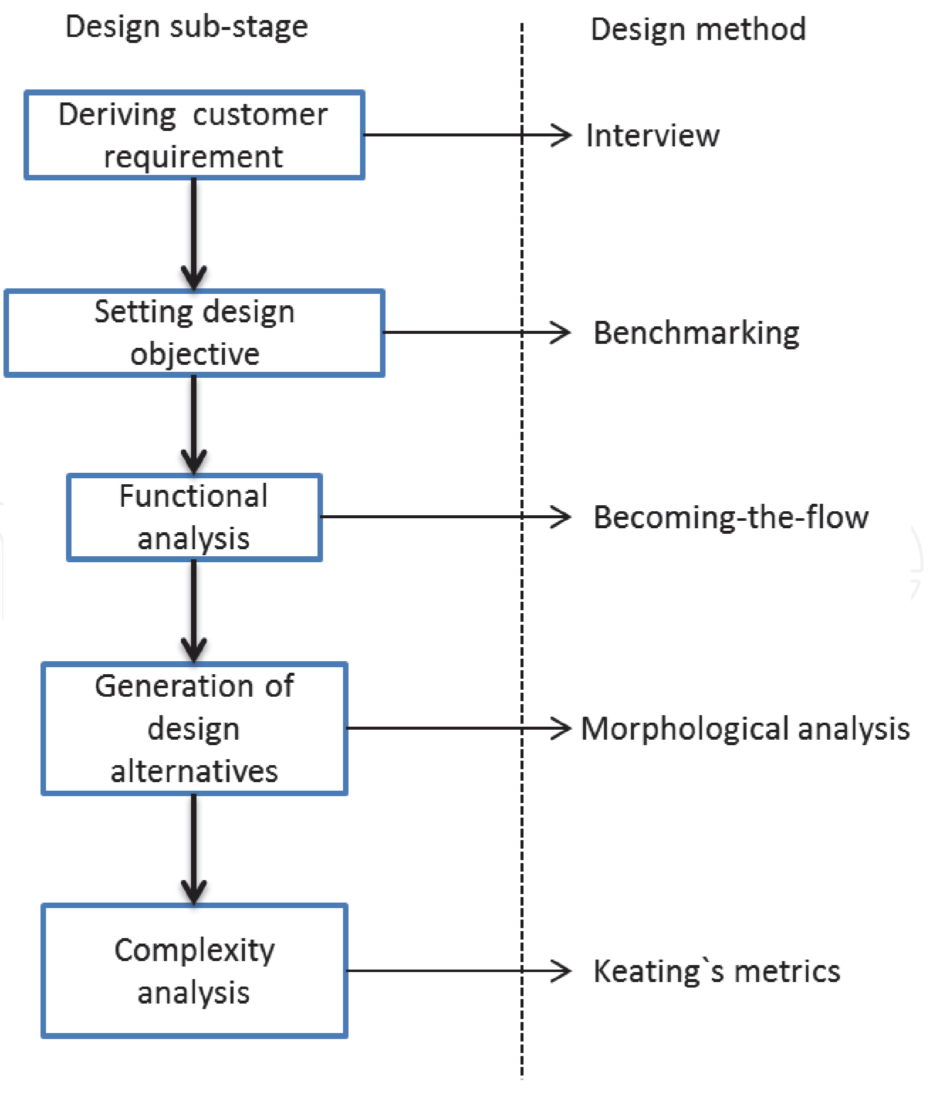

Figure 2.
Design approach for developing a solar tracker.

3.1 Deriving customer's requirements

The requirements of a dual axis tracker were established from an interview conducted with a facility technician at the Phakalane solar plant (Botswana). This was to understand the requirements of a dual axis solar tracker from an expert. The following questions divided into two categories, namely, functional and non-functional aspects were asked in the direct interview:

Functional aspects: The following six (06) questions were asked under functional aspects.

1. What defines the best performing solar tracking, in terms of its;
    a. Level of efficiency
    b. Power consumption
    c. Tracking accuracy
2. How is the solar tracking going to be operated i.e. manually, semi-automatic or automatic?
3. Under which environmental conditions is the device going to operate?
4. Is the device profitable (i.e. what is it payback)?
5. What level of maintenance and repairing is required?
6. What type of technology is required to operate the device?

Non-functional aspects: the following four (04) questions were asked under this non-functional aspect.

1. What method of waste disposal will be used after product life cycle?
2. Is the 3Rs (reuse, reduce and recycle) approach embedded in the product?
3. How will the operation of the device affect wildlife, birdlife and water sources?
4. What level of aesthetics is required for the system?

The requirements described in **Table 3** were identified during the interview.

3.2 Setting design objectives

Firstly, the Universal Track Racks™ by ZomeWorks (in **Figure 3**) was used to come up with the basic functions of a solar tracking system due to its popularity. The tracking system uses two or four *(if is dual axis)* identical cylinders on the edges of a panel frame. These contain a working thermo-fluid (normally a refrigerant). As the position of the sun changes with time, one cylinder receives more thermal power than the other. Due to this, the refrigerant expands and flows to another cylinder through a duct. From this process the function identified is the ability to detect the new position of the sun at a reference point. As the fluid accumulates in the other cylinder, there is difference in weight of the two cylinders. Since system is

Design requirements	Description
Low tracking error	A highly efficient tracking is the one that can position towards the sun with relatively high accuracy, for an improved energy output.
Low energy consumption	For an economically feasible product, the tracking device should consume as little energy as possible or use a mechanism which saves energy.
Fully automated	A machine with little human interface of daily operation, but with ease of use by an operator.
Operational in Array setup (On-Grid)	The tracker should be used on national electrical grid-connected PV system.
Optimum Power output	The solar tracking device should generate enough power either equal or slightly lower than the theoretical expectation, for economical and functional viability.
Optimum Payback period	For an economically viable system there is a need that it has a lower payback period as the profit will be realised in the early period lifetime of the machine.
Environmentally Friendly	Solar energy aids in reducing pollution emission. Therefore, the device should not harm its surroundings e.g. ecological system, water sources, wildlife and birds through generation of toxic waste materials
Aesthetically appealing	Growth in the use of renewable energy technology has led to an increasing interest in many people to comprehend the technology. Therefore, the solar tracking should be aesthetically attractive to attract tourists (i.e. technological tourism)

Table 3.
Identified design requirement for dual axis solar tracker.

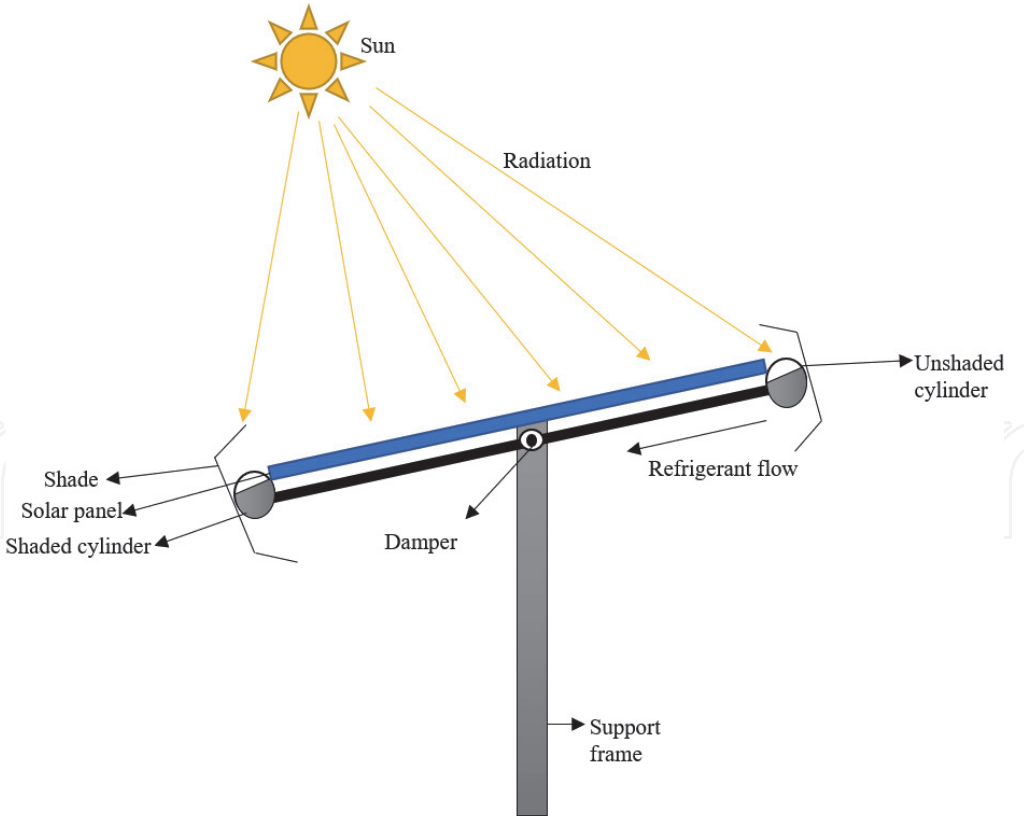

Figure 3.
ZomeWorks passive solar tracker [12].

designed to detect imbalance through a centre pivot, then motion is generated by this effect. To avoid shock on the system, a damper is used to guide and regulate; as other components rotate towards the desired position [12]. From this process four main sub-functions can be summarised as follows;

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a. To precisely determine the position of the sun.

b. To calibrate the positioning mechanism.

c. To generate the tracking motion.

d. To monitor tracking effect.

3.3 Functional analysis

Form follows functions approach was used at this stage. That is, functions establishment should be independent of geometrical state to broaden the solution space [4]. A function is a task that transforms input to output in the system [13]. Therefore, functional modelling is a framework that relates functions in a flow, processes, and the operations to a system.

Retrieval questions	Description	Inputs identified	Type of input (energy, material or signal)	Output
Why is there a need to track the sun for PV application?	There is change in position the sun (triggers the need to measure the change in sun position).	Sun position	Signal	• Sun position • Signal for control
	To increase output of PV by tracking (PV generates electrical energy from sunlight directly)	PV system	Material	• Electrical energy • PV • Solar energy
		Solar energy	Energy	
Can PV system rotate on itself?	There is a need for support structure to provide facilitate motion and solid orientation (the support structure is coupled to the PV)	PV system coupled to the support structure	Material	• PV system + Support structure
How is automation of the system going to be achieved?	The level of interaction with human is low. That is the user only monitors the machine at time of maintenance and unforeseen operations	User	Signal	User
Is the system environmental conditions proof?	The environmental conditions such as wind, rain and cloud shade will affect the tracker	• Wind load • Rain load • Measure of wind • Measure of rain • Measure of cloud shade	• Energy (Wind and rain loads) • Signal (Measure of rain, wind and cloud shade)	• Wind load • Rain load • wind • rain • cloud shade
How is the energy going to be minimised?	This is based on choice of input energy and mechanism (there selection of mechanical energy for providing torque with recycling of waste energy and electrical energy used for power calibration devices can minimise energy)	• Mechanical Energy • Electrical Energy	Energy	Waste energy (heat and noise)

Table 4.
Thought aid process applied for becoming the flow.

Using *"to become the flow"* heuristic approach, the transparent box model was developed to identify the *"function chains"* (i.e. related tasks often performed by a single physical component). **Table 4** shows a thought aid process (e.g. the retrieval questions) used in the "*becoming the flow*" approach. "*Becoming the flow*" approach is based on the flow of energy, signal and material in a system. The first step engaged in this process was to identify the inputs, outputs and following their interactions in the solar tracking system. Inputs in this study are defined as fundamental *"causes"* that ensure that the overall function of the system is performed. Output is the *"effect"* produced in the system i.e. these include; desired and undesired effects. Some of the inputs remain unchanged, while others change (i.e. they are consumed) in a process carried out by a system. These inputs were traced until they exit the system as outputs. To identify inputs and outputs the following guideline were used, a consideration of the requirements (i.e. functional aspect of system), environmental conditions and designer's understanding of the problem.

Transparent box model of a solar tracking device is shown in **Figure 4**. In this model, energy, material, and signal are traced from input to their relative output state. The model was used to identify function chains to achieve relevant tasks. In the stated figure the (SS.) stands for support structure, (tor.) is torque, (sys.) is system, (Ener.) is energy, (mech.) is mechanical, (elec.) is electrical, (Pow.) is power, (Enviro.) is environmental, (Pos.) is position and (Prot.) is protection [14].

3.4 Generation of design alternatives

A morphological Chart was deployed to perform this transitional process, i.e. to present design alternatives generated in this research. Firstly, the function chains identified with the aid of transparent box model were listed in the column of morphological chart (grid). Then possible alternatives (i.e. these are physical components available in market) to perform the tasks of the function chains were identified. Through brainstorming, the grid of the morphological chart was filled by noting (with text) ideated alternatives alongside their relevant function chains (i.e. on the row of the function chain). For example, two alternatives; electronic

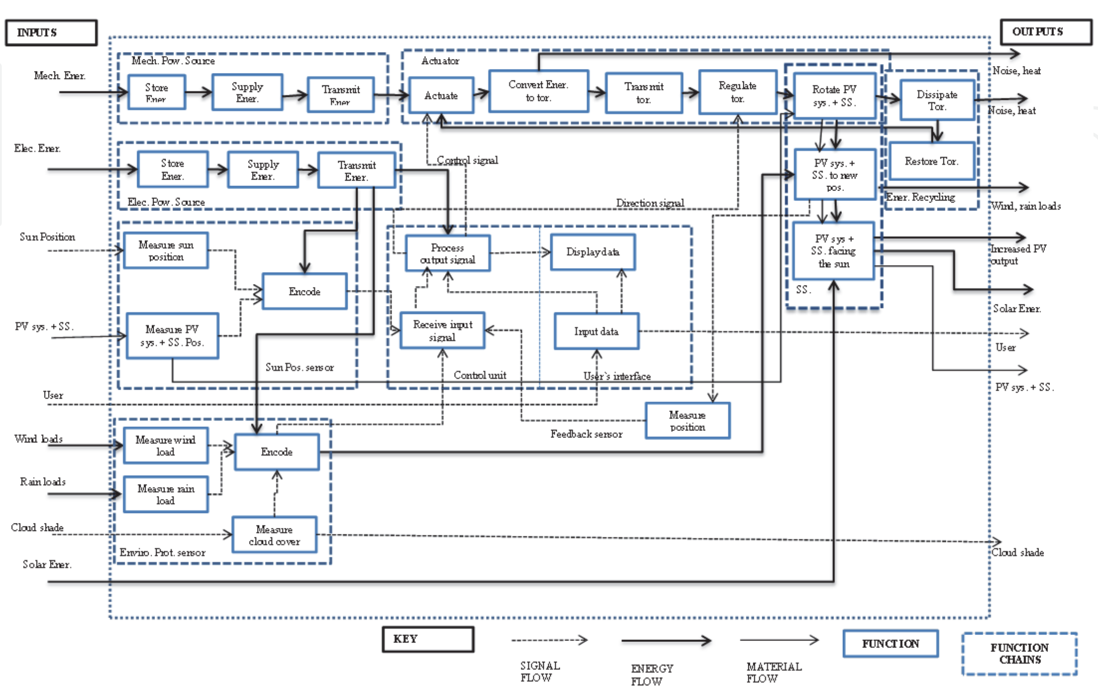

Figure 4.
Transparent box model of a dual axis solar tracking [14].

Function chain (Func.)	Alternatives (Alt.)				
	Alt 1	**Alt 2**	**Alt 3**	**Alt 4**	**Alt 5**
Sun position sensor (Sun Pos.)	Photo sensors	Real-time clock (RTC)	Camera	Global positioning system device (GPS)	RTC+ photo sensor (Hybrid)
Power source (elec.)	Mini PV panel	Grid electricity			
Power source (mech.)	Solar engines	Spring system	Gravity engines		
Control unit (CU.)	Micro controller	Personal computer (PC)	Programmable Logic controller (PLC)	Field Programmable Gate Array (FPGA)	
Actuator (Act.)	Hydraulic cylinder	Pneumatic cylinder	Motor and gearbox	Stepper motor	
User's interface (UI.)	Keypad and LCD screen	Safety switch and LED flashlight			
Support structure (SS.)	Cable mount	Parallel kinematics device (PKD)	Rotating platform (RP)	Polar mount	Counterbalance mount (CBM)
Energy recycling system (ER.)	Spring system	Piezoelectric system	Spring return fluid power actuators	Energy recovery wheel (ERW)	
Feedback sensor (FS.)	Inclinometer	Accelerometer	Magnetometer	Gyroscope	
Wind sensor (WS.)	Electronic Anemometry (EA)	Airflow sensors			
Rain sensor (RS.)	Weighing precipitation gauge (WPG)	Optical rain gauge	Water Sensors		
Cloud sensor (CS.)	Optical sensor	Ceilometer			

Table 5.
Morphological chart present design alternative [15].

anemometry (Alt 1) and airflow sensor (Alt 2) were brainstormed for the function chain; wind sensor (**Table 5**) [15].

$$\text{Possible combinations} = \prod_{i=1}^{n} O \tag{1}$$

$$= 5 \times 2 \times 3 \times 4 \times 4 \times 2 \times 5 \times 4 \times 4 \times 2 \times 3 \times 2$$

$$= 4,147,200$$

The evaluation measures formulated at the planning stage of the design process were then deployed to judge the alternatives. As a way of guiding selection of best alternatives, that will be used to develop a concept. Some of the evaluation measures, which are normally used for evaluation of concepts, are defined below:

- Serviceability/maintainability: This attribute describes the timeliness, relative cost and availability of skilled personnel in the local areas to carry out replacement and/or repair of components.

- Reliability: the ability to maintain an expected functional behaviour at all times and under specific conditions.

- Interfacing/compatibility: the ability of the component to be useable with different configurations and strategies to achieve the desired function.

- Scalability: can a component be easily down or up sized for a specified application.

- Cost: the price value of a single component will affect the total cost of device hence its economic feasibility.

- Availability: ease of access of a component locally or less difficulties in sourcing it.

Evaluation of alternatives was then carried after a five-point Likert scale was established. Then each alternative was scored against the evaluation measure in a relevant manner (i.e. according to the knowledge and discretion of the designer). Points scored by each alternative were aggregated, and the alternative scoring high points were ranked as first choice (refer to **Tables 6** and 7) [15].

Lastly, a concept was developed from aggregating the best-selected alternatives. This resulted in the final design which was modelled using a SolidWorks® platform (**Figure 5** shows the developed concept).

3.5 Complexity analysis

The analysis was carried out by comparing the existing systems' design complexity with the developed concept. In the comparison, the approach used in reference [11] was adopted. This approach uses modules and interactions between the modules to compare design products. A typical Keating's model is given in **Figure 6** whereby the number of components/modules (M), and number of interactions (I), in the design are counted and the inherent complexity computed using (Eq. (2)).

$$C = M^2 + I^2 \tag{2}$$

Table 8 shows a complexity metrics of systems developed in the period, 1997-2017. The average complexity of these systems was found to be 221.43 in this research.

Figure 7 shows a diagrammatic embodiment design of the designed system. Plotting the complexity index of the developed concept against the complexity values of the existing systems give **Figure 8**. The trend illustrated the graph shows a relatively constant increasing pattern at the beginning of the study period up to the year 2005-2007. Generally the system designed is more complex when compared with developed between 1997 and 2004. While from 2005 to 2011 the existing

Func.	Criteria	Alt 1	Alt 2	Alt 3	Alt 4	Alt 5
Sun Pos.		Photo sensor	RTC	Camera	GPS	Hybrid
	Serviceability	4	5	1	3	4
	Availability	5	4	1	3	4
	Interfacing	4	5	1	3	5
	Reliable in cloudy weather	3	2	4	1	4
	Point scored	**16**	**16**	**7**	**10**	**17**
	Rank	**2**	**2**	**4**	**3**	**1**
Electric.		Mini PV panel	Grid			
	Serviceability	5	4			
	Availability	5	5			
	Reliability	4	3			
	Points scored	**14**	**12**			
	Rank	**1**	**2**			
Mech.		Solar engines	spring system	gravity engines		
	Serviceability	5	5	4		
	Availability	4	5	2		
	Reliability	5	2	2		
	Points scored	**14**	**12**	**8**		
	Rank	**1**	**2**	**3**		
Act.		Hydraulic cylinder	Pneumatic cylinder	Motor and gearbox	stepper motor	
	High response	3	4	2	5	
	Controllability	4	4	2	4	
	Interfacing	4	5	2	3	
	Minimal energy consumption	3	4	3	5	
	Compatible to support structure	5	5	3	4	
	Points scored	**19**	**22**	**12**	**21**	
	Rank	**2**	**1**	**3**	**2**	
CU.		Microcontroller	PLC	FPGA	PC	
	Interfacing	5	3	2	3	
	Accuracy and Precision	3	5	4	4	
	Availability	5	4	3	5	
	Serviceability	5	4	2	2	
	Adaptability to control	4	5	5	5	
	Point scored	**22**	**21**	**16**	**19**	
	Rank	**1**	**2**	**4**	**3**	

Table 6.
Evaluation of design alternatives for solar tracking [15].

Func.	Criteria	Alt 1	Alt 2	Alt 3	Alt 4	Alt 5
UI.		Keypad and LCD screen	LED and switch			
	Accessibility of information	5	3			
	High alarm rate	4	4			
	Compatibility	5	4			
	Points scored	**14**	**11**			
	Rank	**1**	**2**			
SS.		Cable mount	Polar	Parallel mech.	CBM	RP
	Optimal land coverage	4	3	2	5	1
	Versatile utility	3	4	2	5	1
	Assemble-ability	5	3	1	5	3
	Optimal material consumption	5	3	1	4	2
	Robust mechanical	1	4	5	3	5
	Points scored	18	17	11	22	12
	Rank	2	3	4	1	5
ER.		Springs	Piezoelectric	Spring return fluid power actuators	ERW	
	Compatibility to control	5	3	5	1	
	Ease of use	4	1	5	2	
	Maintainability	5	2	4	1	
	Availability	4	2	5	1	
	Points scored	**18**	**8**	**19**	**5**	
	Rank	**2**	**3**	**1**	**4**	
FS.		Accelerometer	Inclinometer	Magnetometer	Gyroscope	
	Interfacing	4	5	1	2	
	Cost	5	5	1	1	
	Availability	5	5	2	2	
	Points scored	**14**	**15**	**4**	**5**	
	Rank	**2**	**1**	**4**	**3**	
WS.		Electronic anemometry	Airflow sensor			
	Interfacing	4	4			
	Availability	3	5			
	Scalability	3	4			
	Cost	4	5			
	Points scored	**14**	**18**			
	Rank	**2**	**1**			

Func.	Criteria	Alt 1	Alt 2	Alt 3	Alt 4	Alt 5
RS.		Weighing gauge	optical gauge	water sensor		
	Interfacing	1	1	5		
	Availability	2	3	5		
	Scalability	2	4	5		
	Cost	2	1	5		
	Point scored	7	**9**	**20**		
	Rank	**3**	**2**	**1**		
CS.		Optical sensor	Ceilometer			
	Interfacing	5	2			
	Scalability	4	3			
	Availability	5	1			
	Cost	5	1			
	Points scored	**19**	7			
	Rank	**1**	**2**			

Table 7.
Continuation of evaluation of design alternatives [15].

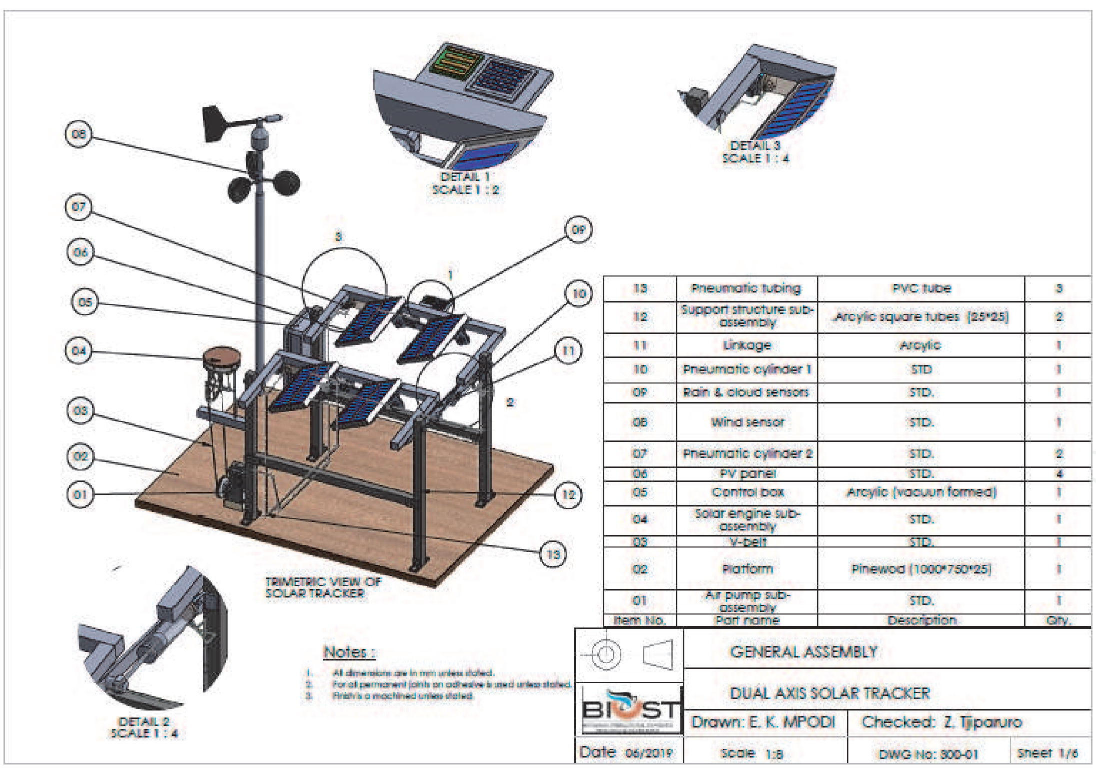

Figure 5.
General assembly drawing of the solar tracking concept developed.

systems are more complex the concept developed in this research study. For period between 2012 and 2017 the system developed and existing system are generally equal in complexity. The pattern was realised because of the advancement which were made to the dual axis tracking such as including weather intelligent features

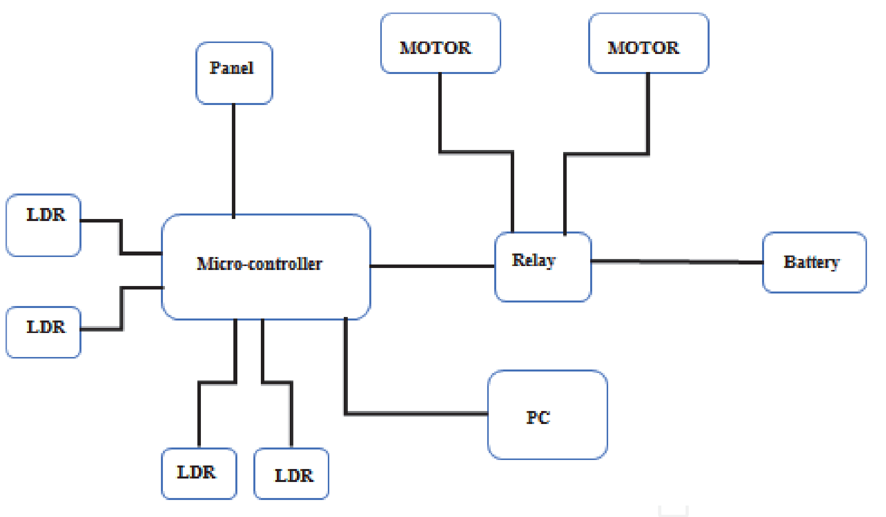

Figure 6.
A block diagram showing module and interaction of system developed by Akbar et al. (2017).

Reference	M	I	C
[16]	4	6	52
[17]	7	8	113
[18]	5	4	41
[19]	10	11	221
[20]	15	18	549
[21]	4	3	25
[22]	6	8	100
[23]	10	10	200
[24]	14	16	452
[25]	13	11	290
[26]	10	10	200
[27]	10	9	181
[28]	10	12	244
[29]	12	11	265
[30]	9	10	181
[31]	10	11	221
[32]	11	13	290
[33]	14	15	421
[34]	9	10	181
[35]	9	11	202
[36]	11	10	221
Average			221.43

Table 8.
Design complexity study of existing solar trackers.

(wind and rain shield systems). In summary the developed system, firstly, falls within the average complexity of existing systems, and secondly, it is 10% less complex than the existing systems.

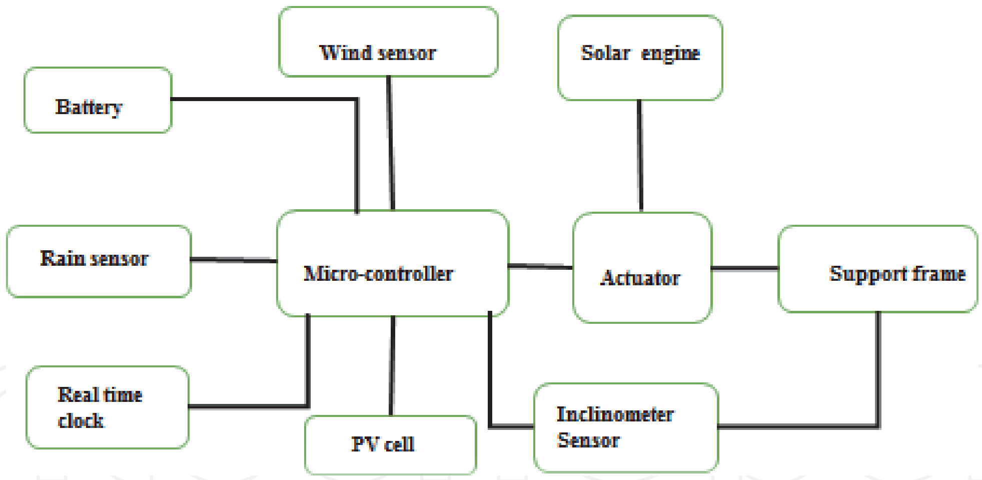

Figure 7.
Embodiment diagram of a solar tracking concept developed.

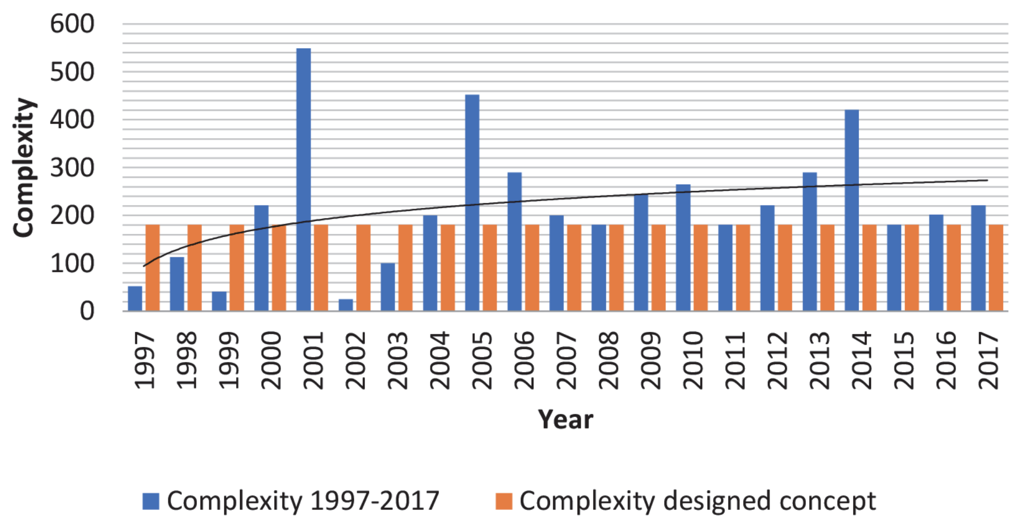

Figure 8.
A comparison of design complexity for the developed concept and existing mechanisms.

4. Conclusion

In this chapter a design of a dual axis solar tracker was used to describe a way of enhancing product's quality, during the early stage of product design. A design and complexity analysis undertaken resulted in a less complex solar tracker. The developed concept was evaluated against the existing solar tracking systems. Therefore, carrying out an analysis of complexity on system at an early stage of product design is important in improving the product functionality and simplicity factor. Consequently, this will relatively reduce the product's cost and design effort.

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Conflict of interest

The author(s) declared no potential conflict of interest in regard to this research, authorship and/or its publication.

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