ASHESI UNIVERSITY

THE DESIGN AND FABRICATION OF A PEDAL POWERED WASHING MACHINE

CAPSTONE PROJECT

B.Sc. Mechanical Engineering

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2020

ASHESI UNIVERSITY

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CAPSTONE PROJECT

Capstone Project submitted to the Department of Engineering, Ashesi University in partial fulfilment of the requirements for the award of Bachelor of Science degree in Mechanical Engineering.

Elisheva Mimi Lustig

2020

DECLARATION

I hereby declare that this capstone is the result of my own original work and that no part of it has been presented for another degree in this university or elsewhere.

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Date:……………………………29th May, 2020..……………………………………….

I hereby declare that preparation and presentation of this capstone were supervised in accordance with the guidelines on supervision of the capstone laid down by Ashesi University.

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Date: …………………………………………………………………………….……

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Abstract

Performing daily activities such as laundry are influenced by available resources which vary concerning demographics and geography. An estimated 14% of the global population live off-grid; a fraction of which live off-grid by choice and the majority do so due to the limited to no electricity supply. The provision of electricity to meet the rate of demand is essential to improve the standard of living; however, our energy and resource consumption habits increase carbon emissions. Large scale laundry habits have been identified as a contributor to climate change with studies concerned by the considerable carbon emissions released by automatic washing machines. However, the alternative handwashing is considered time consuming and labour intensive. These alternative perspectives establish the trade-off faced between labour-intensive and energy-intensive habits or technologies. In the era of accelerated climate change, it is essential for understanding how technological inefficiencies and energy-intensive technologies affect climate change and sustainability. Motivated by addressing the trade-off, this project aimed to design and simulate an alternative powered washing machine. The alternative concept originated from the sustainability initiative of Environmentally Optimized Laundry, which intends to satisfy the need for a less labour-intensive laundry practice specifically communities and households living off-grid and also encourage a less energy-intensive laundry practice for the majority of the population. This project, therefore, offers an unconventional yet more effective alternative to handwashing by mimicking some characteristics of a modern electrically powered washing machine. The outcomes of this project demonstrate the possibility and the benefits of rotating a washing drum with the capacity of 6.5kg using purely mechanical rotational input.

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CHAPTER ONE - PROJECT INTRODUCTION

1.1 Background

Laundry is an activity performed in every household regardless of demographics or geography. This activity is performed in several different ways, using different machines, tools, and cleaning fluids. Due to technological advancements, laundry has been revolutionized to produce clean clothes faster and more effectively than ever before. Hand-washing, including the use of stones and wooden planks to wash clothes date as far before 2800 B.C. [1]. In the 1800s, the need for an alternative less labour-intensive method led to the development of a copper container that used hot water and soap powders to wash clothes [2]. Many other mechanical devices were utilized until the development of electricity in the 1900s, which further required much less human inputs [3]. This development mainly impacted large scale laundry service specifically in hospitals, while small scale domestic laundry services performed in households adapted to electrically powered washing machines later on.

It is estimated that 1.1 billion people, which is 14% of the global population, live off the grid [4]. This population is predominantly developing countries, mainly concentrated in sub-Saharan Africa and Asia; 84% of which are residing in rural areas [4]. Most of these communities tend to result in the method of handwashing due to the limited to no electricity supply, whiles others handwash because of the relatively high cost of electricity and prices of electric washing machines. However, handwashing is considered immensely time consuming and inconvenient, hence the drive for technological advancement over the years. This project seeks to design and fabricate a mechanical washing machine that creates the turbulent flow required to wash clothes efficiently. The project intends to derive design concepts from the years of revolutions of the modern washing machine to enhance the user interface. The design employs the pedal–gear system generally found in bicycles and converts the pedalling input into rotational energy, which generates turbulence within the washing drum. The washing drum hereafter referred to as the drum is the cylindrical area in which clothes are washed. Adequate design of the drum is essential to determine the quality of wash.

1.2 Problem Definition

Although the rate of electricity access by 2030 will be at an all-time high, the awareness and demand for renewable energy are also on the upsurge. Using Ghana as this project's case study; it is estimated that the annual population of Ghana is increasing at a rate of 2.2%, this indicates that the increase in the population growth will reflect an increase in the demand for natural resources especially energy resources [5]. The rate of electricity supply, however, does not meet the rate of demand, as currently the demand for electricity is growing annually at the rate of 10 - 15% [6]. Energy efficiency has been the driving force of the Industrial Revolution; it is imperative to note that references to energy efficiency indicate specifically using less human energy to perform a task [7]. This project aims to challenge the relevance of energy efficiency and its impact on natural resources.

A study carried out in 2009, estimated the global water and energy consumption for performing laundry using electrical washing machines accounted to about 20 cubic kilometre (km^3) and 100 terawatt-hours (TWh) of electricity per year [8]. Using alternative renewable energies to perform daily activities will reduce the rate of demand for electricity. The adaption of these alternative energies is dependent on its relative effectiveness and functional usability. This project aims to design a low-cost, effective human-powered washing machine with comparable efficiency with a modern electrical washing machine. The selected demographic focuses on communities with no electricity or unreliable electricity supply as well as households adopting alternative energy-saving and environmentally friendly practices. The successful execution of this project would provide a more efficient alternative to handwashing and an equally suitable alternative to the use of an electric washing machine, which aims to be a better alternative for the environment by reducing one's carbon footprint. To accomplish this, mechanical theory such as gear systems, torque and friction generation was employed.

1.3 Objectives of The Project Work

The general objective of the project is to design and fabricate a life-sized working prototype of a pedalled powered washing machine designed to produce the desired generic output of any modern electrical washing machine. The project's specific objectives are listed below;

i. To develop a low-cost, effective alternative to the electrically powered washing machine.
ii. To design a pedalled powered washing machine with a maximum drum capacity of 6.5kg.
iii. To design a washing drum, which effectively creates turbulence to achieve the desired quality of wash.
iv. To design a user-friendly, constant speed one direction rotating washing drum to facilitate the washing of clothes.
v. To design a mechanized laundry system which requires less water and detergents to perform one wash cycle as compared to a selected generic modern electrical washing machine and the handwashing method.

1.4 Expected Outcomes of The Project Work

The deliverables expected after the completion of this project, include the following:

i. A well-designed and functional prototype with an efficiency assessment to an already existing washing machine.
ii. Accurate cost and resource consumption assessment to an already existing washing machine.

1.5 Motivation for Project Topic

Mechanical energy is utilized in almost all devices, equipment, and machines today, and with the increasing awareness of global warming and renewable energies, performing daily activities using alternative environmentally friendly options is on the upswing. Communities that either has no or limited power supply will benefit from the mechanical advantage such a project explores. This project is motivated by the possibility of altering the notion that doing laundry effectively is a luxury. The porotype developed aims to provide a mechanized laundry system, accessible irrespective of economic classes whiles contributing to environmental sustainability. Environmentally optimized laundry is the concept from which this project is built. Laundry operations considerably contribute to greenhouse gas emissions with large scale laundry services. On average for every 907 kg of laundry, 22,713 litres of water is used with 7 million BTUs of thermal energy consumed, which causes about 372 kilograms of carbon to be released into the atmosphere [9]. Although this project is specifically targeted at households, the combined effect of small-scale laundry services is significant to greenhouse gas emissions as well.

Similar projects have been undertaken in India and South African with the motivation of limited to no electricity supply whiles America has explored variations of this project for people motivated by an “off-grid" lifestyle. The deliverables in these projects undertaken were fabricated mechanized laundry device implementing the varying concepts of a pedalling system as well as linear inputs. Although these concepts may be equally effective, this project seeks to explore the option of ease of manufacturability which directly affects the cost of production. The prototype developed is purposely low-cost and adopts a standard bicycle in its design which aims to improve the rate of consumer adoption and product accessibility.

1.6 Research Methodology Used

The research methodologies utilized in this project were Systematic Literature Review, Experimentations, as well as Computer-Aided Design modelling and simulation.

1.7 Facilities Used for The Research

The Ashesi University's internet resources and facilities were used to implement the in-depth research phase for this project. The fabrication and testing portion of the project utilized the mechanical workshop and laboratory to ensure the achievements of the project's deliverables.

1.8 Scope of Work

This project consists of a literature review and research, conceptual design, washing drum design, calculations, CAD design and simulation, and the fabrication of a working prototype. This project is limited to the design and fabrication of a pedalled powered washing machine with the system and user requirements.

The type of project management life cycle employed in this project is Iterative, implying that the detailing of the scope will be phased. The following are the phases by which the deliverables of the project will be executed.

i. **Research**: This was performed by using the Systematic Literature Review approach. The findings are documented in Chapter 2.

ii. **Conceptual evaluation**: Based on the research findings, a proposed prototype design was elected by comparing the desired functionality and aesthetics.

iii. **CAD design and simulations**: The results of the simulation were utilized to suggest improved designs and iterations to aid future works.
iv. **Procurement**: The bill of materials drafted was then approved by the project's supervisor, allowing for a purchase order to be made. The items were purchased after market sourcing and delivered to the mechanical workshop on the university's premises.
v. **Fabrication**: This stage was performed in the mechanical workshop and involved several manufacturing processes such as welding and sheet metalwork.
vi. **Testing and Evaluation**: At this stage, the prototype's design was assessed, after which enhancements were suggested to be executed in future works.

1.9 Revised Scope of Work

In light of the global pandemic, the resources provided by the University are at this said time currently unavailable, making some of the intended fabricated deliverables and assessments unattainable.

The following are the revised deliverables present in this report:

i. Research & Conceptual Evaluation
ii. Computer-Aided Design
iii. Static & Dynamic Simulations
iv. Results & Analysis
v. Fabrication of external washing drum shell
vi. Recommendations & Design Improvements

2.0 Chapter Outline

The documentation of the processes by which this project undergoes was divided into six chapters. The First Chapter is titled Introduction, and it details all the information about the project's description, motivation, and scope of the project. The Second Chapter entails all literature review content vital to the project. Chapter Three details the system and user requirements of the prototype which guide the design and fabrication. Chapter Four specifies the methodology implemented whiles Chapter Five documents the results and analysis from the entire project. The project is then concluded in Chapter Six, which discusses findings, limitations and future works.

CHAPTER TWO – LITERATURE REVIEW

2.1 Technological Advancement

19th century America depicts the current 21st century's developing countries, as daily activities were similarly labour-intensive. The use of burning wood for cooking, cast irons for ironing, and handwashing of clothes implied that domestic work required immense human and time inputs. Laundry was considered to be the most detested household chore as a Nevada housewife Rachel Haskell, proclaimed it as 'the Herculean task which women all dread' and 'the great domestic dread of the household' [10]. The first washing device invented to ease the labour intensity was invented in 1797 by Nathaniel Briggs, which consisted of a simple ridged board where clothes would be rubbed against it whiles simultaneously rubbing soap on the clothes [11]. Washing clothes either entirely by hand or with the aid of boards is strenuous and time-consuming. The Industrial Revolution offered an opportunity to develop various technologies to make life easier for humans. The clothes washer technology was developed to tackle the labour-intensive laundry process. The first washing machines were invented by James King, an American made from wood, and the clothes were placed in a drum and were hand-operated [1]. The mangle, a mechanical device, was invented to help squeeze the water from clothes. The design of the mangle posed potential hazards for the user as fingers or hair may be caught by the device. Metal drums later replaced the wooden drums as they could be heated by an open fire causing an increase in the quality of wash.

The first electric-powered washing machine, according to patent records, was invented by Alva J. Fisher [11]. This washer incorporated the electric engine invented by Tesla in 1888 [12]. The Bendix Corporation announced the first household automatic washing machine in 1937 [11]. This was considered very expensive as the components used were relatively new at the time. The design variation between the first electric washer and the first semi-automatic washing machine was the intermediate spinning [13]. The designs of washing machines have evolved over the centuries, making it cheaper, more effective, and more convenient to use.

2.2 Modern Types of Washing Machines

Intending to make washing machines available to the masses, manufacturers have adopted significant technological advancements such as electric motors in order to reduce the cost without compromising on functionality. Technological advancement has led to several design variation caterings to the demand of the market. Features such as built-in sinks, silent washes, washing modes, loading orientation, variable temperatures, rotation speed, spinning times, and modern finishes and material designs are available to the market. The software seamlessly integrated with the hardware makes the user interface better than ever before. Typically, modern washing machines are classified either as Top or Front-loaded due to the axis of washing drum rotation.

2.2.1 Top Loaded

This type of design consists of the wash drum in a vertical position orientating the loading of the washer from the opening at the top as viewed in *Figure 2.1*. Located at the base of the drum, an agitator is positioned, which causes the clothes to rotate in alternate circular directions. Once the washer is loaded, water and detergents are added or vice versa. The door is then closed as the wash cycle begins; the agitator motion produces a pattern of movement for the water and laundry, which creates the friction needed to remove dirt. This design is considered more abrasive as the agitator grads and threshes clothes than the Front-loaded washer. Due to the presence of the agitator, the drum capacity is relatively small. The drum capacity affects the number of load cycles a household may need, which in turn affects the energy consumption [14]. The Top-loaded orientation requires the clothes to be fully immersed, hence increasing the water and detergent required for a load cycle.

Figure 2.1. Top-Loaded Washing Machine

2.2.2 Front Loaded

The front-loaded washer's drum is in a horizontal position, and it has no agitator. Paddles create the friction on the walls of the drum, the rotation of the drum as well as gravitational force acting on the drum [15]. The paddles provide a gentler wash compared to the Top-loaded, by moving the clothes and mixing the water and detergents. This type of washing machine has a larger capacity, and it is typically more expensive. The Front-loaded orientation reduces the water and detergent used in a wash cycle by half in comparison to the Top-loaded washer [14].

Figure 2.2. Front-Loaded Washing Machine

2.3 Environmentally Optimized Laundry

The trade-off between labour-intensive laundry and energy-intensive laundry, especially in terms of commercial laundry services such as the hospitality industry is apparent when considering the amount of carbon emissions released by automatic washing machines. Using the United States as a case study due to the available detailed data on the subject matter; Studies show that on average an American family washes three loads of 5 kg laundry per week which produces over 440kg of carbon emissions each year [16]. Laundry habits are contributors to climate change and hence sustainability initiatives such as Environmentally Optimized Laundry are essential to consider. Evaluating the impact of consumer products throughout its life cycle can spark concern and encourage eco-friendly habits, especially with daily activities such as cooking, cleaning, amongst many others.

2.4 Existing Works

Before the onset of electricity, the washing machine revolution already began. Different forms of generating turbulence were used in some initial washers. Unfortunately, 19th century America conditions are still present in the 21st century's developing countries, mainly in sub-Saharan Africa and Asia. The lack of electricity and poverty makes performing daily activities such as washing strenuous. Manually powered washing machines have been developed a handful of times, but none is currently being mass-produced due to the lack of demand and the labour input required. The lack of demand is not because there is no need, but because the user experience is not prioritized. The manually powered washer requires human inputs and might be considered equally as strenuous, if not more. The consumer finds it difficult to adopt this alternative as compared to the regular handwashing. Pedalling commonly identified with riding a bicycle appears to be a method which can be quickly adopted due to the familiarity. However, pedalling becomes increasingly challenging to do as the loaded drum makes it challenging and tiring.

Pedalled power washing machines have been researched, designed and fabricated a handful of times with different drum orientation and other design considerations. However, this project focuses on the drum design, its orientation and its system integration to create an easily manufacturable and capable laundry system prototype. Local manufacturability offering a low-cost prototype further differentiates this project from existing works.

CHAPTER THREE – REQUIREMENTS

This chapter investigates the design considerations and engineering specifications for this project. The design proposal is documented for reference whiles the conceptual evaluation criteria is performed to arrive at the final prototype proposal. The design considerations highlight both the user and system requirements to assess functionality and the prototype user interface and user experience.

3.1 Design Proposal & Stakeholder Identification

The project baseline objective is to design and fabricate a manual washing machine powered by a rotational input. This system aims to improve the user interface of manual washing and provide an equally good alternative to the modern automatic washers. This project is designed targeting households in communities with no or inconsistent supply of electricity and households with eco-friendly habits by offering an affordable mechanical washer.

In order to reduce the cost of production and increase manufacturability, the washer should be able to mount on almost any existing bicycle frame. The washing machine drum will be designed to provide the best operational results in terms of the quality of wash.

3.2 Requirements

These requirements consider both the user's needs and desires as well as functionalities of the system. The user in this project would be operating the pedalled-powered washer as often as their lifestyle demands. Still, for uniformity, it is estimated that the user will use the system a minimum of once a week. The basic functionality of the system is to provide the desired level of quality wash after a wash cycle.

3.2.1 User Requirements

The user should be able to:

1. Find the prototype less time and labour intensive than the method of hand washing.
2. Find the prototype cheaper than most automatic washing machines.
3. Use the system completely off-grid, making it an eco-friendlier option than automatic washing machines.
4. Use water efficiently when using the system; promotes water savings as compared to the selected automatic washing machine.
5. Use less detergents when using the prototype washer.
6. Use the washer without producing overly distracting noise.
7. Have a pleasant user interaction when using the prototype washer.

3.2.2 Non-functional Requirements

Some of the user requirements overlap with non-functional requirements. The non-functional requirements refer to the requirements not necessarily required for the system to operate and does not affect the baseline objective.

REQUIREMENT TYPE	NON-FUNCTIONAL REQUIREMENTS	NOTES/JUSTIFICATION
Non-func.Req.1 Cost	The washer must be affordable, i.e. market price must range between \$30 - \$60.	Typical washing machines' estimates range between \$250 - \$2050 [17].
Non-func.Req.2 Manufacturability	Materials used to fabricate the washer must be locally sourced.	Easy to fix, maintain & manufacture due to easy accessibility.
Non-func.Req.3	The size of the entire system must be	For an individual/household with a bicycle, the

Adoption	comparable to the size of a regular bicycle.	additional space required by the washer will be negligible.
Non-func.Req.4 Cost	The washer must be able to fit the frame of most bicycles when setting up the washer's parts.	For an individual/household with a bicycle, only the washing drum and stand is required which further reduces the cost of purchase.
Non-func.Req.5 Durability	The washing drum must have no leaks.	Any leaks will contribute towards water consumption and may affect the quality of wash.
Non-func.Req .6 Durability	Function for at least 11 years, assuming at least once a week use.	The average life expectancy of new automatic washing machines is 11 years [18]
Non-func.Req.7 Adoption	The washer must be culturally acceptable, meaning it must have a suitable appearance and user position, for easy adoption.	
Non-func.Req.8 Adoption	The washer must be comfortable for the user to interact with often.	

Table 3-2-1 Non- Functional Requirements

3.2.3 Functional Requirements

In order to formulate the prototype's functional and system requirements, a modern washing machine is selected. As one of the objectives of the project is to fabricate an effective alternative to electrically powered washers, the washer selected aided in performing an accurate assessment of the prototype. The maximum load capacity and power consumption were used as the determinants for the selection. The load capacity plays a major role in structural failure, and power transmission will provide insight into carbon emission analysis. Based on the determinants, with a maximum load capacity of 6.5kg and power consumption is 400 Watts was selected [19].

The prototype should be able to:

1. Operate without the use of electricity.
2. Use a maximum of 15L of water per load.
3. Produce washed clothes with a similar quality of wash as those washed using the Panasonic 6.5.
4. Produce washed clothes with a similar or better quality of wash as one hand-washed.
5. Produce clothes which wearing occurs at a slower rate than hand-washing (hole/tear growth).
6. Preform a wash cycle within 20 – 30 minutes per 3kg – 6.5kg of laundry, including rinsing but excluding drying.
7. Effectively creates turbulence to aid the washing process.
8. Wash clothes effectively only utilizing a constant direction of rotation.
9. Have the maximum drum capacity of 6.5L and the weight of the washer must not exceed 15kg, including the bicycle frame.

3.2.4 System Requirements

The system requirements further specify essential requirements supported by engineering studies or knowledge. Some functional requirements overlap with the system requirements, which is referenced as the parent requirement in *Table 3-2-2*.

REQUIREMENT TYPE	PARENT REQUIREMENT	ENGINEERING REQUIREMENT	JUSTIFICATION

System.Req.1 Consumption	Functional Requirement 2	Total usage of water is 15L per load.	The most efficient washers use less than 18.9 L per load [20]; hence, the proposed washer must be equally efficient.
System.Req.2 Performance	Functional Requirement 3 & 4	Rinse water is equally clean, specifically 5-20 NTU.	As the range 5-20 NTU is considered an acceptable range to measure the quality of the wash [21].
System.Req.3 Performance	Functional Requirement 6	Preform a wash cycle within 20 – 30 minutes per 3kg – 6.5kg of laundry, including rinsing.	An average load of laundry takes between 30 - 45 minutes, including drying [22].
System.Req.4 Performance	Functional Requirement 7	Effectively creates turbulence utilizing drum rotation and pedals.	Adequate contact must be achieved between detergents' particles, and the clothing to achieve a quality wash [23].
System.Req.7 Structure	Functional Requirement 10	The washer should be able to carry up to 6.5kg which means the maximum weight of the washer including the bicycle frame must not exceed 15kg.	The factor of safety considering the maximum load must ensure the safety of the user and structural integrity of the system.

Table 3-2-2 System Requirements

3.3 Conceptual Evaluation Criteria

3.3.1 Washing Drum Rotation Mechanism

Based on the requirements, a conceptual evaluation was performed to select drum design. Conventional washing machines rotate alternately in the clockwise and anti-clockwise directions, implementing this using a pedalling system was evaluated. The results aim to support the overall system functionality.

		BASELINE	ALTERNATIVE SOLUTIONS	
CRITERIA	WEIGHT	ALTERNATIVE DIRECTIONS WASHING DRUM ROTATION	WHITWORTH QUICK RETURN MECHANISM	ONE DIRECTION WASHING DRUM ROTATION
OVERALL EFFICIENCY OF SYSTEM	5	2	3	4
EFFICIENCY OF WASH	5	3	4	4
EASE OF USE (INPUT INTENSIVE)	5	1	2	3
COST	4	1	3	3
EASE OF MANUFACTURING	3	1	3	3
DURABILITY	3	1	2	3
TOTAL	25	9	17	20

Table 3-3-1 Rotation Concept Evaluation

The first option implements a planetary gear system, the crank of the pedalling system is attached to the red gears, as shown in *Figure 3.1*. The red gears are both on the same rotational axis and rotate at a constant velocity and direction. At a specific rotational angle, the sun gear (the centre red gear) causes the direction of the blue gear to change, which in theory is attached to the washing drum. This planetary gear system allows for the drum to rotate in two directions as a conventional washing machine does.

However, the disadvantage of this system is the increased rate of wearing the gears experiences, as well as the amount of input needed to overcome friction when the gears cause a change in direction. The increased wearing rate will cause an increase in maintenance cost as gear replacement will be needed often. Based on these disadvantages, this option was not selected for design and fabrication.

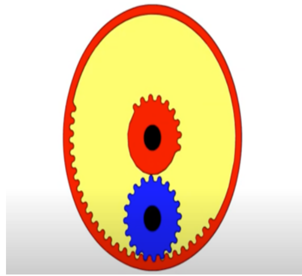


Figure 3.1. Alternative Directions Gear System [24].

The Whitworth quick return mechanism is similar to the single direction rotational system. It requires a linear motion input rather than the rotational motion input of the pedals. This mechanism was considered because of the disadvantages of rotational motion input, such as its labour intensity. However, implementing this option would imply an increase in manufacturing and production cost as compared to the alternative, which is readily available. Based on this evaluation, the single direction rotation system was selected.

3.3.1 Washing Drum Axis

As mentioned earlier in Chapter Two, 2.2.2 Front Loaded, horizontally positioned drums require less water than the vertical axis drum. This is because the horizontal axis drum only requires half the drum to be filled as it uses gravity to create turbulence, which washes clothes above the waterline after which the clothes fall back into the water. Based on this, the front-loaded drum orientation was selected. In Chapter Four,

4.4 Material Selection, further detailed deductions on the material used for the drum is discussed. However, a conceptual evaluation is performed in Table 3-3-2, to determine which axis and base materials will be considered in the material selection process.

		BASELINE	ALTERNATIVE SOLUTIONS		
CRITERIA	WEIGHT	FRONT-LOADED WASHING DRUM (STAINLESS STEEL)	FRONT-LOADED WASHING DRUM (PLASTIC)	FRONT-LOADED WASHING DRUM (ALUMINUM)	FRONT-LOADED WASHING DRUM (GALVANIZED)
EFFICIENCY OF WASH	5	5	4	5	4
COST	4	0	4	4	3
EASE OF MANUFACTURING	3	2	2	3	2
DURABILITY	3	3	2	3	2
INTEGRATION WITH ANOTHER COMPONENTS	3	1	1	2	2
RUST RESISTANCE	1	1	1	1	0
CORROSION RESISTANCE	1	1	1	0	1
TOTAL	20	13	15	18	14

Table 3-3-2 Drum Concept Evaluation

CHAPTER FOUR – DESIGN & IMPLEMENTATION

4.1 Methodology of Study

This chapter provides an in-depth look into the components and material selection and the manufacturing processes used to design and fabricate the pedal-powered washing machine.

4.2 Assumptions

To perform calculations and further analysis, realistic assumptions must be made considering system functionality. These assumptions consider very likely instances by incorporating relevant research data and desired technical requirements.

The pedalled powered machine must function suitably:

1. Assuming all tubes and stays of the bicycle are straight tubes along its lengths.
2. For a user within the weight bracket of 50kg – 70kg, as the average weight of an adult in Africa is 60.7kg as of 2012 [25].
3. For one cycle wash, the washing drum must contain a minimum of 5kg of laundry as 1 kg of a load of laundry is about one regular pair of denim jeans or ten t-shirts.

4.3 Conceptual Structural Design

As the entire project is built on the concept of reducing households' carbon footprint by providing an effective off-grid alternative in terms of doing laundry. It is imperative to consider recycling and sustainability in terms of its structural design and fabrication. Manufacturability for the selected demographic is a core consideration with regard to the system's design. There are three main parts which form the manual washing machine, explicitly a bicycle without the rear mudguard, the washing drum and the system's support. Founded on the assumptions that bicycles are easily accessible, a pre-existing bicycle is incorporated in the system design, which further reduces cost.

4.3.1 Functionality Overview

Several drum orientations and its connections to the rotational input are possible, however considering system requirements and conceptual evaluations, the drum and wheel contact orientation was selected.

Figure 4.1. Functional Block Diagram

From existing works, it was observed that connecting the drum directly to a gear system caused difficulty in pedalling due to the drum's weight and in some cases possible gear complexity. The drum and wheel contact orientation, as demonstrated in Figure 4.1, proposes the drum's weight be distributed across the bicycle frame and the drum's support to reduce pedalling difficulties and in turn labour intensity.

4.3.2 Washing Drum Design

The washing drum consists of two separate cylindrical structures. The outer shell houses water, detergent, laundry and the inner shell. The external shell is connected to the supporting frame with bearings and its contact with the wheel will cause it to rotate. The inner drum freely rotates within the outer drum creating differences in the washing drum's moment of inertia. The inner drum uses its paddles to aid in the creation of turbulence as well as allow for drainage as seen in *4.6.3 Internal Washing Drum.*

4.4 Material Selection

Manufacturing was locally sourced, whiles the available materials were evaluated on the following characteristics: Property requirements, Manufacturing concerns and Geometry considerations. The material selection is concentrated on metals (stainless steel, aluminium and galvanized steel) since manufacturing plastic is relatively complex and challenging to do locally.

4.4.1 Property Requirements

Based on 3.2.3 Functional Requirements, the washing drum prototype must be lightweight in order to reduce the amount of human input needed for the drum to rotate. The non-functional requirements of durability also influenced the material selection as vibrations, and cyclic loadings are present in the system.

The mechanical properties needed to satisfy these requirements are:

i. **Corrosion:** Since the internal washing drum will be immersed in water, a corrosion-resistant material must be used. Based on this constraint, aluminium offers excellent corrosion resistance as its exposure to the atmosphere causes the formation of a thin oxide barrier [26]. Likewise, stainless and galvanized steel resistance to corrosion is a result of a similar oxide layer on its surface.

ii. **Density:** The mass per unit volume of an object is considered in the material selection process since the washing drum must be as light as possible to reduce the force acting downwards on the rear wheel. The reduction in the force results in using less effort to rotate the rear wheel and in turn, the drum. Comparing steels and aluminium, density prioritized for the trade-off between Young's modulus and density for the intended application. Using CES software, it was observed that aluminium's density is only one third that of steels [26].

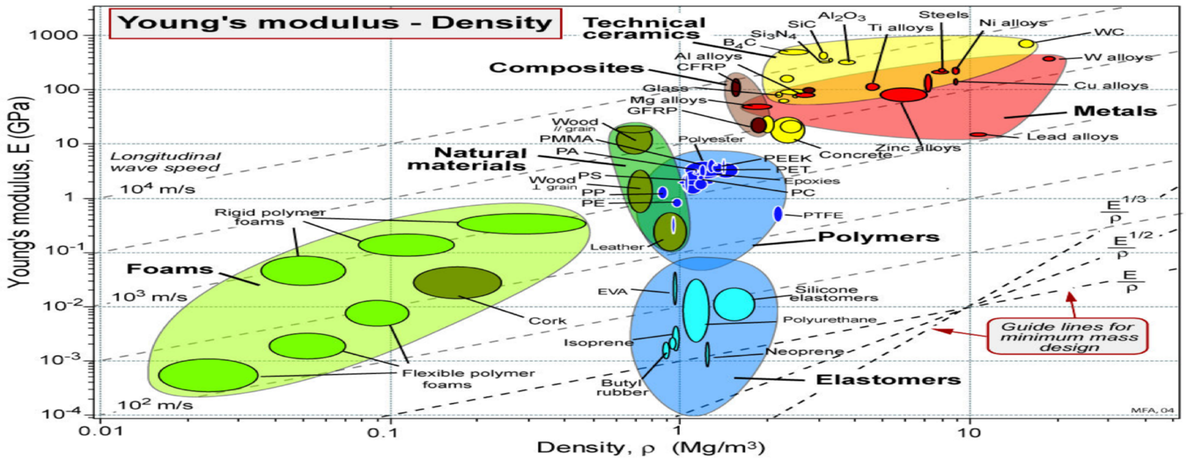


Figure.4.4.1.Young's modulus vs density [24] .

iii. Damping capacity: This is the ability of a material to absorb vibrational energy. This mechanical property is essential to the functionality of the system as failure may occur due to deformation and fracture due to vibrational fatigue.

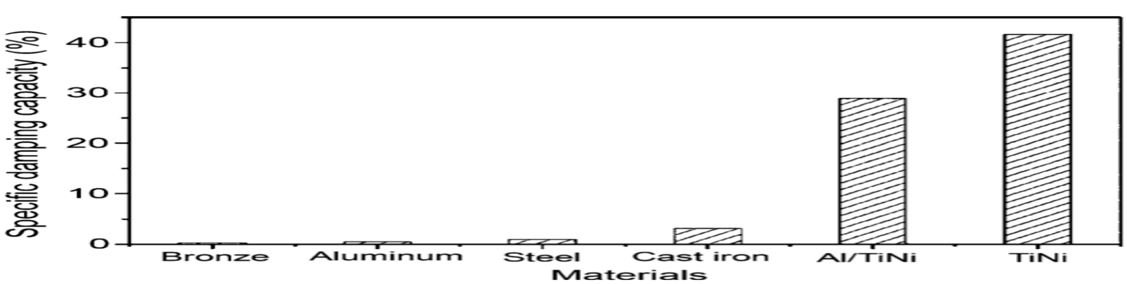


Figure.4.4.2. Comparison Of Specific Damping Capacity For Various Materials [28].

A large damping capacity is required for materials exposed to vibrations in this operation. From *Figure.4.4.2,* it is noticed that bronze to cast iron has small damping capacities. This means vibration energy is transmitted through these materials without dilution. Whiles titanium nitride a very hard ceramic material has the highest specific damping capacities. However, comparing aluminium and steel, it is noted that neither of these materials has a desirable damping capacity.

4.4.2 Manufacturing Concerns

Based on the 3.2.2 Non-functional Requirements, the prototype must be low-cost with the parts locally accessible. In order to reduce the cost of production and in turn reduce product cost, the bicycle frame is to be outsourced by the user. This implies that an already existing bicycle can be assembled with the washing drum and its stand. Further cost concerns limit the variety of materials to consider. In terms of the cost aluminium alloys and stainless steels, aluminium alloys relatively cheaper.

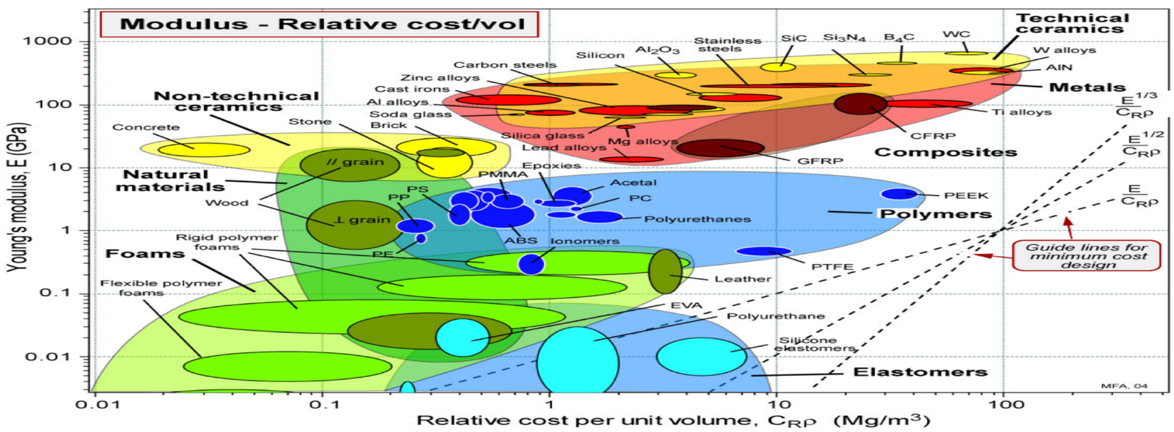


Figure.4.5.3.Young's modulus verse Cost [27] .

4.4.3 Geometric Considerations

The size, shape and complexity of the system and the washing drum is illustrated and analysed by a dimensioned sketch represented in *Figure.4.4.2.1*. The geometric complexity has been reduced by dividing the system into subsystems with simpler geometries. This improves the rates of manufacturing and eradicates serious measurement errors. The tolerances of the stand and the washing drum are ±5.00, allowing some room for error and further reducing manufacturing complexity.

Additionally, only parts of the external washing drum need surface finishing to mesh with the rear wheel of the bicycle. A part of the external washing drum will be covered by a similar tyre material of the bicycle predictably synthetic rubber. This surface finishing can easily be replaced when extreme wearing occurs without disrupting the system's functionality.

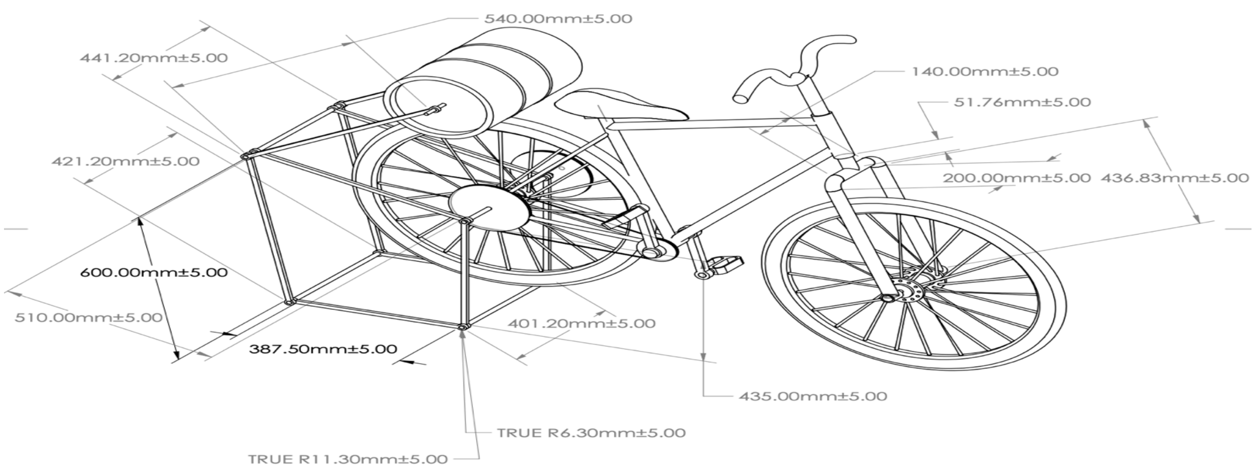


Figure.4.4.2.1. Dimensioned 3D SolidWorks Model of Prototype

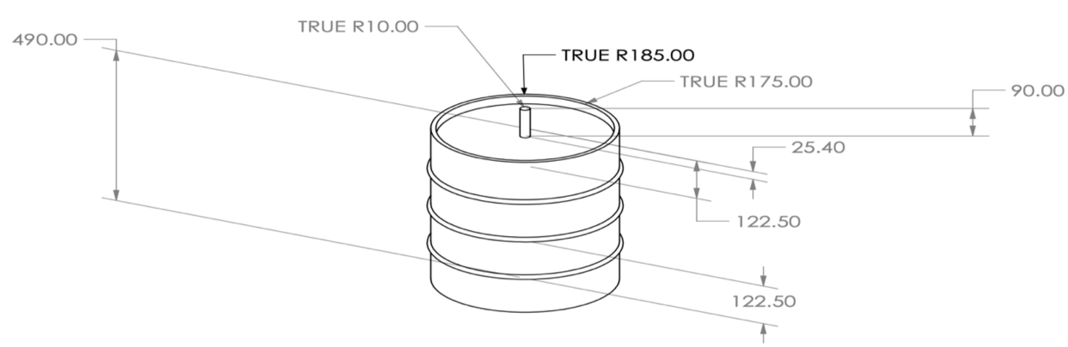


Figure.4.4.2.2. Dimensioned 3D SolidWorks Model of External Washing Drum

4.4.4 Materials Selected

Aluminium was selected for fabricating the washing drum due to its high corrosive resistance, low density, manufacturability, low cost and availability. Synthetic rubber was incorporated to facilitate meshing and galvanized hollow steel pipe was selected for the drum's supporting frame as it's known for its strength. Galvanized steel is also cost about 4.60 cedis per pound, whereas stainless steel is over three times the price of galvanized steel [29].

4.5 Manufacturing Process

Hardware implementation of this project is centred around the fabrication of the washing drum, which involves several manufacturing processes, that are categorized under Sheet Metalworking.

4.5.1 Prototyping

During the design and fabrication process, Low-Fi and High-Fi prototyping was employed to understand further and iterate the conceptual design. Noticeably, the final prototype design as compared to the cardboard prototype is less bulky. Additional experimentations such as the meshing for the external drum surface and the tyre were explored, hence the decision to use synthetic rubber.

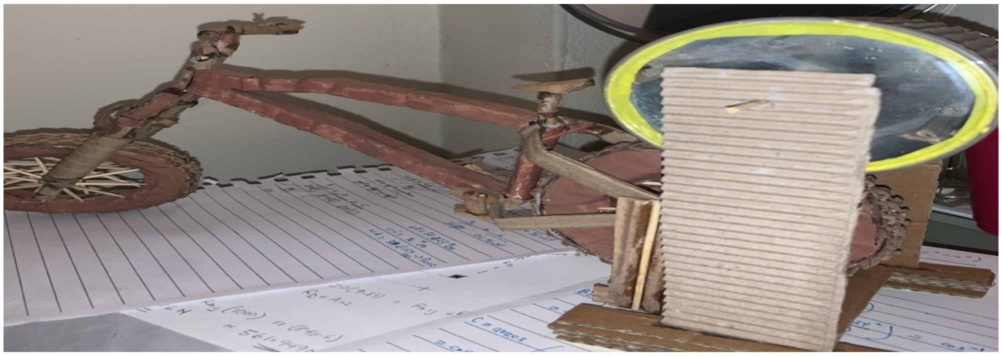


Figure.4.5.1. Cardboard Prototype

4.6 Sheet Metalworking

4.6.1 External Washing Drum

Numerous iterations of shearing and bending are performed all with the use of hand tools and little to no machined tools. Locally, these operations are executed by "Tin Workers", in order to explore the possibility of locally manufacturing, I shadowed a tin worker in Timber Market, Accra. After which, I fabricated the external shell of the washing drum using the skills acquired.

Figure.4.6.1. Sheet Metalworking of Drum

The lid of the drum was also fabricated but without the handle. The handle when fabricated will aid the opening and closing of the drum. Since the drum has to be watertight, a steel barrel clip lined with water-resistant rubber as seen in Figure.4.6.2. All other spaces created by the shearing and joining of aluminium sheets were filled with putty filler to prevent leakages.

Figure.4.6.2. External Aluminium Shell

4.6.3 Internal Washing Drum

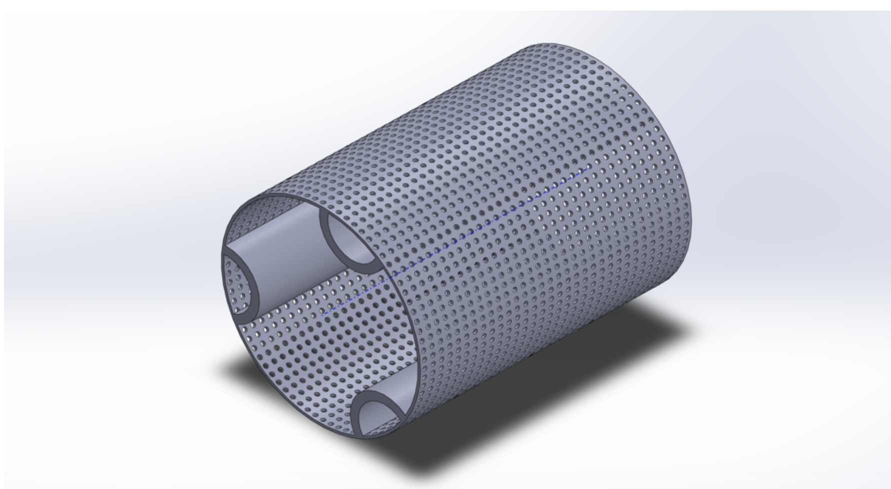


Figure.4.6.3. Internal Aluminium Shell

The internal shell drum is designed to slide into the external shell with ease. This allows the possibility of changing the inner shell to a different design depending on the fabric type or desired level of wash. This feature mimics the different modes available on conventional washing machines. The holes allow for water to drain out of the drum as there is a two-way valve located on the external drum.

4.7 Leakage Test

The drum was put through a leakage test, where it was placed horizontally and filled halfway with water and rotated. The rotation was simulated by pushing the drum on a level floor at varying application forces. The results indicated a few areas that needed additional putty filler after which no additional leakages were observed.

CHAPTER FIVE – RESULTS & ANALYSIS

This chapter discusses the various engineering analysis performed on both the application of the drum and the entire laundry system. The results from these simulations ensure that the project's objectives and functionalities can be achieved.

5.1 Dynamics of Rotational motion

5.1.1 Torque Transmitted

The calculations are performed in sections (***From Crank to Chain,*** **From Chain to Sprocket, From Sprocket to Rear Wheel** and **From Rear Wheel to Drum)**, isolating the torque transmitted from one part of the system to another.

Assumptions:

1. Masses of the bicycle and rider are combined and acts along the same axes.
2. The initial pedal position is laying on the horizontal plane, i.e. Ø = 90º.
3. Pedalling occurs at a constant speed.
4. User assumes the position of "hands-on the drops", implying 40% front and 60% rear weight distribution.
5. All other losses expect friction is negligible.
6. No slippage present.

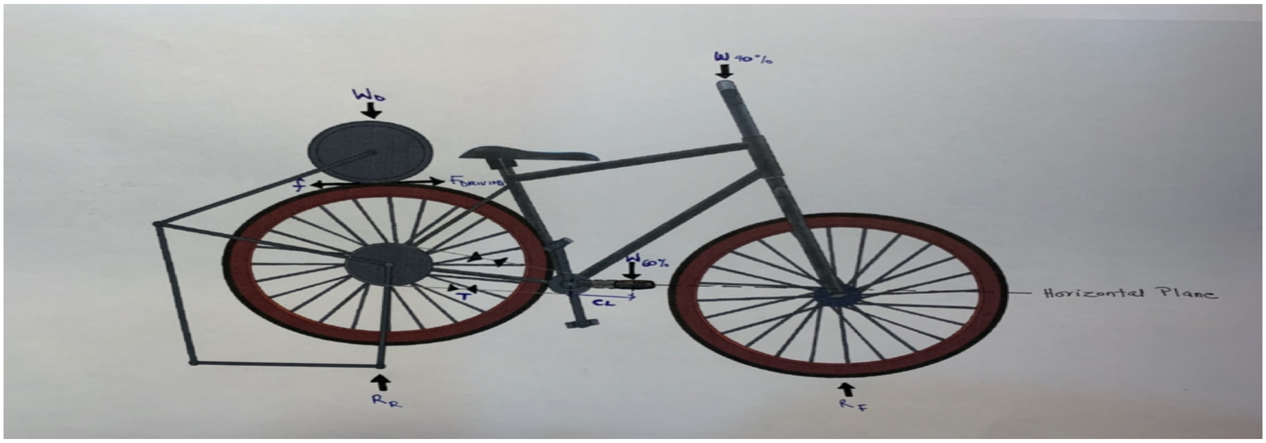


Figure.5.1.1. System Free Body Diagram 1

TOTAL TORQUE

$$\tau = rF\sin Ø \tag{1}$$

$$\tau_{Total} = TR_C - FR_p - FR_s - fR_D \tag{2}$$

All variables values are obtained from the dimensional structures or literature.

Where: τ = Torque, T = Tension in chain, F= Force applied by the user, f = Friction causing the rotation, $F_{Driving}$= Driving force, T_{chain} = Tension in chain, R_p = Pedal to centre of Crank length, R_c = Radius of Crank, R_s = Radius of Sprocket, R_w= Radius of Rear Wheel, W_D= Weight of drum, F_T = Tangent force, F_R = Radial force, d_{drum} = Diameter of drum, ω = Rotational speed

Given: R_p = 0.19m, R_c = 0.075m, R_s = 0.03m, R_w = 0.29m, W = 60% (60.7kg) = 36.42kg, N = 6.5kg, g = (9.81m/s^2) = 63.765N

FROM CRANK TO CHAIN

$$\tau = TR_C - FR_p \tag{3}$$

$$T_{chain} = \frac{FR_p}{R_C} \tag{4}$$

$$T_{chain} = 905 .10984 \text{ N}$$

FROM CHAIN TO SPROCKET

$$T_{sprocket} = T_{chain} R_s \quad (5)$$

$$T_{sprocket} = \frac{FR_p}{R_C} R_s \quad (6)$$

$$T_{sprocket} = 27.1533\text{N}$$

FROM SPROCKET TO REAR WHEEL

$$F_{Driving} = \frac{FR_s R_p}{R_w R_C} \quad (7)$$

$$F_{Driving} = 93.632N$$

FROM REAR WHEEL TO DRUM

Considering the coefficient of friction of rubber on rubber:

$$f = \mu N \quad (8)$$

Given: μ_k = 1.16 [30]

$$f = 73.97N$$

$$F_{Driving} > f$$

The driving force causes the rear wheel to rotate and since the generated friction is not equal to the driving force, the washing drum is expected to rotate as desired.

5.1.2 Power & Revolution per minute

$$\text{V} = R_w 2\pi f \quad (9)$$

$$V_{wheel} = 1.822 \text{ m}/s^2$$

$$\text{P} = F_{Driving} \times V_{wheel} \quad (10)$$

$$P = 170.596 \text{ W}$$

$$\tau_{wheel} = F_D R_w \quad (11)$$

$$\tau = 27.153 \text{ N.m}$$

$$\text{Revolution per minute} = \frac{V}{R_w(0.10472)} \approx 60\text{rpm} \quad (12)$$

A study carried out by the University of Johannesburg, claims that pedalling with the range of 50 -70 rpm for an hour is efficient and not strenuous for the user generating energy [31]. With the result falling within this range, it is expected that the user will not experience severe exhaustion whiles using the pedal powered washing machine.

5.1.3 Turbulence

The turbulence created in a washing machine is responsible for removing dirt from clothes. The more energetic the turbulence flow, the more adequate the creation of contact between the detergent particles and the clothing fabric [23]. In order to measure the quality of wash in the instance that turbidity cannot be measured; the mechanical power produced by a motor is calculated for a given size of a drum. In conventional washing machine's the motor produces an amount of mechanical power which ensure a turbulent flow field. In the following calculations, it's important to note that detergent in water only affects surface tension and not viscosity.

Where: $L =$ Diameter of washing drum, H = Height of the drum, ρ = Warm soapy water density (about same as standard water density) [23], v = Soapy water viscosity(same as pure water viscosity at 30°C) [23], d_{min}= Distance required for soap to be effective at removing stains (shortest eddy scale), $\eta =$ Ratio of mechanical power to electrical demand

Given: L = 0.35m, H = 0.49m, ρ = 999kg/m^2, v = 8.0 x 10^{-7}m/s^2, d_{min}= 12μm, η = 0.85

$$V = (\pi L^2/4)H \quad (13)$$

$$V = 0.04714m^3$$

$$m = \rho v \quad (14)$$

$$m = 47.096kg$$

$$\varepsilon = \frac{v^3}{{d_{min}}^4} \quad (15)$$

$$\varepsilon = 2.469 \text{ W/kg}$$

$$P_m = \varepsilon\, m \quad (16)$$

$$P_m = 116.28W$$

$$\frac{P_m}{P_e} = \eta \quad (17)$$

$$P_e = 136.8W_e$$

$$P = 170.596 \text{ W} > P_m = 116.28W$$

The mechanical power required to produce adequate turbulence is less than the mechanical power actually produced by the driving force. This infers that the quality of wash desired by the user can be achieved by using the pedal-powered washing machine.

5.1.4 Gear Ratio

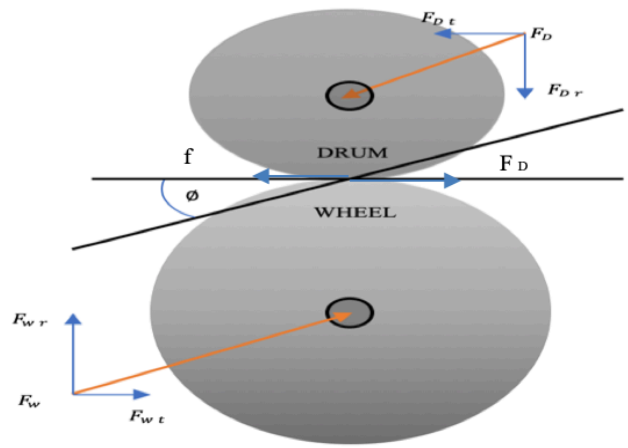
$$\text{Gear Ratio} = \frac{FR_{Driven}}{FR_{Driver}} = 17.5 : 29 \quad (18)$$

The dimension of the drum (driven gear) is intentional as the user experience isn't required to be strenuous but still provide some form of exercise.

5.1.5 Gear Forces

Considering the rear wheel and the washing drum as spur external gears due to tyre patterns in contact as a parallel axis external gear mesh.

Free Body Diagram:



Since there is a difference between $F_{Driving} >$ f, the drum will rotate.

Given: ω = 350mm
Assuming: ∅= 30°

$$F_T = \frac{60(1000)P}{\pi d_{drum}\omega} = 155.151\text{N} \quad (19)$$

$$F_{radial\ total} = F_T tan\emptyset + W_D tan\emptyset \quad (20)$$

$$F_{radial\ total} = 126.39N$$

$F_{radial\ total}$ represents the total force acting on the rear wheel.

5.2 Simulations Results Interpretation

5.2.1 Static Simulations

Stress

Analysing the stress, the majority of the weight of the drum and the user is applied along the axis of the rear wheel, which is supported by the bicycle frame and the drum support. The frame provides the majority of the support to the system as it hovers the bicycle frame and the supports the entire weight of the drum.

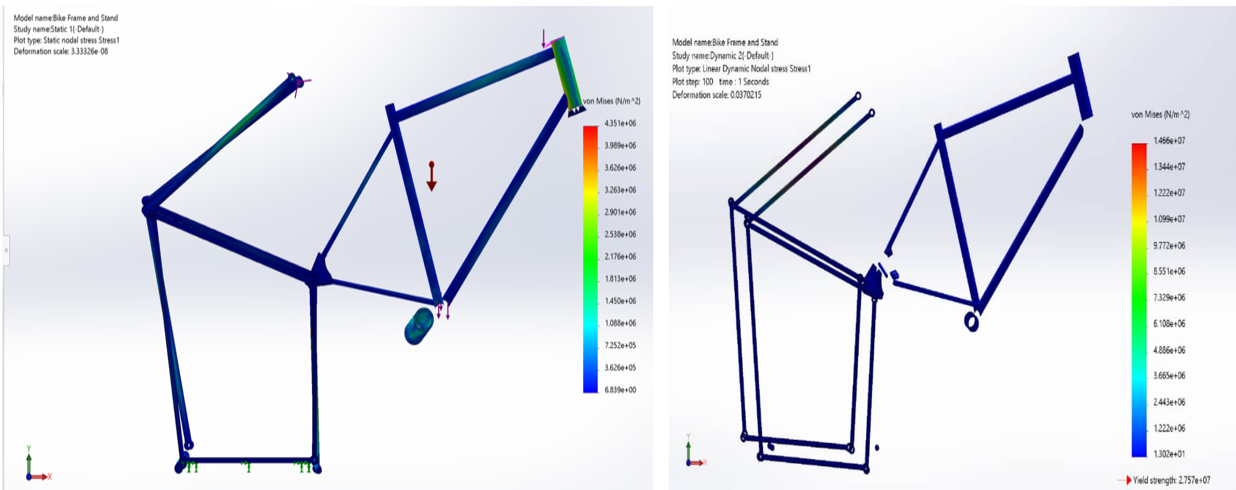


Figure.5.2.1. SolidWorks Stress Plot of Prototype frame

From the stress simulation, it is observed that the maximum stress occurs at the top tube of the supporting frame as well as along the vertical axis of the handling bar. The stress experienced in these areas were desirably below the yield strength of 27.57 MPa; hence, the frame will be able to support the worst-case weight scenario successfully. The force applied was $F_{radial\ total} = 126.39N$ with the additional force attributed by the user as 297.734N.

Strain

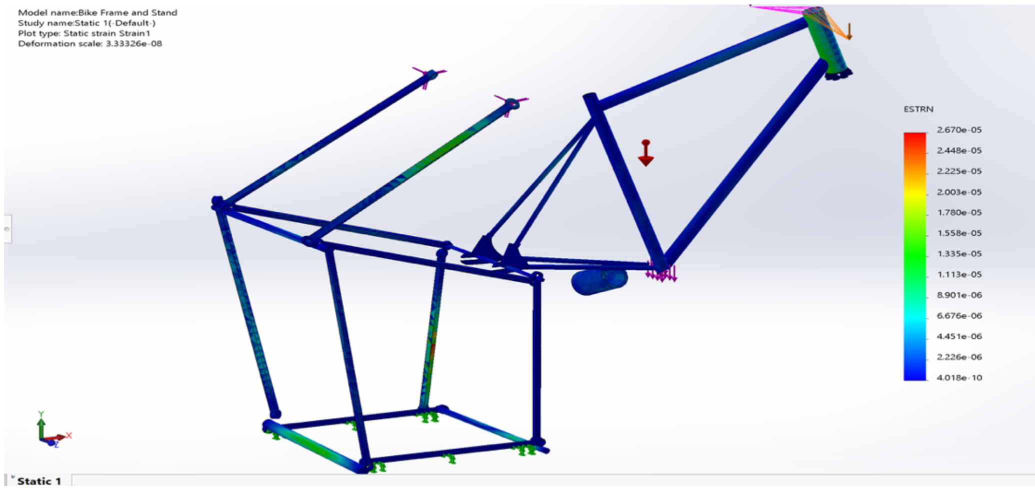


Figure.5.2.2. SolidWorks Strain Plot of Prototype frame

As expected, the maximum strain occurs in the same areas of the frames, including its base tubes is far below the deformation scale.

Deflection Scale

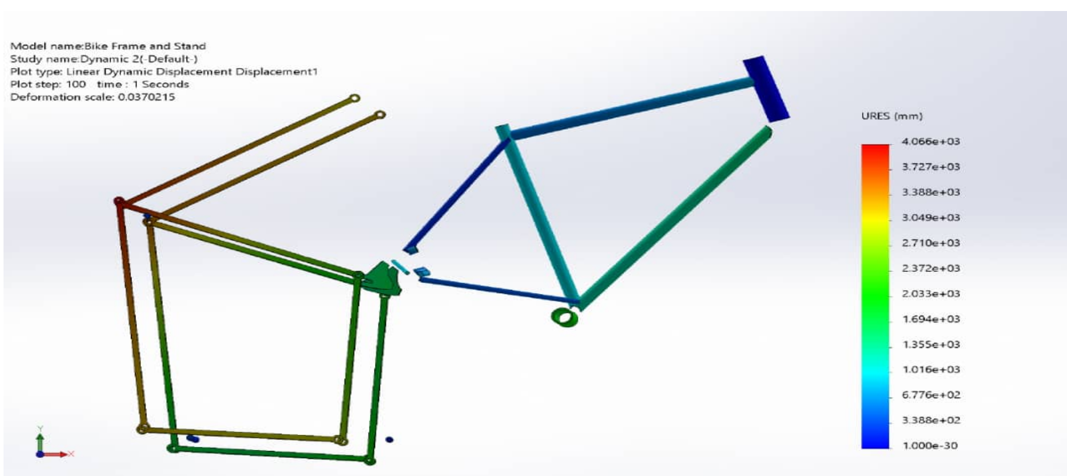


Figure.5.2.3. SolidWorks Static Displacement Plot of Prototype frame

Results from the static displacement simulations depict significant displacement along the top tubes connected by bearing to the drum. This is expected as the rotation of the washing drum would cause the drum to tilt offsetting its balance from the rear wheel with the initial stand design.

The forces were applied in directions mimicking pressure from the drum. Due to this, additional support acting as a stopper at the two bearing ends of the drum has been included in the frame simulations.

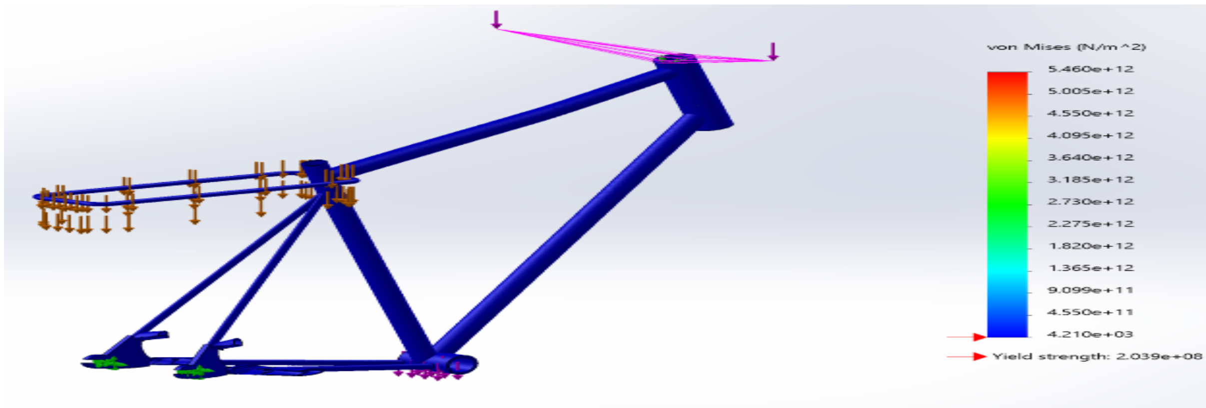


Figure.5.2.3.1 Additional Stopper Support of Prototype frame

Factor of Safety

Further static simulations of the porotype's bicycle frame show that the frame has a minimum Factor of Safety of 15, which typically similar simulations of bicycle frames give a result of 23 or above [32]. This reduction is expected due to the additional load experienced at the rear. It is important to note that when the settings are changed to "Areas below the factor of safety" of 100, the value 1.5 of FOS is recorded.

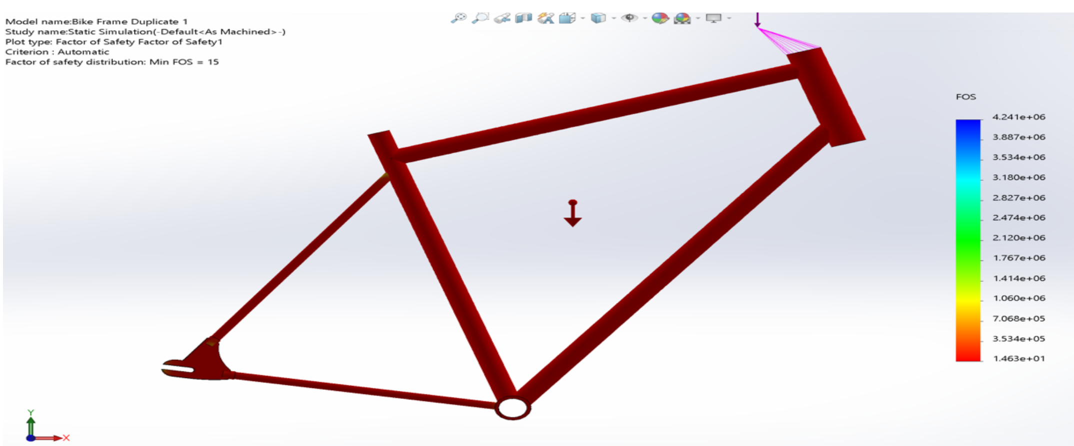


Figure.5.2.4. SolidWorks Safety Factor Plot of Prototype frame

5.2.2 Dynamic Simulations

Vibration Analysis

As the drum rotates, vibrations will be experienced, and this may lead to system failure and a noisy prototype. Focusing on the deformation caused by the vibrations, a harmonic linear dynamic displacement simulation is performed.

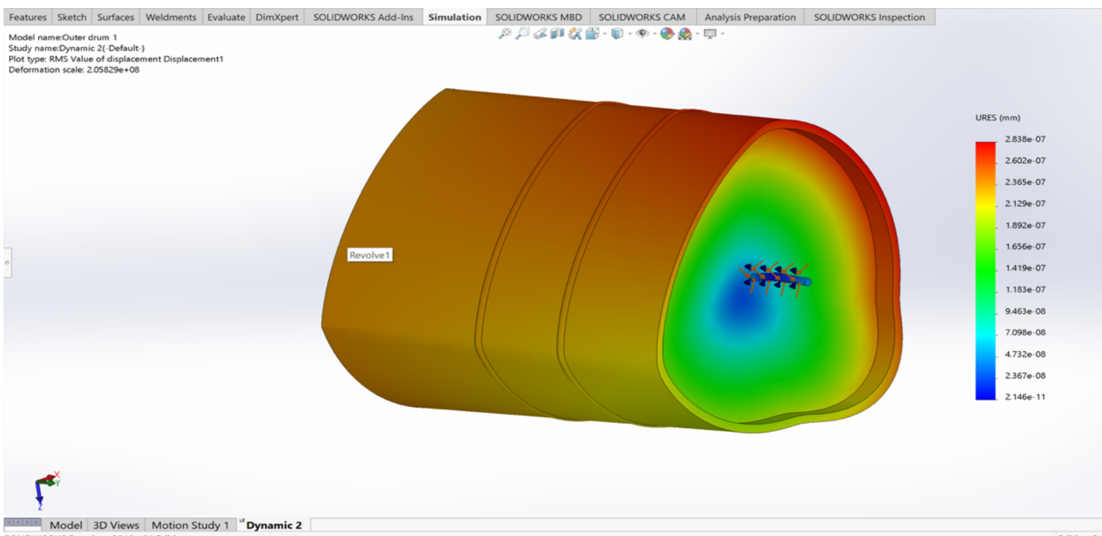


Figure.5.2.7. SolidWorks Linear Dynamic Displacement Plot of External Washing Drum

From the simulation animation and results, noticeable deformation occurs on the surface of the washing drum. Since it was a random vibration study, the minimum and maximum frequency was 0 Hz and 100,00 Hz respectively. This will affect the functionality of the system as the contact made with the rear wheel might be disrupted, leading to operational failure.

CHAPTER SIX – CONCLUSION & FUTURE WORKS

6.1 Discussion

Through the conceptual design and simulations processes, this project has explored the possibility of an alternative washing system using mechanical energy as its sole input. The project's application used in off-grid homes has the potential of been further developed into a more efficient system based on the findings in this report. The project undertaken verified that 60% of the user’s weight input will supply adequate torque to the drum to generate relevant turbulence to achieve a desirable wash quality. Additionally, the design of the supporting structures, including the use of a generic bicycle frame was validated as results show a high factor of safety.

6.2 Results/Objectives Assessments

In order to evaluate the deliverables of this project, an assessment was carried out to determine how the prototype performed against the conventional washing machine in terms of quality of wash, cost, energy efficiency and consumption rates.

6.2.1 Quality of Wash

This criterion measures the turbidity of the rinsing water and the presences of stains after the wash cycle. Quality of wash is affected by multiple factors such as type of detergents used, adequate turbulences creation, type of fabric used, and even the hardness of water. As physical experimentation could not be undertaken due to the closure of the university, turbulences creation for machine washing alone was the only parameter that was measured and was used in this assessment.

Relative to the Panasonic 6.5, which produces 340W of mechanical power, assuming 0.85 efficiency [19], the prototype designed only generated 116.28W. Although this may seem like an underwhelming result, it is relevant to disclose the difference between adequate and excessive turbulence. The increased turbulence may produce a high quality of wash in a shorter period, but it will also increase the rate of wear and tear, the clothes experience.

6.2.2 Cost

The bill of materials referenced in Appendix C, achieves the cost projection stipulated in the non-functional requirements. The total cost of the prototype including the bicycle, is estimated at $55, whereas typical electrically powered washing machines' range between $250 - $2050 [17].

6.2.3 Energy Efficiency

The Panasonic 6.5, power consumption is rated at 400W whiles the prototype does not consume any electric power. This implies no carbon emissions were produced in the electricity generation process for the operation of the prototype. This may seem insignificant; however on a larger scale, the rate of carbon emissions will reduce as the demand for electrically powered laundry does.

6.2 Limitations

However, this project did not satisfy all the objectives and requirements specified at the project initiation stage. Unforeseen risks such as the closure of the university due to the global pandemic, COVID-19, severely hinder the initial project scope. Due to which, the system prototype could not be entirely fabricated and tested for the following:

1. The prototype adoption rates by measuring the user comfortability whiles interacting with the prototype.
2. System durability.
3. Wearing rates of clothes used in the system.

6.3 Design Improvements & Future Works

Analysis of the results from this report, demonstrate significant design improvements to be considered in future works. The external drum due to vibrations requires an alternative material with a higher damping capacity such as polymers. This will prevent the drum from deforming and affecting system functionality. The following are future works to be carried out to improve on the current findings and design:

1. Comparable detergent and water consumption per washing cycle relative to the selected electrical washing machine.
2. Fabrication of the entire system components.

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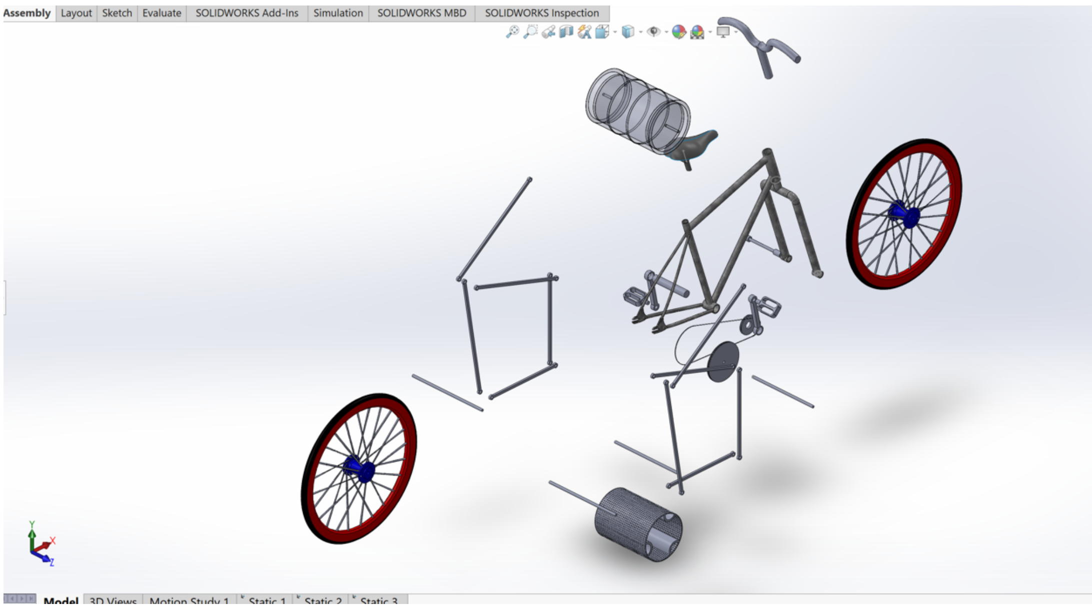
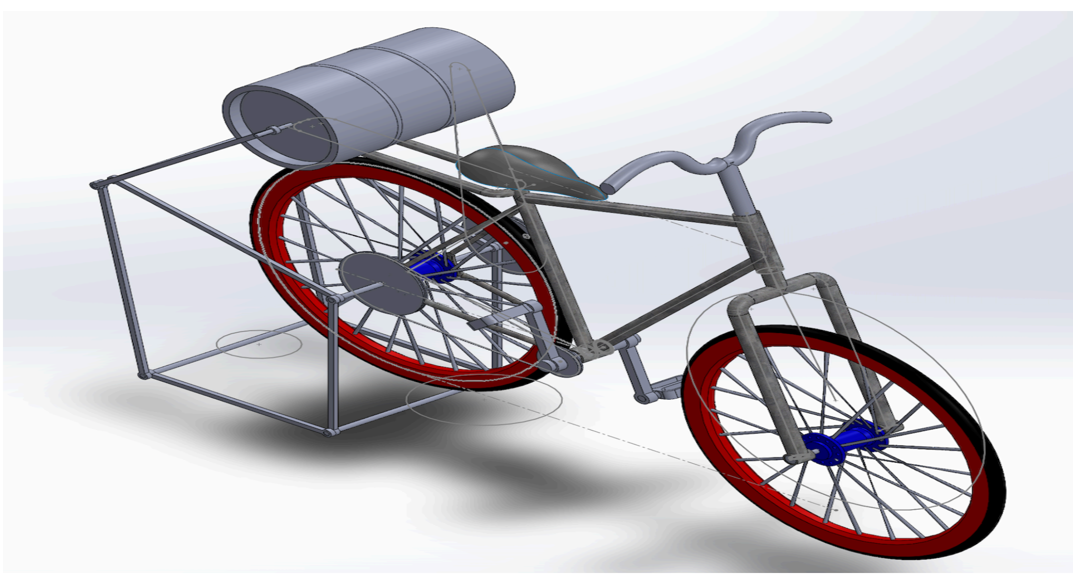
Appendix A


OWNER: ELISHEVA LUSTIG
DATE: 9TH MAY, 2020.
TITLE: EXPLODED VIEW OF BIKE ASSEMBLY

Appendix B


Assembly
Layout
Sketch
Evaluate
SOLIDWORKS Add-Ins
Simulation
SOLIDWORKS MBD
SOLIDWORKS Inspection
Model
3D Views
Motion Study 1
Static 1
Static 2
Static 3



Appendix C

	BILL OF MATERIALS - PEDALED POWERED WASHING MACHINE					
ITEM	**ITEM DESCRIPTION**	**QUANTITY**	**SOURCE**	**PART NUMBER**	**PRICE UNIT**	**PRICE**
						Ghc
1	***MECHANICAL STRUCTURE***					
	Bicycle (Used)	**1**		**N/A**	**100**	**235**
	0.6mm Aluminmum Plate	**2**	**Timber Market**	**N/A**	**100**	
	1" Galvanized Square hallow bar stock	**1**	**Alhaji Gab Moro - Kwabenya**	**N/A**	**35**	
2	***JOINTS***					
	#300 metallic Oiles Bearings	**2**		**30B-253316**	**30**	**60**
	(16mm length, 33 Diameter inner & 25 Diameter outter)					
3	***PLUMBING***					
	Silicone Sealant	**1**	**Kwabenya**	**N/A**	**12**	**20**
	Valve PVC-U 3/4"	**1**	**Kwabenya**	**D24SS SCH40**	**5**	
	Valve Stopper PVC-U 3/4"	**1**	**Kwabenya**	**N/A**	**3**	
	GRAND TOTAL					**Ghc 315.00**

Appendix D

Dynamic Simulations

For the further dynamic simulations, cyclic loading of the system was simulated in order to estimate the life cycle of the porotype.

Fatigue

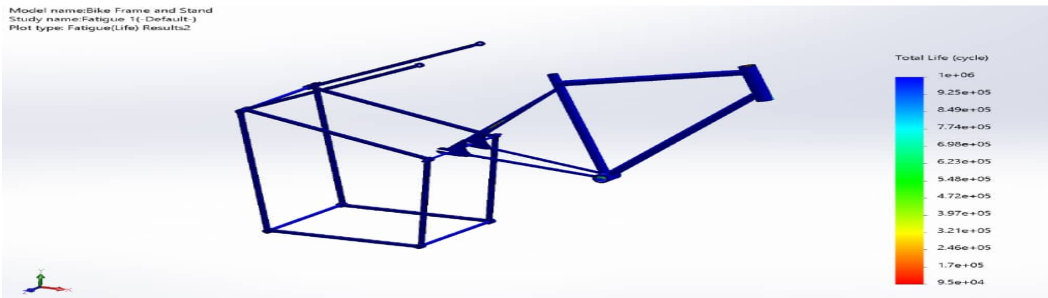


Figure.A.1. SolidWorks Fatigue Study of Prototype frame

Based on the non-functional requirement on durability, the estimated loading cycles of 2,464 which implies that the washing drum was loaded and unloaded four times per week for 11 years was implemented in the fatigue simulation. From the fatigue total life plot, the prototype's design is can withstand over 2,464 cycles of the specified loading characteristics.

Damage Percentage

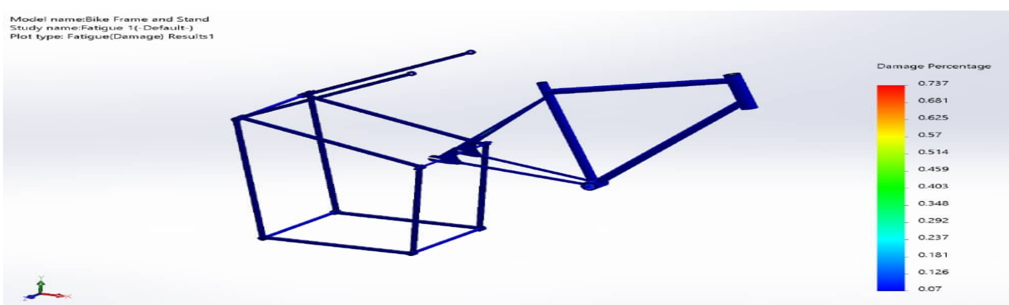


Figure.A.2. SolidWorks Damage Percentage Plot of Prototype frame

The damage percentage plot indicates values below 1, this implies that there will be no defined fatigue events which will consume 100% of the prototype life in any location along the various parts.