Design for a Specialist Washing Machine for use in Refugee Camps

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Abstract

This report details the design for a washing machine built specifically for refugee camps. The primary objectives of this project were to design a device that is economical, easily transportable and once programmed should be autonomous. Given that the typical design for a washing machine is widely understood, this report focuses on the specifics of the design that deviate from industry standards.

The first section of this report focuses on the physical design of the machine, specifically how changes have been made to a typical design in order to optimise the machine for its environment. The second section details the power requirements for the machine and how the electrical systems have been designed to fulfil these requirements. An assessment of how effective the machine's power systems can operate has been conducted via running and analysing a simulation of the washing machine's control system.

Contents

1 List of symbols

- E – Young's modulus
- E_{crank} – Energy produced by the hand crank
- E_{panel} – Energy collected by the panel
- E_{solar} – Energy collected by the solar array per day
- E_T – Total energy required to run the machine for a 30-minute wash cycle
- $e(t)$ – Error value
- F – Force applied
- i – Current
- J – Inertia
- K_D – Damping constant
- K_d – Derivative gain
- K_F – Back EMF constant
- K_G – Gear ratio
- K_i – Integral gain
- K_p – Proportional gain
- l – Length of the hand crank
- M_1 – Materials index calculated for the panels of the washing machine
- M_2 – Materials index calculated for the hand crank of the washing machine
- P – Power
- P_{crank} – Power generated by the hand crank
- P_{ref} – Power required to run the reference washing machine (Hoover H3WS495TACE spin washing machine)
- P_{solar} – Power of the solar array
- P_T – Power required to run the machine
- R – Resistance
- T – Torque required to run the motor in the solar tracking system
- t – Time
- $u(t)$ – Process variable
- V – Voltage
- ρ – Density
- σ_y – Yield strength
- τ – Torque generated
- $\omega = \frac{d\theta}{dt}$ – Angular velocity
- $\omega^2 = \frac{d^2\theta}{dt^2}$ – Angular acceleration
- ω_{crank} – Angular velocity of the hand crank
- ω_{drum} – Angular velocity of the washing machine drum
- ω_{ref} – Angular velocity of the drum for the reference washing machine (Hoover H3WS495TACE spin washing machine)

2 Introduction

One of the leading issues across the developing world is hygiene. Lack of water infrastructure and poor sanitation leads to rapid transmission of disease, which inevitably leads to large numbers of preventable deaths. These issues are heightened in refugee camps, where the high population density compounds these problems.

With the rise of COVID-19, cheap, effective sanitation in refugee camps is vital. A possible solution to this problem is the washing machine. Over the last fifty years in particular, the drum washing machine has become a widespread tool across households in the developed world. Its benefits are obvious, with estimates suggesting that in developing countries people can spend up to 20 hours per week washing clothes (White, 2020). Not only is this highly time consuming, but hand washing clothes in this manner can also cause skin irritation, as well as chronic back pain (White, 2020).

The main issue, however, is that washing clothes in this manner is often not very effective. Often the clothes will not be washed thoroughly, meaning that viruses and pathogenic bacteria can survive on the clothes, increasing the chance of transmission of disease. It is therefore obvious that washing machines would be of enormous benefit to refugee camps.

The current issue is that most washing machine designs currently are very similar; there are very few variations of the machine. In its current state, the standard design for a washing machine is unsuitable for a refugee camp. The standard design is very large and heavy. Refugee camps are often located in remote places, making transport to them difficult, and thus having this cumbersome design is unacceptable. The current design is also very complex, meaning if faults occur a specialist is required to fix them. Once again, this is a problem in refugee camps, where access to engineers is highly unlikely. Finally, the current washing machine design is very expensive, making it difficult for refugee camps, where there are limited funds, to purchase them.

Therefore, in order to try and develop a solution to the aforementioned problems, the aim of this project is to design a cheap, lightweight washing machine that can be easily transported and that can operate independently, without access to mains electricity.

This will be achieved via a number of objectives:

- Design the basic shape and geometry of the washing machine using CAD.
- Select the appropriate materials for the washing machine to be made from.
- Determine a suitable power source.
- Design the necessary electrical systems in order for the machine to work independently of human interaction.

3 Literature review

3.1 Effect of hygiene in refugee camps

There is an extensive body of research describing the significance of hygiene in refugee camps. One paper in particular entitled “An analysis of mortality trends among refugee populations in Somalia, Sudan and Thailand” (Toole and Waldman, 1988) collected mortality data from several refugee camps. This data was then analysed to ascertain the cause of death, and expressed in the form of a graph, as shown in Fig. 1.

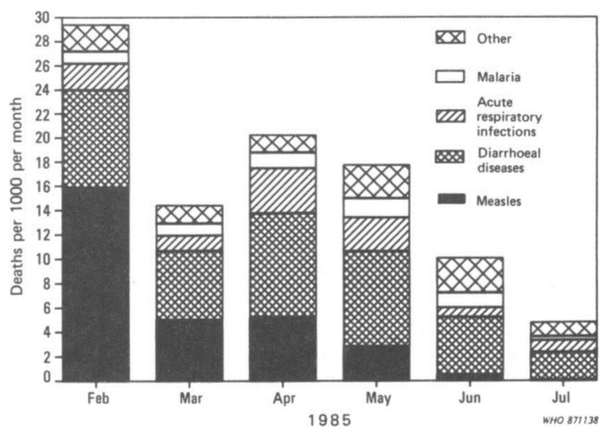

Figure 1: Cause–specific mortality rates across three camps in eastern Sudan, February–July 1985. (Toole and Waldman, 1988).

The graph in Fig. 1 shows the majority of deaths are due to viruses and pathogens that are easily spread via the air or human contact. This shows the importance of cleanliness, with the conclusion of this report describing sanitation as “essential for the immediate and long-term well-being of refugees.”

Whilst this research from Toole and Waldman is clearly very valuable, it is also very generic. This paper was published in 1988, decades before the emergence of COVID-19, and so while the broad conclusions are applicable to this project, there is no specific information about how Coronavirus might affect a modern-day refugee camp.

Therefore, another more recent research paper entitled “The potential impact of COVID-19 in refugee camps in Bangladesh and beyond: A modelling study,” (Truelove et al., 2020) is relevant to this project, given that this is research focused on the specific circumstances that are of interest.

This paper focused on three scenarios, low, moderate and high transmission, with each scenario yielding different results. However, even in the “best case scenario” where transmission was minimal, the outcome was catastrophic. Infections rise exponentially in the first month, and after 136 days hospitalisation capacity is exceeded. The authors of the paper themselves state “our findings suggest that a large-scale outbreak is likely after a single introduction of the virus into the camp," going on to conclude that "our findings suggest that a COVID-19 epidemic in a refugee settlement may have profound consequences."

One difference of note between this recent paper, and the one published by Toole and Waldman is the methodology. Toole and Waldman based their research off data collected over several years across numerous sites, allowing for a large sample size, which in turn makes the conclusions more reliable. However, the research published by Truelove et al. is entirely model based. This means the reliability of their conclusions could be called into question if the model used was found to have flaws.

However, the model used by Truelove et al. was a SEIR (Susceptible Exposed Infectious Recovered) transmission model. This is a model that was introduced in 1927 (Kermack and McKendrick, 1927), and is used frequently today to model the potential effects of epidemics. Similar papers, such as those published by Ahmad (2020) and Maugeri et al. (2020) also analysed the effect of COVID-19 using similar models. It is therefore reasonable to assume that the conclusions made by Truelove et al. are valid, given that the model utilised has been shown to be reliable across a number of papers, over a long period of time.

All of these research papers draw the same conclusions: current infrastructure within refugee camps is massively under-equipped to deal with an epidemic. This shows the massive need for cheap, effective sanitation services within refugee camps in order to reduce the spread of COVID-19.

3.2 Current designs for washing machines

Having established the need for washing facilities, the issue then becomes how would these facilities be provided. The standard washing machine design across the developed world is shown in Fig. 2. Whilst the sketch in Fig. 2 is from a patent submitted by a specific company (LG Electronics Inc., 2005), virtually all major companies follow this blueprint. The door is front facing, with a series of buttons and dials on the top to control the various settings on the machine. Roughly the bottom quarter of the machine is left empty, allowing for a more ergonomic design. Whilst there are clearly benefits to this type of

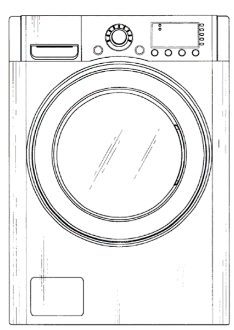

Figure 2: Design for a drum washing machine (LG Electronics Inc., 2005).

design, several aspects clash with the aim of this project. For one, this design is large and heavy, making it difficult to transport. The size also poses an economic problem, as it makes this type of design very expensive. Finally, the major issue with this design is the way in which it is powered. Standard washing machines are designed to be powered by mains electricity, however, this is unlikely to be available in a refugee camp, and so is not a viable design. Therefore, a more appropriate model to focus on is a design by Navjot Sawhney and Alex Hughes. Sawhney and Hughes designed a portable washing machine, exclusively for use in refugee camps, with the design shown in Fig. 3. They named this design the "Divya."

Figure 3: Design for a portable washing machine operated via hand crank. (Hughes and Summerfield, 2019).

The Divya is now the basis for "The Washing Machine Project," a non-profit organisation whose aim is to "create a single, standalone, off the grid washing solution that will be affordable, portable and accessible for everyone, everywhere," (White, 2020).

This mission statement is very similar to the main aim of this project, and so the design by Sawhney and Hughes works well as a blueprint to build off. The design is light and easy to transport, with the cost of the machine estimated at just $35 (Mercer, 2021). Moreover, the device is not powered via mains electricity, rather it functions entirely off a hand crank. All these features align with the aims and objectives of this project.

There is however one major issue which clashes with one of the objectives of this dissertation. The Divya only functions while the hand crank is being turned, meaning a human must always be present. This clashes with the fourth objective of this project, to design a machine that can "work independently of human interaction."

3.3 Possible power sources

While both designs in Fig. 2 and Fig. 3 show promise, powering the machine is going to be difficult, given the environment. Since mains electricity is not an option, the Divya seems to be a more relevant option, given that it is powered by a hand crank. However, the design for this project is likely to be bigger, and therefore more power intensive, than the Divya, and so a secondary power source will be required.

Wind power offers an obvious option, with the paper "A novel miniature wind generator for wireless sensing applications," (Zhu et al., 2010) proposing a design for a miniature wind turbine. While standard wind turbines are typically built at a height greater than 80 metres tall (Tong, 2010), the design proposed by Zhu et al. suggests a wind generator with a height of only 12cm. A design this small could easily be attached to a design for a washing machine, providing an alternative power source that could provide electricity passively. An issue with this concept, however, is that due to its compact nature, this design only produces a power output of 1.6mW. This power output is far too small to be of use, and so for this design to be effective, the device would have to be made significantly larger in order to produce more power.

An alternative power source could be solar panels. Given the arid conditions that typical refugee camps are found in, solar cells could be the ideal power source, given the vast amounts of sunlight available. However, during the course of the day the sun moves throughout the sky. When sunlight is not striking the solar cell directly, the efficiency of the cell is reduced.

A proposed solution to this problem is given in the paper "Solar Tracking System: More Efficient Use of Solar Panels," (Rizk and Chaiko, 2008.) This paper details how an actuator can be used to rotate a solar panel to keep the panel perpendicular to the sun's rays.

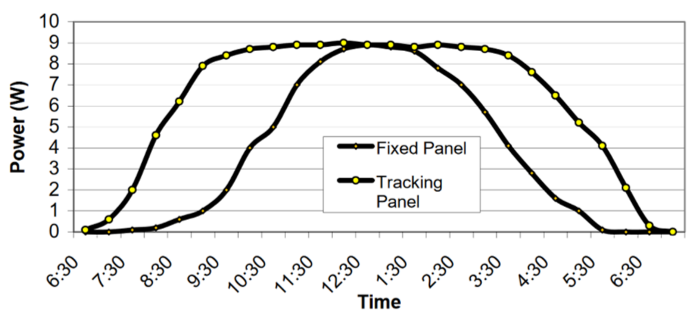

Figure 4: Graph comparing energy collected by a fixed panel vs a tracking panel. (Rizk and Chaiko, 2008).

The results of this paper are shown in Fig. 4. The energy collected can be calculated as shown in Eq. 1.

$$E_{panel} = \int P \, dt \quad (1)$$

Based on Eq. 1, the area under each line in Fig. 4 represents the total light energy collected, with the area under the tracking panel significantly larger than the area under the fixed panel. This shows that the use of solar tracking increases the efficiency of solar cells.

One potential drawback to this design is that operating the motor will require energy, and so the tracking system will act as a parasitic load. Therefore, to determine whether the solar tracking is an effective system for this washing machine, calculations will need to be done specifically for the specification of the washing machine design.

3.4 Final analysis

Having analysed the relevant literature, the need for cheap, effective sanitation in refugee camps is clear. A plethora of research papers have all shown that a washing machine can be an effective tool in reducing and containing the spread of the COVID-19 virus.

In terms of the specifics of how the machine should be built, the designs by LG Electronics Inc., 2005 and from the Washing Machine Project seem to be the most relevant to this project. Therefore, the final design should incorporate features from both these designs in order to meet the requirements of the aims and objectives for this dissertation.

4 Physical design

As mentioned in the *Introduction*, very few refugee camps will have access to an electrical power grid, and so this machine is powered via alternative methods. Across the papers discussed in the *Literature Review*, three options were presented:

1. Use of a hand crank.
2. Use of wind power.
3. Use of solar cells.

The hand crank is the most viable option, given that it is easy to implement, and has already been successfully used in certain designs, such as the Divya (see *Current designs for washing machines* section for details). Therefore, for this design, a hand crank has been used as a power source for the machine.

However, utilising a hand crank as a singular power source is unlikely to yield the required energy to power the machine (see *Power Requirements* section). Therefore, another power source is required. Whilst the miniature wind generators offer promise, these devices do not produce the required power (see *Possible power sources* section for details) for a machine of this size. It is conceivable that these devices could be enlarged to increase their power output, but increasing the size of the device would then make appending the device to the washing machine virtually impossible.

Consequently, solar cells work far better as a secondary power source. Solar panels are flat, and so add very little volume to the device. This is an important point to consider regarding the aim, since this device must be "easy to transport," and thus the machine must be compact. Moreover, most refugee camps are found in arid environments, where the abundance of sunlight allows for higher efficiency of the solar cells. Finally, the use of solar tracking (see *Possible power sources* section for details) means that the panels are more frequently in direct contact with the sunlight, further increasing the efficiency of the cells, resulting in a larger power input.

To summarise, the power sources for the washing machine are a hand crank and solar cells that make use of solar tracking. These were both fitted onto a design for a drum washing machine. A CAD drawing for this design is shown in Fig. 5. (For further sketches from different angles of the machine, see *Appendix 1*).

As shown in Fig. 5, the design is a front facing, drum washing machine. As opposed to other standard, commercial washing machines (see *Current designs for washing machines* section for details), this design has been made in a cubic shape. This significantly reduces the volume of the machine.

This design is also significantly less complex than typical washing machines. Whereas most machines have a variety of settings that can be used, this machine has a simple keypad attached that will be limited to a small number of options. The machine can be used for either a 20 or 30 minute cycle, with the angular

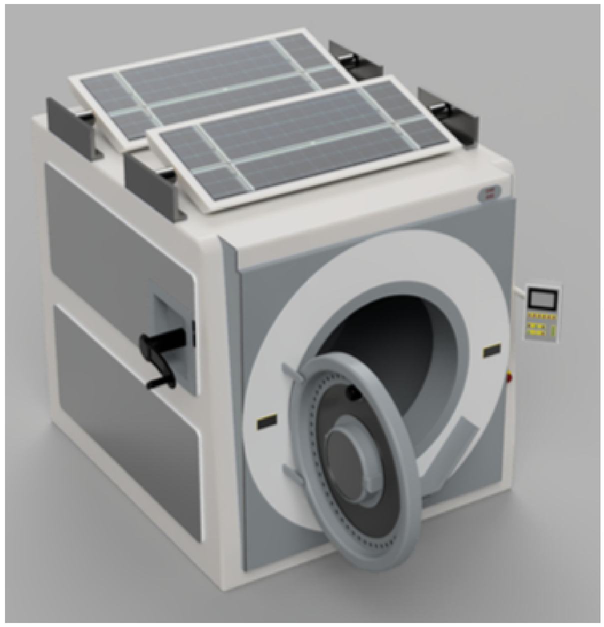

Figure 5: CAD design for proposed washing machine design (designed using Autodesk Fusion 360).

velocity fixed at 300 rpm. This simplicity not only makes the design cheaper, but removes much of the inner electronics of the machine, making the device more compact.

On the left-hand side of the design, the hand crank is shown. Once again, in order to make the design more compact, the interface between the hand crank and the rest of the machine is slightly indented. On the other side of the interface is a system of gears, designed to maximise the power input. This gear system is connected to a small generator, which converts the rotational energy into electrical energy. This energy is then stored in a small battery.

On the top of the machine are solar cells. These panels are mounted on axial rods that are connected to motors on top of the machine. These motors will be controlled via the solar tracking system, allowing for the maximum amount of light to be in direct contact with panels. This energy will then also be stored in the battery.

5 Material selection

The majority of the machine shown in Fig. 5 will be made from standard, off the shelf components. This significantly reduces the complexity of the design, making the overall production process cheaper. Moreover, given this is a charitable initiative, it is reasonable to assume that a deal could be agreed, so these components could be purchased cheaper than the typical market price.

However, given the requirements of the design, two sections of the machine will be manufactured specifically for this design:

- The panels of the machine – the design needs to be lightweight and compact. The easiest way to accommodate these design requirements is to specifically design the panels of the machine.
- Hand crank – one of the methods for powering the machine will be via a hand crank. Given that this will need to be of a specific size and dimension, this part will need to be manufactured.

In order to establish the ideal materials for these components, it was first necessary to consider what the function of the component would be. Then, using this description, a material index was calculated. This material index value was then inserted into a database to establish the most appropriate materials.

The purpose of the panels of the machine are purely structural. They form the skeleton of the machine, holding all the components inside, while having a relatively low density to reduce the weight of the machine. As a result, the panels were designed to be light and stiff. These material properties can be used to derive the material index for the panels, as shown in Eq. 2.

$$M_1 = \frac{\rho}{E^{1/3}} \quad (2)$$

The hand crank needs to be designed such that it is easy to rotate, but is also robust enough to not deform under the applied force. Therefore, the hand crank was designed to be light and strong. These material properties can be used to derive the material index for the hand crank, as shown in Eq. 3.

$$M_2 = \frac{\sigma_y}{\rho} \quad (3)$$

In order to find the ideal materials for the panelling and hand crank, the software GRANTA EduPack 2020 was used. This software is ideal given it contains an extensive list of materials that are commercially available and allows for sorting of these materials via specific properties. Using the material indices calculated in Eq. 2 and Eq. 3, the materials in the GRANTA EduPack database were sorted to find the most suitable for the application. The result can then be plotted graphically, as shown by Fig. 6 and Fig. 7.

The graphs in Fig. 6 and Fig. 7 show all the 4169 materials listed in the GRANTA EduPack database. In order to ascertain which are the optimum materials, the material indices calculated in Eq. 2 and Eq. 3 were plotted on

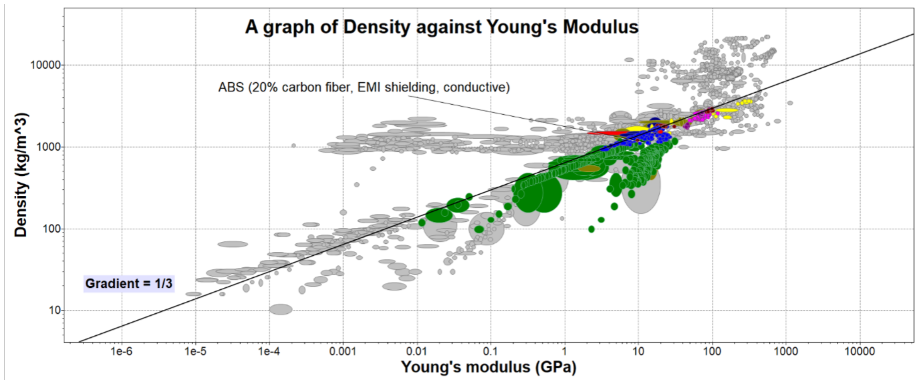

Figure 6: Graph to find the ideal material for the panels of the washing machine.

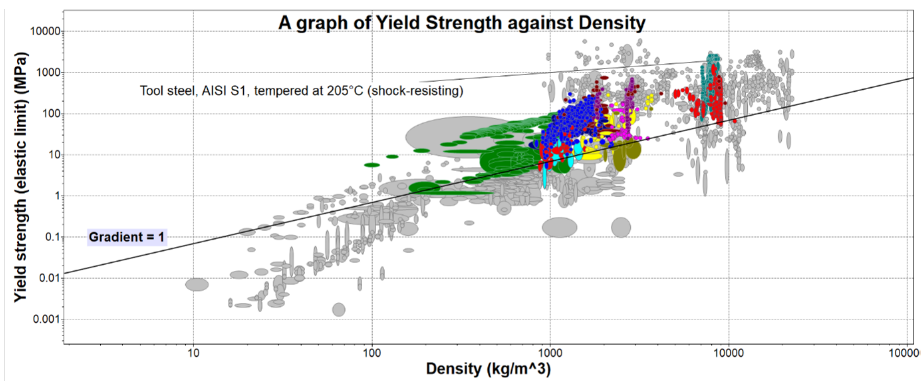

Figure 7: Graph to find the ideal material for the hand crank.

Fig. 6 and Fig. 7 respectively, where the material index determines the axis used, and the gradient of the line.

When considering the requirements for the design, it is desirable for the material index in Eq. 2 to be minimised, hence in Fig. 6 only materials that fall below the line were considered viable materials. Conversely, in Eq. 3 it is desirable to maximise the material index, hence in Fig. 7 only materials above the line were considered. This technique allows for a quantitative method of removing unsuitable materials, making it easier to identify the most ideal materials. (In Fig. 6 and Fig. 7 materials that were considered unsuitable are coloured grey).

Additional parameters were also used to further refine the search. The parameters used were to limit the price to £10/kg, to ensure the materials used were economical, and to only allow bulk materials in the search.

As shown in Fig. 6, the material chosen for the panels of the washing machine was Acrylonitrile Butadiene Styrene reinforced by carbon fibre (in the GRANTA

EduPack database this is listed as "ABS (20% carbon fibre, EMI shielding, conductive).") ABS is an ideal material for the washing machine panels. Not only does it have a low material index value of $0.48 kgm^{-3}Pa^{-1/3}$, but it is also cheap and widely used across the plastics industry.

As shown in Fig. 7, the material chosen for the hand crank was Tool Steel (in the GRANTA EduPack database this is listed as "Tool Steel, AISI S1, tempered at 205°C (shock-resisting).") Tool steel is the ideal material to make the hand crank from, primarily because it has a very high material index, $0.24 MPakg^{-1}m^3$. Furthermore, tool steel has a very high toughness. Given that this is a component that is going to undergo large amounts of low intensity, cyclic loading, it is important that the hand crank be resistant to fatigue failure so that over long periods of time it can still function properly.

Finally, one significant advantage to selecting these materials is that they are both widely used across the materials industry. Therefore, in an effort to further reduce the material cost, these materials will be sourced from the waste stream of factories. Whilst these materials will obviously be of a lower standard compared to materials that have been purchased as new, these waste stream materials will be significantly cheaper. Ideally, given that this project is a charitable initiative, companies would be more willing to allow access to these materials, likely in exchange for good publicity.

6 Power requirements

Given that there will be a wide range of users for this machine, the strength of each individual will vary, and as a result the power they produce will also vary. Given that the majority of people are capable of lifting a 15kg mass (roughly equivalent to producing a force of 150N), this is the standard that will be used for these calculations.

The hand crank for this design is likely to have a length of 30cm. Therefore, the torque generated can be calculated, as shown in Eq. 4.

$$\tau = Fl = 150N \times 0.3m = 45Nm \quad (4)$$

It is reasonable to assume that the time period for one complete rotation of the crank will be approximately 2 seconds. Using these figures, the power generated from the crank can be calculated, as shown in Eq. 5.

$$P_{crank} = \tau\omega_{crank} = 45Nm \times \frac{2\pi}{2} rads^{-1} = 141.4W \quad (5)$$

To calculate how much time the crank would have to be turned for, the total amount of energy required to power the machine must be calculated. By completing a number of calculations (shown in *Appendix 2*) a relationship between power and angular velocity of the machine was determined, as shown in Eq. 6.

$$P_T \propto \omega_{drum}^3 \quad (6)$$

Calculating the total energy needed to power the machine would require a series of complex calculations. Moreover, a number of assumptions would need to made, likely leading to a significant error in the final result. Therefore, a more accurate method of determining the energy required is to use the relationship given in Eq. 6 and input existing data. For the purposes of this calculation, input data has been taken from the Hoover H3WS495TACE spin washing machine (Product information sheet, 2021), since this model has similar parameters to the design for this project. The Hoover model has the following parameters:

- Spin cycle of 1400 rpm
- 66kW power rating

Using this information and given that the washing machine for this project will have an rpm of 300, Eq. 6 can now be adapted to find the total energy required to power the washing machine, as shown in Eq. 7.

$$P_T = P_{ref} \times (\frac{\omega_{drum}}{\omega_{ref}})^3 = 66kW \times (\frac{300rpm}{1400rpm})^3 = 649.4W \quad (7)$$

As mentioned previously (see *Physical design* section) the length of each washing cycle will be fixed at 30 minutes, in order to reduce the complexity of the design. With this given time, the total amount of energy required to power the machine for one cycle can be calculated, as shown in Eq. 8.

$$E_T = P_T \times t = 649.4W \times 1800secs = 1.17MJ \quad (8)$$

Using the same equation, the energy generated by turning the crank for an hour can be calculated.

$$E_{crank} = P_{crank} \times t = 141.4W \times 3600secs = 0.509MJ \quad (9)$$

These two energy values can now be compared. By calculating a ratio between these two values, the time taken to provide enough power for one washing cycle can be calculated.

$$\frac{E_T}{E_{crank}} = \frac{1.17MJ}{0.509MJ} = 2.30hours \quad (10)$$

Eq. 10 gives the minimum time required to turn the crank in order to power the machine for one washing cycle. However, thus far none of these calculations have considered the solar panels. Calculating the power output of solar cells typically leads to large uncertainties regarding the results, since these calculations are based upon the weather, a phenomenon that is impossible to predict. Consequently, several assumptions have been made for these calculations in conjunction with using the conditions from the paper "Solar Tracking System: More Efficient Use of Solar Panels," (Rizk and Chaiko, 2008.) (NB, this paper was discussed in the *literature review*, see *Possible power sources* section for more details).

Given that they are lightweight and have already been tested, the Solarex 9W solar array used in this paper has also be used for this project. In the research paper, it was found that over a 12-hour period, the solar cells managed an efficiency of 71%, giving a power output of 6.3W. As shown in Fig. 5 (see *Physical design* section), the washing machine has two separate solar cells. Therefore, assuming 12 hours of daylight, the total amount of energy collected per day by the solar array can be calculated, as shown in Eq. 11.

$$E_{solar} = number of solar cells \times P_{solar} \times t = 2 \times 6.3W \times 43200secs = 0.544MJ \quad (11)$$

Using the value calculated in Eq. 11, the amount of time needed to charge the washing machine for one full cycle can be calculated, if the solar cells were to be used as a singular power source (the hand crank was not used to generate any extra power).

$$\frac{E_T}{E_{solar}} = \frac{1.17MJ}{0.544MJ} = 2.15days \quad (12)$$

7 Simulation of solar tracking system

When calculating the values for the power produced by the hand crank (see *Power sources* section for details), established formulae were used in conjunction with real life electrical properties. As a result, the calculations for the hand crank can be considered reliable. However, a number of assumptions were made whilst performing the same calculations for the solar tracking system, and so these conclusions cannot be said to be as reliable. Therefore, a simulation was run to assess how effective the solar tracking system can operate, in order to ascertain whether the assumptions made were valid. The design for this simulation has been adapted from Brian Neiswander (2021).

In order to run the simulation, a control system was designed. This was done via the software SIMULINK. Both the motor and the motion of the panel needed to be modelled. Given that the motor was modelled on Eq. 13, and the motion of the panel was modelled on Eq. 14, these two equations were used to design the corresponding systems, as shown in Fig. 8 and Fig. 9 respectively.

$$\frac{di}{dt} = \frac{1}{L}(V - Ri - K_G K_F \frac{d\theta}{dt}) \quad (13)$$

$$\frac{d^2\theta}{dt^2} = \frac{1}{J}(T - K_D \frac{d\theta}{dt}) \quad (14)$$

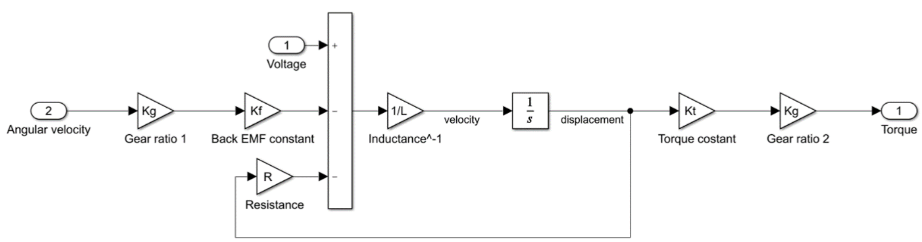

Figure 8: Model for the motor section of the solar tracking system, based on Eq. 13. Model made using SIMULINK.

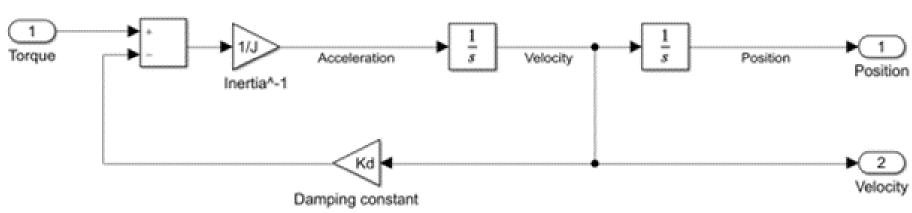

Figure 9: Section of the control system that models the movement of the panel in the solar tracking system, based on Eq. 14. Model made using SIMULINK.

Both Fig. 8 and Fig. 9 represent subsystems for the overall system. These subsystems were then connected in the appropriate way, forming the overall control system.

Given that the input data for this system constantly changed (the position of the sun changes constantly throughout the day), some form of PID (proportional, integral and derivative) control system needed to be used. This was because a PID controller is a simple, effective way to have a system respond to a set error. When the panel was not perpendicular to the sun, an error was detected. The system was set up in a feedback loop, so the system responds such that the error is continuously lowered until the error is zero. The PID controller is based on Eq. 15 (Ogata, 2002).

$$u(t) = K_p e(t) + K_i \int e(t)dt + K_d \frac{de(t)}{dt} \quad (15)$$

In order to determine which type of PID controller was used, each term was defined so its suitability for this system could be assessed. On the right-hand side of Eq. 15, the first term represents the proportional part of the controller. The proportional term is determined by the error (the difference between the process variable and the set point). This term is necessary to ensure the system responds to the change in environment quickly. The second term represents the integral part of the controller, which integrates the error over time. This is necessary to reduce the steady state error. The final term is the derivative term, which causes the output to change if the process variable changes rapidly. However, this is not a scenario that will occur in this system since the sun will move steadily across the sky. Therefore, the derivative term was not required for this system.

As a result, a PI controller was used in this system. This controller was then placed in a feedback loop with the other two subsystems, and then tested using a step input, as shown in Fig. 10.

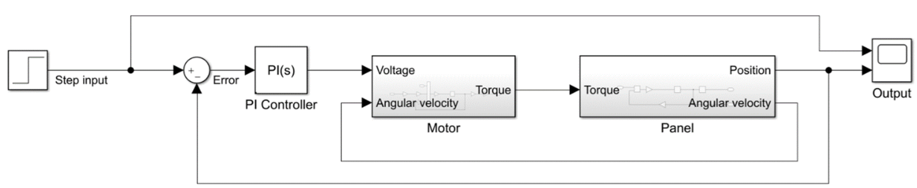

Figure 10: A design for the complete control system, utilising a PI controller in a feedback loop. The two subsystems for the motor and panel are shown in Fig. 8 and Fig. 9 respectively. Model made using SIMULINK.

The system in Fig. 10 was then tested to observe if it can adequately respond to a step input. Given that the sun moves steadily across the sky, a step input represents an extreme example of how the sun will behave. Thus, if the system can respond well to a step input, it follows logically that the system will respond well to the movement of the sun.

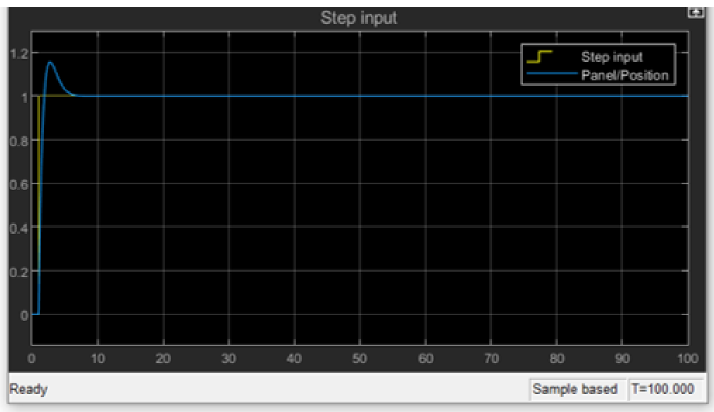

Figure 11: A graph showing how the control system shown in Fig. 10 responds to a step input. Graph produced using SIMULINK.

Fig. 11 shows that the control system designed in Fig. 10 was able to respond well to a step input. The rise time is short, and although there is a small amount of overshoot, as mentioned before this test case is an extreme example, hence this overshoot was unlikely to be a significant problem.

Given that the control system was able to pass the testing phase, the system was then tested using real life sun data (Neiswander 2021), as shown in Fig. 12.

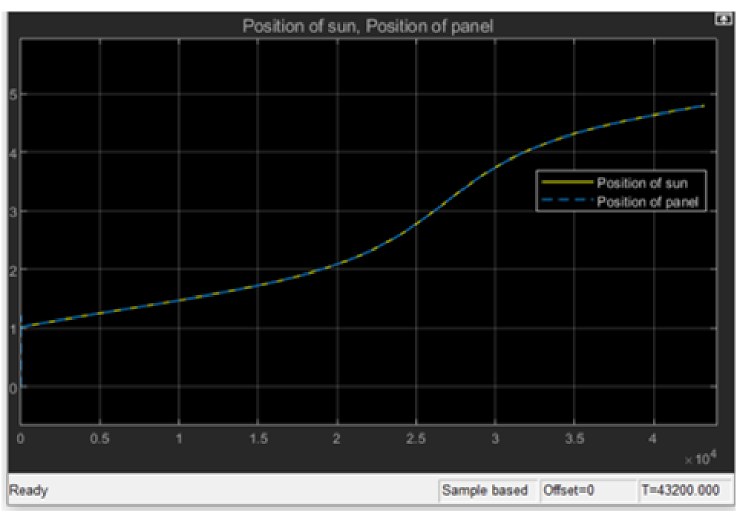

Figure 12: A graph showing how the control system shown in Fig. 10 responds to real-life sun data. Graph produced using SIMULINK.

8 Discussion

To summarise the results of the previous calculations (see *Power sources* section for details), the following results were determined:

- If the machine were to be solely powered via the hand crank, it would take 2.30 hours to power the machine for one wash cycle.
- If the machine were to be solely powered via the solar cells, it would take 2.15 days to power the machine for one wash cycle.

The calculations performed for the power of the hand crank were based off established mathematical formulae and empirical data, and so this conclusion is reliable. However, the calculations involving the solar tracking system made two important assumptions:

- The panel was perpendicular to the sun for the entirety of the day.
- The solar tracking system did not use a significant amount of power.

As a result, the reliability of the conclusions for the calculations relating to the power of the solar cells is predicated on these assumptions being correct. Therefore, a simulation was run (see *Simulation* section for details) to determine the validity of these assumptions.

The first assumption can be assessed by analysing Fig. 12, which shows that over the course of the day the panel is able to track the position of the sun extremely well, with there being no observable error in this graph. When increasing the resolution, it can be shown that there is a tiny amount of steady state error. This is to be expected, and given that the error calculated is $1.38 \times 10^{-5}\%$, this error can be considered negligible. As a result, the initial assumption that the panel is constantly perpendicular to the sun is valid.

The second assumption was analysed by considering the voltage used by the solar tracking system during the simulation. Data from the simulation shows that the voltage spiked briefly at the beginning of the simulation for less than one hundredth of a second, then reduced to a value of 1.58mV and remained at this value until the simulation finished. When considering that the amperage used by the tracking system is 0.75A, Eq. 16 was used to find the power used by the solar tracking system.

$$P = IV = 1.58mV \times 0.75A = 1.19mW \quad (16)$$

It is known that the power produced by the tracking system is 6.3W, hence using Eq. 16 it can be established that power used by the tracking system is 0.019% of the total power produced. This value is negligible, and so the second assumption is also valid.

9 Conclusion

The initial objectives of this project were to:

- Design the basic shape and geometry of the washing machine using CAD.
- Select the appropriate materials for the washing machine to be made from.
- Determine a suitable power source.
- Design the necessary electrical systems for the machine to work independently of human interaction.

The first two objectives both relate to the physical design of the machine. The design is largely based upon the standard drum washing machine. However, the design is more compact, less complex and cheaper, each of these parameters being key parts of the aim. The materials selected also reinforce this, by making the machine lighter, thus easier to transport, and cheaper. As a result, it is reasonable to conclude that the first two objectives for this project were met successfully.

The final two objectives both relate to the energy and electrical systems within the machine. In the *Power requirements* section, the time taken to power the machine via either the hand crank or the solar cells were both calculated. However, some of these calculations were predicated on certain assumptions. As a result, a simulation was run (see *Simulation of solar tracking system* for details) to determine the validity of these assumptions. When analysing the results of the simulation (see *Discussion* section) it was confirmed that the assumptions made were valid, hence the original calculations can be said to be reliable.

As a result of this, the timings calculated in the *Power requirements* section can be considered as a valid maximum estimate. Therefore, the final consideration to take into account is whether these timings are viable, i.e., would this design be able to function in a real-world refugee camp. Whilst separately the two power sources are perhaps not powerful enough, when combined the power produced is likely to be sufficient.

For example, a likely scenario could perhaps be that the machine has not been used for a day. As a result, over this period of time the solar cells on top of the machine would have charged for 44% of a wash cycle. Therefore, at this point if a user wanted to use the machine, they would only need to turn the hand crank for 58 minutes. If the machine was left for two days unused, this value would drop further to only 13 minutes needed to turn the hand crank.

It is also worth noting that this design gives flexibility to the user. If the person is physically immobile due to age or illness, they can wait the required time for the solar panels to charge up to use the machine. Alternatively, if the user is physically capable, they can use the hand crank to accelerate the process.

Overall, this design seems to work well. Further work could be done on the physical design, specifically in the interior of the machine, by selecting materials to further reduce the weight and size of the machine. However, the current design functions well, adapting existing concepts and adding new ideas to design a machine that can effectively meet each of the objectives and aims.

10 Acknowledgements

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- Faraz Khan
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The following software was used in the research and creation of this report:

- Autodesk, 2020. Cloud Powered 3D CAD/CAM Software for Product Design — Fusion 360.
- CES EduPack Software, Granta Design Limited, Cambridge, UK, 2020.
- MATLAB, 2020. Version 9.8.0 (R2020a), Natick, Massachusetts: The MathWorks Inc.
- The Latex Project, 2021. Latex
- Microsoft Corporation, 2018. Microsoft Excel
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12 Appendix 1

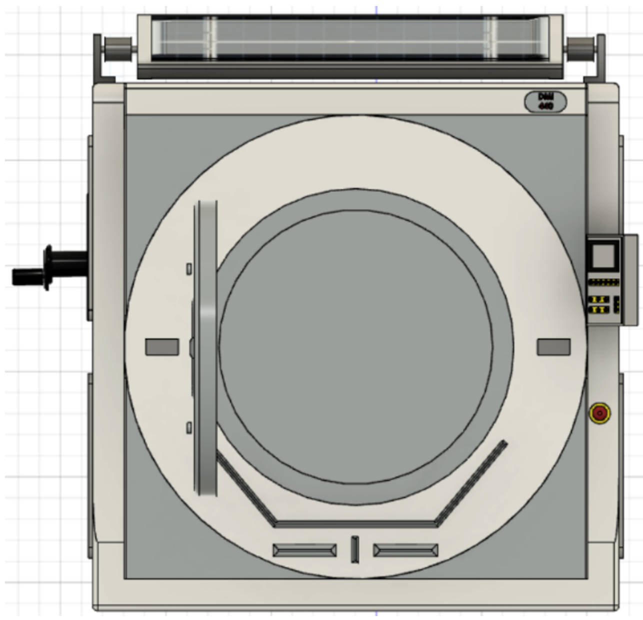

Figure 13: Sketch of the proposed washing machine design, viewed from the front. Designed using Autodesk Fusion 360.

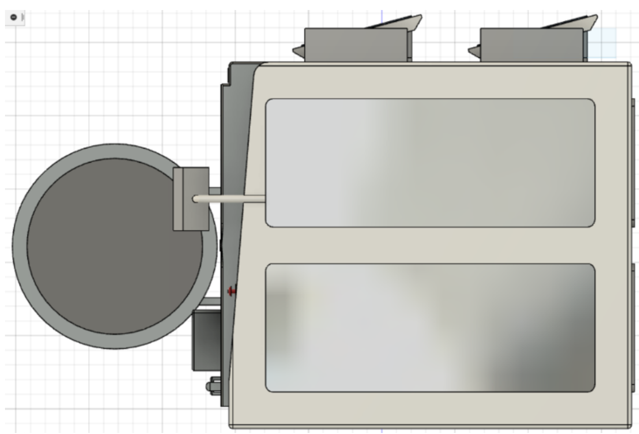

Figure 14: Sketch of the proposed washing machine design, viewed from the right. Designed using Autodesk Fusion 360.

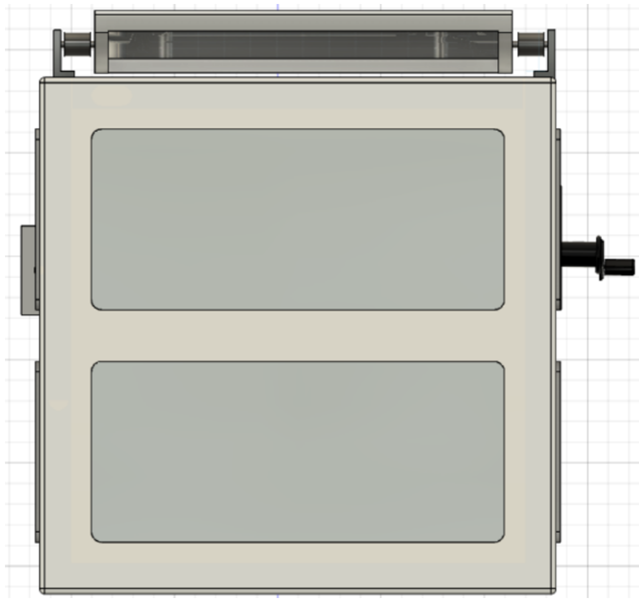

Figure 15: Sketch of the proposed washing machine design, viewed from the back. Designed using Autodesk Fusion 360.

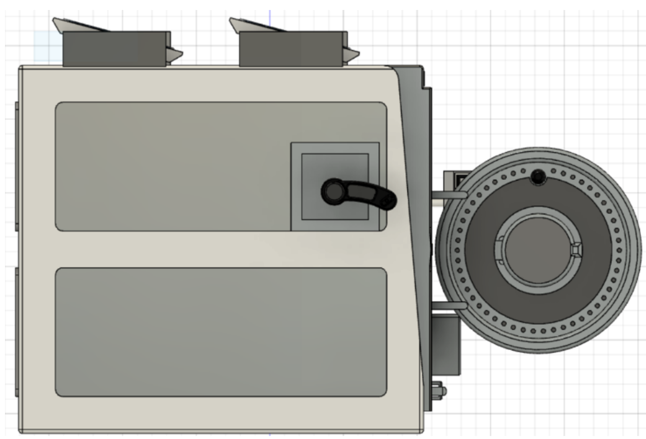

Figure 16: Sketch of the proposed washing machine design, viewed from the left. Designed using Autodesk Fusion 360.

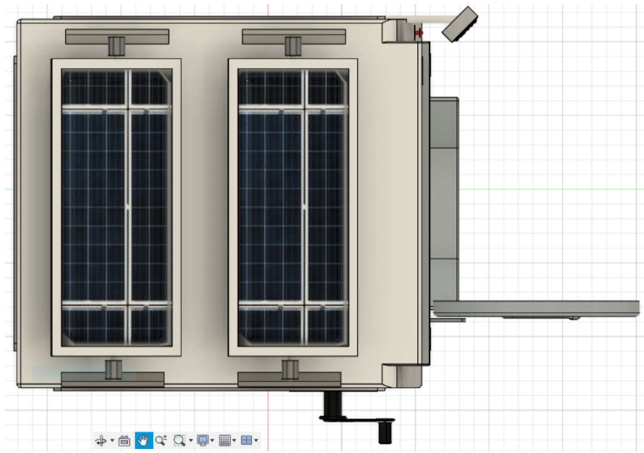

Figure 17: Sketch of the proposed washing machine design, viewed from the top. Designed using Autodesk Fusion 360.

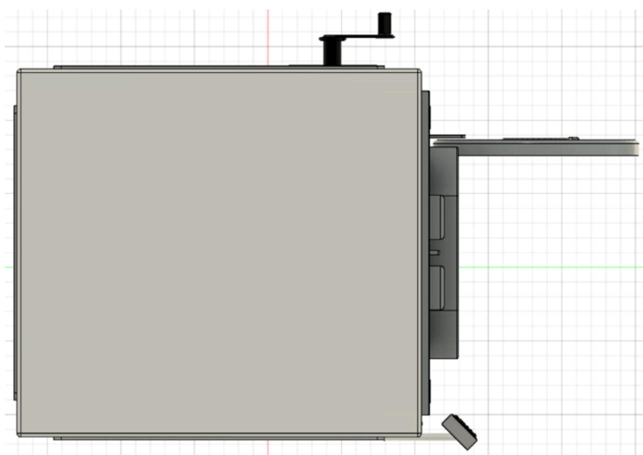

Figure 18: Sketch of the proposed washing machine design, viewed from the bottom. Designed using Autodesk Fusion 360.

13 Appendix 2

The rotation of the drum of the washing machine can be considered as a solid cylinder, rotating about its centre of mass. If such a cylinder were to be pushed along a horizontal plane, the linear velocity, v, could be expressed as the product of the angular velocity, ω and the radius of the cylinder, r.

$$v = \omega r \quad (17)$$

The centripetal force, F, acting on this cylinder can then be written as in Eq. 18, where m represents the mass of the cylinder.

$$F = m\omega^2 r \quad (18)$$

Using the definition of power as the product of force and velocity, Eq. 17 can be multiplied by Eq. 18 to form an equation for the power of the cylinder.

$$P = Fv = \omega r \times m\omega^2 r \quad (19)$$

The weight and size of the drum are not going to change throughout the washing cycle; hence the radius and mass can be considered constant. Hence, by removing these physical constants from Eq. 19, a relationship between power and angular velocity can be formed, as shown in Eq. 6.

$$P_T \propto \omega_{drum}^3 \quad (6)$$