Affordable Exercise

Abstract

This paper outlines analysis to improve the design of a stationary recumbent bicycle for a bariatric client. Systems Engineering Analysis techniques are used to comprehensively analyse the Recumbent Bicycle, with particular focus on the need to accommodate the unique anthropometric characteristics and economic constraints of the project. Analyses include study of the Energy flows of the design, Time of the manufacturing process and Materials choices and their environmental impacts. Optimisation in the aims of improving reliability is completed, and finally economic considerations are outlined. Anthropometric factors are coupled with qualitative and quantitative analysis of the scope of the system. Finally, the analysis concludes that a "mini cycle" design in a recumbent configuration provides the best outcomes in terms of economic, anthropometric, environmental and reliability factors.

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Introduction

Problem Statement

The client is a male in his mid-forties who has a height of 2.3m and mass of 210kg, with existing medical issues such as arthritis and carpal tunnel syndrome (CTS). This presents a unique challenge for cardiovascular exercise due to the restricted activities in which the client can participate. Based on previous research focusing on the requirements of the client, stationary bicycles modified for the client's use have been identified as the most suitable solution to assist weight loss (ENGN2225, 2014). In particular, recumbent machines have been suggested. This project will focus on analysis of these machines to evaluate their viability as a solution for the client.

The recommendation of stationary exercise bikes is predominantly due to the client's physical stature and secondary health conditions. CTS occurs in hands causing pain, tingling and other unusual sensations. It occurs as a result of compression on the median nerve in the arm, causing discomfort during everyday tasks such as driving, reading and picking up objects (Becker et al., 2002). Arthritis occurs in joints throughout the human body causing pain, cartilage damage and stiffness (Arthritis Australia, 2012). Arthritis may be the direct result of obesity or the cause of obesity due to physical immobility (Amarya et al., 2014).

These conditions eliminate high impact exercise such as running and hence place a great deal of restriction on how the client can exercise. This makes it particularly important to identify whether or not the recommended solutions are appropriate. To achieve this, this project will focus on analysing recumbent exercise machines to determine their suitability for the client; and will then explore improvements of an existing recumbent bicycle design to cater for the needs of the client.

1.0 System Scoping

1.1 Stakeholders in the project

Client, gym equipment manufacturer, client's family, doctor, friends and carer

1.2 Use Case

The exercise machine will be used within the home, and the design will therefore consider the setup, space and economic constraints associated with this use.

2.0 Quantitative Analysis

2.1 Estimations of Energy use for Different Exercise Machines

The total calories burnt during a 30 minute exercise period for various activities are calculated by a formula developed by University of Colorado Hospital (University of Colarado Hospital, 2004), which states that: energy expenditure (calories) = 0.0175 x MET (metabolic equivalent, given for many exercises on the webpage) x weight (kg) x 30 (minutes). Walking at three different paces and stationary cycling at three different intensities were compared with controls of running and sitting.

Walking and stationary cycling historically been recommended as the two best forms of exercise for people who are obese (Livestrong, 2014, Better Health Channel, 2014), with exercise bike riding being favoured due to the lower stress on the joints of the body (Sava et al., 2010). Estimations show that the energy expenditure for stationary cycling is significantly higher at most intensity levels than walking (3-7MET and 1-3.5MET respectively). Therefore, stationary cycling can be confirmed as a suitable exercise type for the client due to the energy expenditure benefits and reduced risk of new injury or aggravation of existing conditions.

3.0 Qualitative Analysis

3.1 Survey

Although physical ability is a large limiting factor for this project, there are other factors to consider when choosing the design solution for this project. It is important to account for the client's mental health by implementing a solution that will be enjoyable to use. To account for this in the design process, a survey was conducted to determine people's exercises habits and what they find enjoyable about exercising. The results of this survey formed the qualitative analysis for this project.

3.2 Survey Results and Coding

81 survey responses from people of varying age, gender and fitness level were collected and analysed to gain a better understanding of attitudes towards exercise, both in general, and in regards to specific activities. It was found through these responses that the majority of people prefer cardio vascular types of exercise, specifically, running, walking and cycling. The most popular exercise performed, overall, is walking, with cycling closely following.

Considering these responses in conjunction with previous research of the client's health conditions and the energy expenditure benefits of cycling over other forms of exercise, the most suitable exercise type for this project is stationary cycling. Therefore, the project will analyse an affordable recumbent bicycle solution that the client can use from home.

4.0 Human Factors

The client is a 210kg, 2.3m tall male in his mid-forties. The existing medical issues such as arthritis and CTS present challenges in terms of ensuring the final design can meet his unique anthropometry whilst providing a high level of comfort.

4.1 Anthropometry

Given the extreme height of the individual, standard tables of anthropometric measurements do not necessarily apply. As a result, several sources were used in order to gain knowledge of specific measurements.

Using data based on correlation ratios, and taking measurements for the 99th percentile (United States Marine Corps, 2006, Rose and Jeeverajan, 2008), ratios of height to measurement could be ascertained. Using these ratios, rough measurements of critical dimensions could be calculated based on the given height of 2.3m:

- Leg length, based on buttock to heal: 141cm
- Sitting height to eye level (head rest): 104cm
- Arm length (back to closed fist): 107cm
- Hip width: 51cm
- Popliteal height (back of knee): 58.4cm
- Buttock to knee length: 62.9cm.

Using a recumbent-bicycle fitting calculator (Beauchamp, Unknown), the crank length could be determined to be 180mm.

Particularly, due to the obese state of the client, the measurement of hip width is likely to be inaccurate. Instead, in this case, commercially available bariatric briefs were used to calculate this value. Bariatric briefs have values in the range of 70-90 inches (Attends Healthcare, 2014) . If one assumes the waist to be roughly circular, one can obtain a diameter of 56.6-72.8cm. It is expected that there would be some compression and widening of the body whist in a seated position, which makes this estimate somewhat inaccurate. Furthermore, the assumption that the waist is circular may not be entirely accurate. As a result, a chair width of as much as 80cm may be required.

A result of this analysis is that the design must be both highly adjustable and able to compensate for the added weight requirements. This analysis also establishes that the design would greatly benefit from being able to integrate with existing bariatric chairs.

4.2 Ergonomics and Comfort

Comfort is an important consideration, both physically and psychologically for the client. Great importance is placed upon this point as increased comfort will likely lead to higher usage of the device. Psychologically speaking, stationary exercise machines are repetitive and can be boring, as mentioned in section 3. Strategies or design elements to combat boredom are therefore a design aim, discussed in Section 6.2 where the addition of a TV monitor is considered. Physical comfort could be affected by the client's health conditions such as his CTS and arthritis, so appropriate consideration of movement that may exacerbate these conditions is important. In order to account for this, the survey discussed in section 3 was written.

Several factors outside the scope of the system greatly effect comfort including the local environment which influences temperature, humidity and airflow. Further considerations such as clothing and the availability of medical attention (safety) are also excluded from the system scope. These factors suggest the design should focus on flexibility of the device so it can be used in a comfortable location.

Recumbent bicycles have several comfort benefits (Looney and Rimmer, 2003):

- Reclined seat, wider seats that provide lower back support and more comfortable for the overweight
- Shoulder level handle bars alleviate wrist pressure
- Provide a low impact cardiovascular workout
- Alleviate impact on joints and lower back
- May allow users to exercise longer as their legs are not bearing the weight of the body
- Compensate for balance issues associated with obesity
- Low probability of injury
- Stationary Recumbent bicycles are easier for obese people to mount than upright bicycles
- Typically do not cause leg angles less than 90°, reducing knee pain.

Key outcomes

Using the anthropometrics calculated previously, the following design was formed:

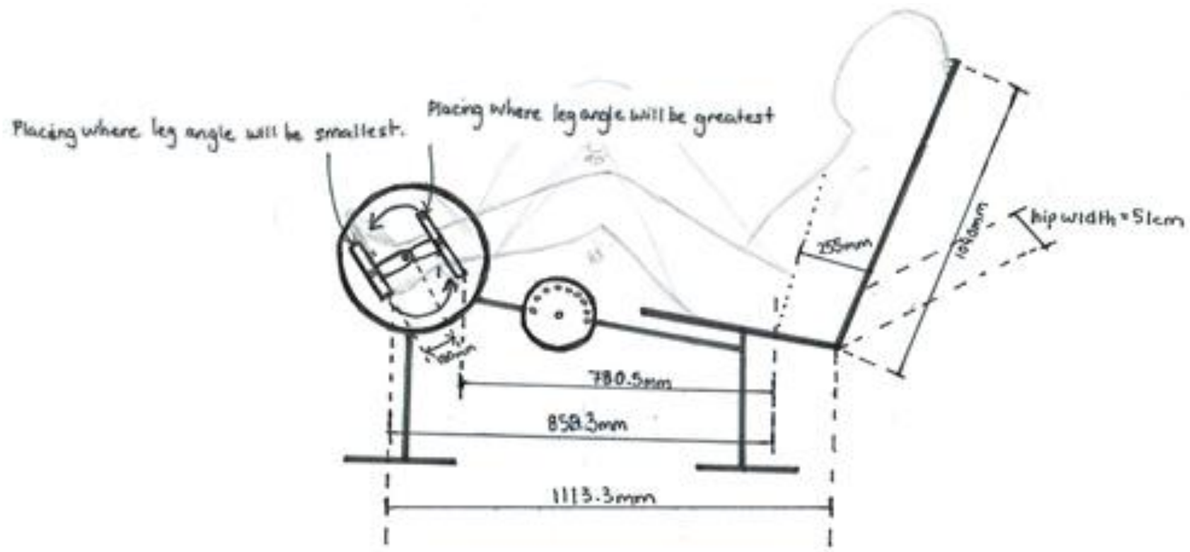

Figure 1 Anthropometric Measurements of Stationary Recumbent Bicycle Design

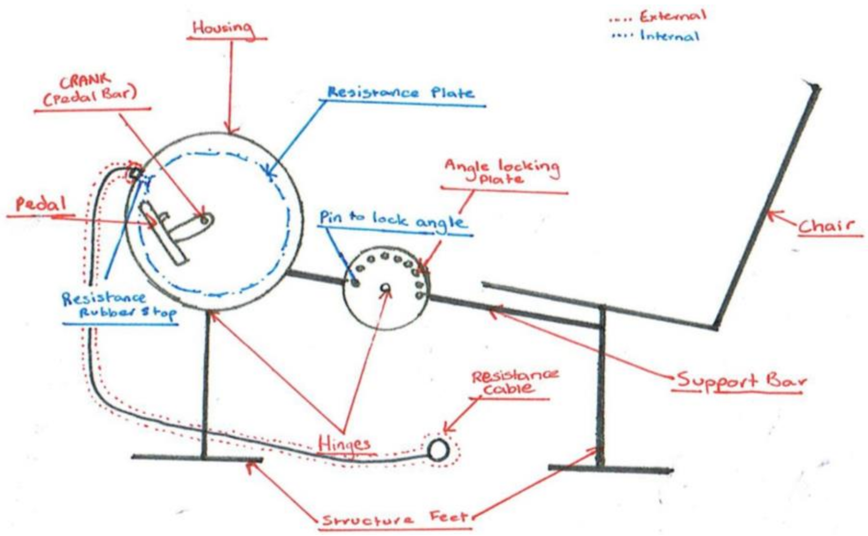

Figure 2 components of Stationary Recumbent Bicycle Design

This analysis has indicated the importance of adjustability, customizability and flexibility in the design as key goals.

5.0 Time Analysis

5.1 Queue Theory

Queue theory can be an important part of the time analysis for a project. For Affordable Exercise, the applications of queue theory were identified through the use of the critical path method. This method was applied to the production stage. Initially this project spanned over 24 days, because the production stage had a 13 day break where the workers waited for the delivery of the chair. However, by identifying where the chair was needed in the production process, it became obvious that the project could be 'crashed' to a smaller time period by beginning the cutting of individual components towards the end of the chairs expected delivery time, rather than starting once it had been delivered. This application of queue theory is seen in a comparison of the two PERT charts in ANNEX A and two samples of the manufacturing Gantt charts presented in table 1 a and b.

Activity/Day	1	11	12	13	14	15	16	17	18
Purchase Chair (10-14 day delivery)									
Purchase Hinges									
Cut frame components									

Table 3 a) Gantt chart before application of queue theory

Activity/Day	1	11	12	13	14
Purchase Chair (10-14 day delivery)					
Purchase Hinges					
Cut frame components					

b) Gantt Chart after application of queue theory

5.2 PERT and Gantt Charts

Timing of an engineering project is paramount to a successful outcome. For this project, time analysis is necessary to break down the production stage of the design process. To do this a PERT and a Gantt chart (ANNEX A) were made to outline necessary steps to produce a completed product.

By using these charts, the production stage for this project has become clear. The PERT chart has shown a flow of the project, indicating steps and outcomes. Gantt charts work in a similar way, though they are less streamlined. The Gantt chart would be utilized most as a check list of sorts, providing a project manager with a restricted time line. The PERT chart is more useful for constructors, as it outlines which components need to be made first, indicating the other mechanisms of the design rely on their production.

Key outcomes

The Gantt chart in ANNEX A was a simplistic approach to a convoluted process; this is both an advantage and a disadvantage. It broke a complex system down into a simplified form, but it did not have the same flow as the PERT chart in ANNEX A. It did not show the order in which individual components on different days needed to be constructed, instead giving a general overview of the progress that was necessary that day. Overall, by using both charts, the project has been broken down into smaller, more manageable pieces.

This break down is integral in structuring later analysis techniques. When performing materials, energy, optimisation and cost analyses, it is essential to consider the timing of the project's stages. If, through these evaluations, the design becomes altered, the timing of the project could change significantly. In the case of manufacturing, should aspects of the design be adjusted to allow more standardized parts in the frame, less processing of base materials will be required, resulting in less wastage and hence lower overall costs for components. Using PERT and Gantt charts, the areas where this can occur become clearer. It is easy to see where standard parts can be switched, resulting in a shorter manufacturing time. Additionally, if the client already has a bariatric chair available then the cost, embodied energy and manufacturing time of the project will be reduced significantly.

6.0 Energy Analysis

At this stage in the systems analysis, the design is a custom-made recumbent exercise bike system that consists of a commercially bought, bariatric chair attached to a wheel with two rotating pedals with adjustable resistance. The I=PAT equation, Energy-Mass Balance Audit and a Sankey Diagram are methods that will be used to analyse aspects of the system's energy. These methods allow the systems relationship with energy to be explored with the goal of highlighting aspects of the design that can be improved such as energy efficiency as well as cost and environmental impact.

6.1 Human Energy Expenditure- I= PAT and Energy Mass Balance

For this project, the I=PAT equation is used to investigate the energy expenditure of a person undertaking weekly exercise. Equation 1 shows an I=PAT equation that breaks down the energy expended per week into the number of exercise sessions completed in a week, length of time of each session and the amount of energy expended in a given length of time. The weight loss goal of the client is directly related to energy as reducing the energy (calories) stored in the body can result in a reduction of weight. Therefore, expending more energy per week will result in a loss of unwanted weight so increasing the "impact" is desired.

$$\frac{Energy\ expended}{Week} = \frac{Sessions}{Week} \times \frac{Time}{Sessions} \times \frac{Energy\ expended}{Time}$$

Equation 1. ***I=PAT equation of the relationship of a persons weekly energy expenditure***

Figure 3 shows two connected energy-mass balance (EMB) audits that consider the energy flow within the bicycle user and the recumbent bicycle. Only energy flow is considered as the system is static and there is no flow of materials. The top EMB in Figure 3 shows chemical energy from the consumption of food as the input to the system where it is stored in the body as body fat or muscle until it is expended from the body as heat or mechanical energy.

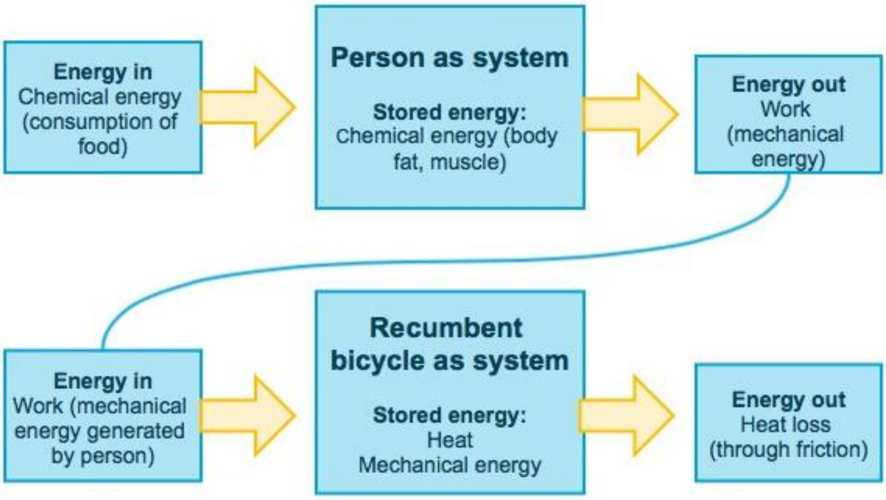

Figure 3 Energy Mass Balance of bicycle user and recumbent bicycle.

This section of the energy analysis looks at human energy expenditure and has provided information that can be shown to the client to explain how to achieve their weight loss goal while using the recumbent bicycle. Due to conservation of energy, in order to decrease the amount of stored energy, the work expended from exercising must be greater than the input energy. This will allow the stored energy as well as the input energy to be converted into the output energy. To achieve larger output energy than input energy, the client would either need to reduce their consumption of food or increase their energy expenditure. The I=PAT equation in equation 1, indicates that to increase the energy expended per week, either the number of exercise sessions per week, the length of time of each session or the energy expended each session (e.g. increasing the workout speed or resistance of the recumbent bicycle) could be increased.

6.2 Converting Human Power to Electrical Energy- Sankey Diagrams

The bottom EMB in Figure 3 shows the energy input of the bicycle is the mechanical energy output of the bicycle user. This energy is then stored in the system until it is lost as heat through friction. The EMB highlights a possible energy efficiency improvement to the design since the mechanical energy expended by the bicycle user is not utilized. The mechanical energy generated by the user could be converted, stored and used as electrical energy to power an electrical device such as a TV monitor. The addition of an entertainment device would provide the client something to focus on whilst exercising as often people find using stationary bicycles to be boring, as mentioned in Section 3 and 4.2.

Depending on the strength of the bicycle user and the rate they are pedalling, between 50-400W of power can be generated in an hour using a stationary bicycle (Gibson, 2011, Haji et al. 2010, Mechtenberg et al, 2012, Podmore et al, 2011). The electrical energy required to power a TV monitor ranges from 50-200W depending on the model (*Calculate your appliance running cost*, 2014). However, the energy generator devices required for energy conversion have a range of 40-70% possible energy loss during conversion. (De Decker, 2011). The Sankey diagram in ANNEX B shows the energy flow of a generator that looses 67.5% of energy during conversion (De Decker, 2011). According to this range, to power a 100W TV monitor for an hour, 200-300W of power needs to be generated. It is important to note the uncertainty in this calculation, as the power output of the user is unknown so they could actually produce significantly less or more power that has been considered for this analysis. Also, improvements to the energy efficiency of storage generator designs could make them more practical in the future.

While it is possible to generate enough power for a TV monitor whilst cycling, it requires the additional cost of an energy generator, starting at $400 (The Pedal-A-Watt Stationary Bike Power Generator, 2014) and the energy loss during conversion is not efficient so this idea is not practical for the Affordable Exercise project. Also, it is more than likely the client already has a TV at home he can use that is powered by electricity from a power grid at no more than $100 a year (Calculate your appliance running cost, 2014).

Key Outcomes

This analysis process looked at the energy flow of a stationary recumbent bicycle and the user of the bicycle to identify energy efficient improvements that can be made to the current recumbent bicycle design. Although, no improvements were made to the design as it was determined the addition of a TV monitor and energy generator are not suitable to this particular project, the energy analysis process was able to highlight ways the client can increase their energy expenditure in order to achieve their weight loss goals.

7.0 Materials Analysis

The materials analysis of the design was completed for the *Cradle to Gate* portion of the lifecycle using Embodied Energy (Ingrao et al., 2014, Hu et al., 2014, Slavković and Radivojević, 2014, Zendoia et al., 2014). The functional unit defined is the stationary bicycle, which has a temporal horizon of approximately 10 years (Stuller, 1985). This section does not consider any electrical components, as noted in section 6, they will not be integrated into the design.

The materials audit table for the stationary recumbent bicycle, which quantifies the embodied energy of each component and provides description of the end of life destination is shown in ANNEX C. Values of specific Embodied Energy and specific carbon output were sourced from the Inventory of Carbon and Energy ('ICE') from the University of Bath (UK) (Kara and Manmek, 2009, Unknown, 2014, Hammond and Jones, 2006). Values of material quantity (measured in m^3) are based on estimates of design dimensions from design sketches as seen in Figures 1 and 2.

The “end of life” issues for the system were considered and the total energy committed to landfill, recycling and reuse were calculated. Overall, 0.01kg of the system is committed to landfill, representing 1.9MJ of embodied energy, 31.46kg and 1926MJ are committed to recycling and 31.54kg and 2590MJ are committed to reuse; a total of 4518MJ in a 63kg system.

Discussion

Overall this application to the project gives some insights. There are several sources of error, the largest associated with the values of specific Embodied Energy, the estimates of material quantity. Detailed estimates of material quantity may come from detailed engineering drawings. The estimated mass of 63kg is comparable to that of commercially available stationary recumbent bicycles (Target, 2014), validating the estimates somewhat.

The table in ANNEX C allows for clear comparison between material choices based on embodied energy. On first observation, Aluminium would be chosen over Steel and Carbon Fiber. Aluminium is comparably inexpensive against carbon fiber (Hibbler, 2005) and has a lower embodied energy than that of steel. However, the materials audit table does not take into account the materials' properties. Aluminium has a Young's Modulus of 73GPa, less than half that of mild steels (200GPa) (Hibbler, 2005). Taking this into account, the embodied energy of aluminium components becomes significantly larger as more aluminium is required than steel under equivalent load. The trade-off between weight and environmental impact is negligible as the system is not required to move regularly. In comparisons between fiber glass and plastics, a plastic will be chosen for similar reasons. These material choices reduce the embodied energy total from 7180MJ to the current value, a reduction by 37%.

For the resistance sub-system, using an aluminium plate and rubber stop is an industry standard. A fan based resistance system consisting of a polyvinylchloride fan, may be an economically viable alternative. This system would have embodied energy of approximately 100MJ, a 20% reduction in embodied energy for this component. Furthermore, a fan based mechanism may be favourable by improve the comfort of the user, as they provide gradual changes in resistance with pedalling speed.

To cater for the client, the seat material requirements are large, contributing 57% of the system's embodied energy. It is therefore recommended that the design integrate into the client's existing bariatric chair, removing the need for this (likely extraneous) component. This may also improve comfort outcomes, as rigid rubber may be a poor choice. Commercially available "mini cycles" may fill this need as seen in Figure 4 (Target, 2014). An alternative is to ensure the chair is reused, as indicated in the end of life analysis.

Figure 4 Example of a "mini cycle" showing capacity for use with an existing chair in a recumbent position, and for use in both upper and lower body exercise (Target, 2014)

End-of-Life analysis shows that approximately half the system's mass is committed to reuse, and the other half to recycling. These calculations do not take into account the fact that only a certain percentage of a given material mass may be recycled. More detailed analyses would address this factor.

An issue to be considered is whether or not standard sized pieces are used. Use of standard pieces will reduce environmental and economic manufacturing and assembly costs. Some materials, such as polyvinylchloride in the case of the pedals, were chosen in order to use industry standard pieces.

An extension of this application would be to determine the price of each material per kilogram in order to determine the overall materials cost of the device. Comparisons of materials based on density, colour, comfort (hardness) and other factors could be explored in more detail. Such analysis would go beyond the aims and techniques discussed in this paper. Particularly cost analysis requires a consideration of manufacturing costs, timelines and locations. Another extension would be to determine the maximum lifespan of given components in order to determine the lifespan-cost and lifespan-embodied energy trade-offs.

Key outcomes

This Life Cycle Inventory has established the environmental impacts of a stationary recumbent bicycle and has informed design choices. The current design has a total Embodied Energy equal to 4518MJ, total carbon output of 230kg and the total weight of the device will be 63kg. The current design will be almost 50% reusable and 50% recyclable given idealisations, with few components being discarded due to wear. Steel and plastic are recommended in favour of aluminium, carbon fiber and fiberglass components. It is recommended that a “mini cycle” design is integrated with an existing bariatric chair, to remove the chair subsystem entirely from the design. A fan-based resistance mechanism should be investigated. Materials choices will reduce energy requirements by 37% and the proposed design changes may reduce the embodied energy of the chosen design by 57%, while improving customer comfort.

8.0 Optimization and Reliability

The optimization and reliability theory applied here looks at identifying the most important reliability components of the recumbent bicycle design. The first section looks at identifying these critical components by employing pareto and bathtub curve concepts and looking at the warranty information offered by other manufacturers on existing recumbent bikes. Suggestions for modifications to the existing design based on the research performed here and in previous sections are then presented.

8.1 Critical components- Pareto Analysis

Most manufacturers of recumbent bicycle machines offer a product warranty that varies in length depending on the part that has failed. The warranties offered by several companies on their recumbent bikes, as well as maximum user weight ratings, resistance mechanism and cost of the bike, were analysed. The products represented a wide range of the cost spectrum available. Bestfitnessadvisor.com was used to source the warranty and max weight information, and amazon.com was used to source the costs. This is tabulated in ANNEX D.

While the frame warranties offered for all of the bikes analysed are high, the max user weight rating is substantially lower than that of our client. This means that the frame of our design is likely to impact heavily upon reliability. All of the bikes mentioned in Table 1 have magnetic resistance mechanisms, which eliminate the wear and tear common to direct-contact braking resistance systems *(Ashley, 2014)*. The direct-contact resistance system will thus also impact heavily on reliability.

If we assume the failures within our recumbent bike design to follow a bathtub curve shape, then the burn-in region will be small due to the lack of electrical components, and the wear-out region will be large due to the large dependence on mechanical components and the frictional nature of the device (Makhnin, 2013). This implies that components such as the rubber stop and flywheel, which are in constant contact, and the frame of the bike that will support large stresses, are going to impact strongly upon reliability.

It is thus concluded from the warranty information above, as well as the considerations for our specific bike design and constraints, that the two most important aspects for reliability will be the frame and resistance systems.

Discussion

The identification of the design's critical components have relied upon the following assumptions. The hazard function of our system (where failures are likely to occur) may not follow a strict bathtub curve pattern, and thus by focusing on mechanical wear out failures some of the critical factors for reliability may be missed. Due to a lack of resources/information detailing the common causes of failure in current recumbent bicycles, a strict Pareto analysis as detailed in the course theory was not applied. Instead we looked at the warranty information for the components of many existing recumbent bikes and assumed a correlation between these warranties and the reliability of the bike component. These warranties may not accurately reflect the reliability of each component for various reasons, including company policies, ambiguity in component definition etc.

By performing a design of experiments on existing recumbent bicycles, or a prototype of our design, a more accurate measure of the critical components could be obtained. Due to the nature of testing failures over a products lifetime however, such a design of experiments is not feasible under the scope of this report.

In the materials analysis section it has been recommended that an external 'mini-cycle' system be used as an external resistance mechanism to reduce cost and total embodied energy. Using such a system could provide many benefits from the perspective of the reliability research performed here. It would eliminate the need for a connecting frame between the recumbent chair and resistance mechanism and would allow more money to be invested into the mini cycle system, further improving reliability. To obtain an estimate of the improvement to reliability, Meant Time Between Failure (MTBF) calculations could be carried out for the two different designs, with respect to the frame and resistance components. If we make the assumptions stated in (NASA, 2008), then the MTBF is equal to the arithmetic average of the lifetimes of the considered components. The MTBF is derived as seen in ANNEX D. Due to the quality of the resistance mechanism increasing when replaced with an external mini-cycle, and failures within the frame being completely removed, we would see an increase in the MTBF for the new design..

Key outcomes

The optimization and reliability section of this paper has allowed identification of the most important aspects of the recumbent bicycle design with respect to reliability; the frame components and the resistance mechanism. A design change proposed in the materials analysis section recommending the use of an external mini-cycle system has been evaluated from a reliability perspective. It has shown to provide many benefits by removing the need for the frame components and allowing more money to be spent upon using a more reliable resistance mechanism; the mini-cycle. The new design has also been theorized to provide life-cycle costing benefits by reducing acquisition, maintenance and supply support costs.

9.0 Cost Analysis

With all possible solutions to our problem identified, cost analysis determines which is the most viable from a financial standpoint.

Because of the client's large physical stature, the choice of machines that will function adequately is somewhat restricted, which is challenging from a financial perspective. As identified in an optimisation analysis, the critical areas of design reliability are the frame's ability to support a larger load and the deterioration of mechanical resistance mechanisms over time. From research, the weight that most stationary recumbent exercise machines (for home use) can support has an upper limit of around 180kg. The materials analysis found that the machine's frame contained the most embodied energy out of all the components and should therefore be made from steel to keep this to a minimum. This is not only beneficial from an energy perspective however; steel can support much higher levels of stress than other available materials such as aluminium, addressing the conclusions of the optimisation and reliability analysis.

Three systems are considered being; purchase of a commercial system capable of supporting at least 210kg: Monark Cardio Comfort 837E (habdirect.com.au), membership to a gym with: Club Lime Canberra city and purchase of a "mini cycle" machine + bariatric chair: Bodyworx ADPE Duo Bike, Doability 300kg bariatric chair. (southsidefitness.com.au, doability.com.au)

9.1 Life-Cycle Analysis

In regard to the assumptions, there is a distinct lack of information about the maintenance costs for stationary exercise machines. It will be assumed then, that preventative maintenance or repairs for the Monark 837E would need to be conducted twice during the life cycle, at a cost of $200.00 per instance.

Factors such as warranty and the capital of a bariatric chair are considered in this life cycle costing.It is assumed that the travel costs associated with a gym membership would be a return bus trip, 3 days a week (Action Buses). Stay at home options were assumed to require an initial training cost that consists of two, 1-

hour personal training sessions (Body to Burn, Canberra). For end of life, there are no available prices for any of the options in used condition, so a worst-case of disposal to a metal recycling company is assumed. (Ezy Scrap)

Table 2 Life Cycle Costing for a recumbent bicycle

Option	Bike	Mini	Gym
Initial cost	$3,959.00	$959.65	$717.00
Shipping/transport	$100.00	$68.93	$8.52/week
Training	$169.00	$169.00	-
Maintenance	$400.00	$172.28	-
Membership	-	-	$717.00/year
Disposal	$22.00	$22.00	$0.00
Total	**$4,650.00**	**$1,391.86**	**$5,800.20**

9.2 Pay-Back Period

With all the monetary inputs of each option identified, the total cost can be plotted against time. If the cost timelines of the available options are compared on a graph, it can be determined which will cost the least over the desired life cycle.

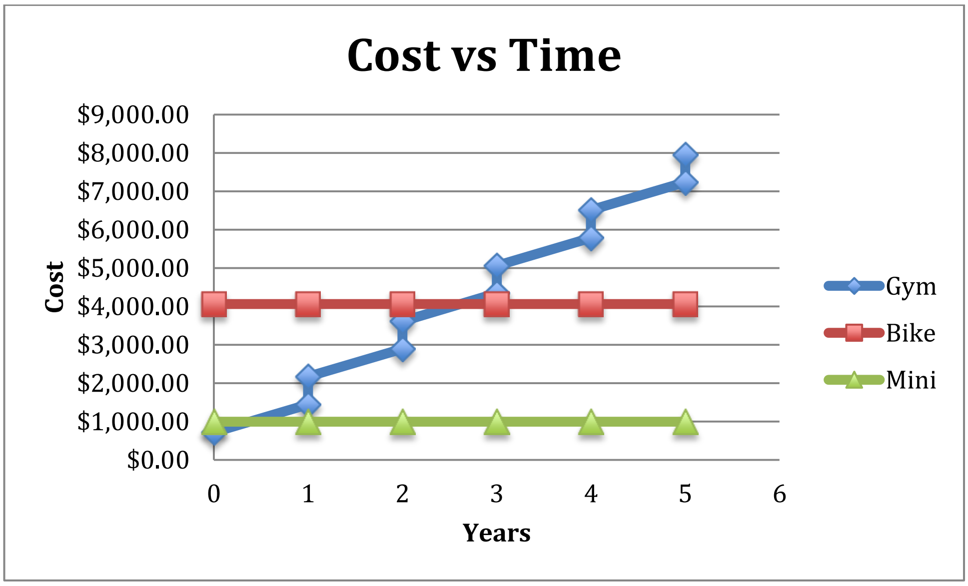

Figure 5: Payback period analysis for viable solutions

Key Outcomes

From the analyses already conducted it was determined that the range of possible solutions comes from existing solutions. Although a custom-made machine with the addition of an entertainment monitor is a possibility, the development and manufacture time of such a solution would be considerable, as would the embodied energy due to non-standard parts. These culminate in a solution that would not be viable, financially or otherwise. Membership with a commercial gym was not a desired option was for client, but was included as a benchmark for comparison as it is a common solution under less restricted conditions.

The Monark 837E is a machine is a commercial rehabilitation system with a large, steel frame and a load capacity large enough to support the client. This addresses the embodied energy and frame reliability concerns, however the resistance mechanism is the belt-friction type, leaving the possibility of deterioration in the machine's life cycle. Of the compared options, the Monark had the largest initial cost but had a payback period of around 2.5 years over the gym membership benchmark.

The Bodyworx Duo consists of a stand-alone pedalling system. It addresses the frame reliability concerns by removing it from the system and using an existing bariatric chair instead, and features a magnetic resistance system, identified as the most reliable in the optimisation analysis. The overall reduction in size results in a significantly lower embodied energy and cost. The Bodyworx Duo would take less than a year to be paid back compared to a gym membership.

Based on these results, and the conclusions of the reliability and materials analyses, it is determined that a stand alone "mini cycle", used in conjunction with an existing bariatric chair, is the best solution for the client.

Conclusions

The systems engineering analysis of an affordable exercise solution for a bariatric client has resulted in a recumbent exercise bike design with two main components: a bariatric chair and a mini cycle. Through consideration of quantitative and qualitative analysis, the client's health conditions and human factors such as 22anthropometry, ergonomics and comfort, it was decided that a stationary recumbent bicycle was the most suitable exercise type. Cost, materials and optimisation and reliability analysis all agreed that a "mini cycle" was the best recumbent bicycle design option as it was the most economical option making use of an already available solution. The manufacturing time and the embodied energy of the design are reduced greatly and the reliability is increased as one of the most critical aspect of the design, the frame, has been removed completely. Energy analysis also looked at the addition of a human-powered TV monitor to increase the enjoyment whilst using the bicycle but this idea was not affordable or efficient. The integration of Systems Engineering Analysis techniques has resulted in a well-developed design for the Affordable Exercise project client.

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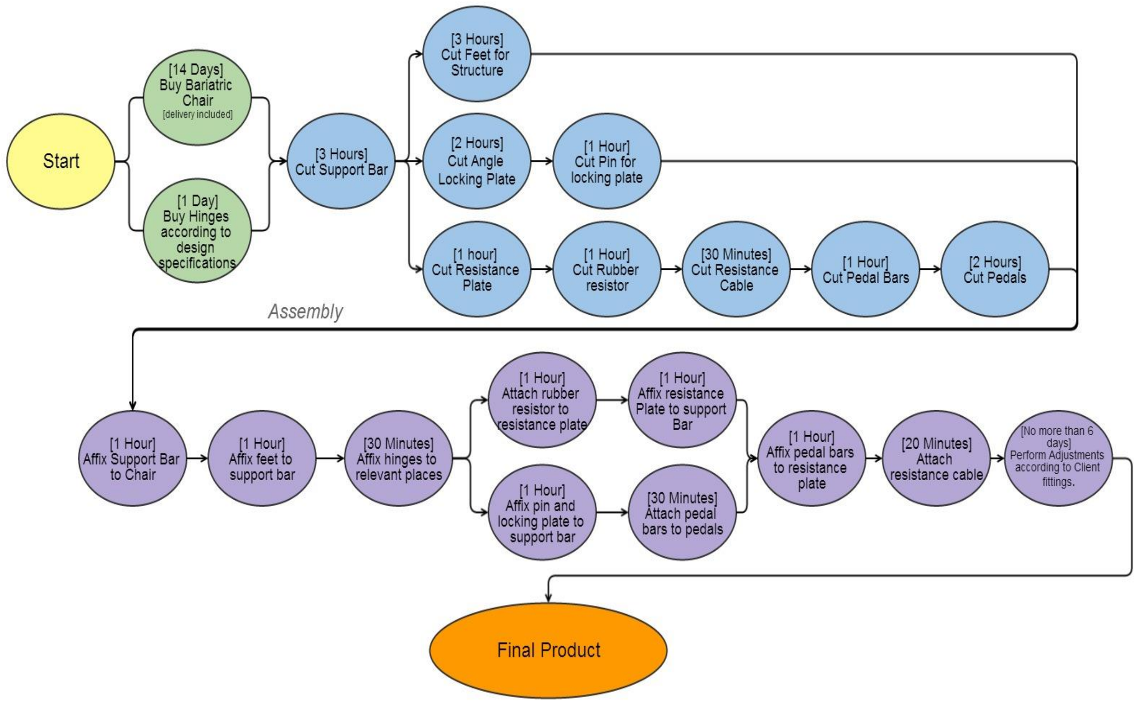
Appendices

ANNEX A – Gantt and PERT Charts

Activity/Day	1	11	12	13	14	15	16	17	18	19	20	21	22
Purchase Chair (10-14 day delivery)													
Purchase Hinges													
Cut frame components													
-Support Bar													
-Feet for structure													
-Angle locking plate (for pin)													
-Pin for locking angle adjustments													
-Resistance Plate													
-Resistance cable													
-Resistance-Rubber Stop													
-Pedal bars													
-Pedals													
Fit frame components													
-Support Bar to chair													
-feet to support bar													
-Affix Hinges to relevant places on support bar													
-Affix pin and locking plate to support bar													
-Assemble Resistance-rubber stop and resistance plate													
-Affix Resistance plate to support bar													
-Attach pedal bars to pedals													
-Affix pedal bars to resistance plate													
-Attach resistance cable													
Adjustment													
-Put Client on bike and note necessary adjustments													
-Adjust as needed													
-Refit and repeat if necessary													

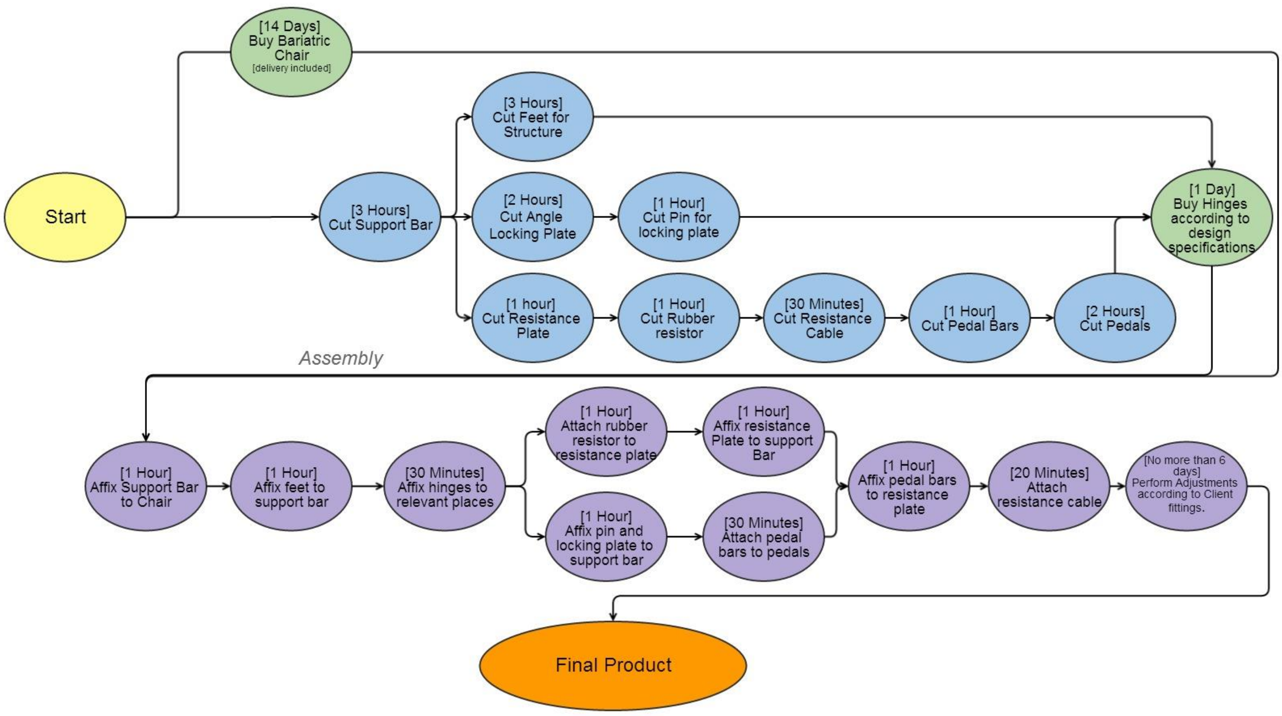
	= Possible Timing
	= Predicted Time for individual task
	= Predicted Time for Series of Tasks

Above; Gantt chart for manufacturing of initial recumbent bike solutions

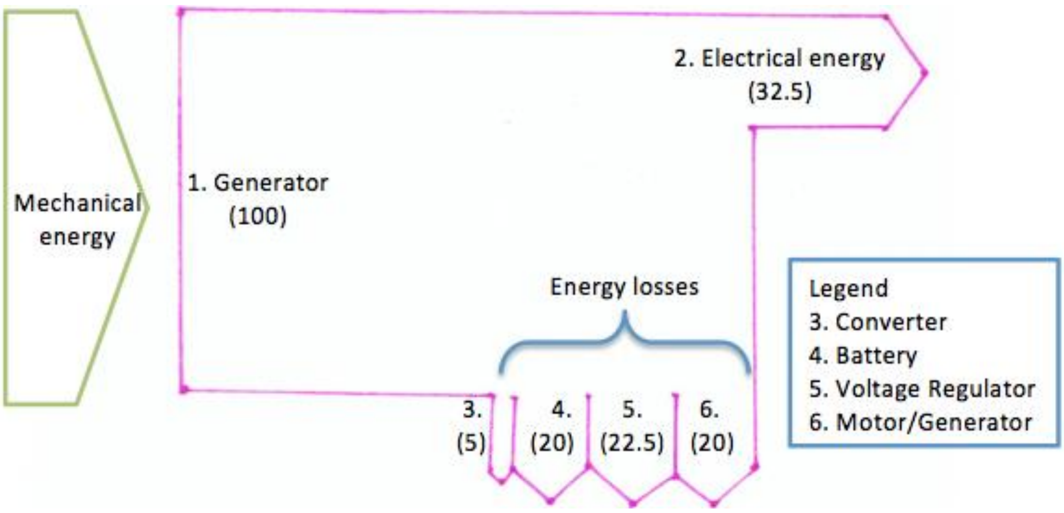


Above; PERT chart before critical path method implemented.

Below; PERT chart After Critical Path method implemented.



ANNEX B- Affordable Exercise Sankey Diagram.



Sankey diagram of highest energy loss in pedal powered generator (De Decker, 2011)

ANNEX C- Affordable Exercise Materials Audit

Complete Materials Audit Table

Component	Material Options	Quantity (m^3)	Density (kg/m^3)	Estimated Total Mass (kg)	Specific Embodied Energy (MJ/kg)	Embodied Energy (MJ)	Specific Carbon Output (kg CO2/ kg)	Carbon output (kgCO2)	End of life Destination
Structure Feet	Stainless Steel	5.00E-04	7850	3.93	56.7	222.5475	6.145	24.119125	Recycled
	Aluminium	5.00E-04	2700	1.35	155	209.25	8.2561	11.145735	Recycled
	Carbon fiber	5.00E-04	1600	0.80	315	252	1.2	0.96	Recycled
Support Bar	Stainless Steel	2.00E-03	7850	15.70	56.7	890.19	6.145	96.4765	Recycled
	Aluminium	2.00E-03	2700	5.40	155	837	8.2561	44.58294	Recycled
	Carbon fiber	2.00E-03	1600	3.20	315	1008	1.2	3.84	Recycled
Angle locking plate (for pin)	Stainless Steel	3.00E-04	7850	2.36	56.7	133.5285	6.145	14.471475	Recycled
Pin for locking angle adjustments	Stainless Steel	3.00E-05	7850	0.24	56.7	13.35285	6.145	1.4471475	Recycled
Resistance Plate	Aluminium Rolled	3.00E-04	2700	0.81	155	125.55	8.2561	6.687441	Recycled

Resistance cable	Steel Galvanised	2.00E-04	7800	1.56	22.6	35.256	1.45	2.262	Recycled
Resistance-Rubber Stop	Rigid Rubber	1.00E-05	1200	0.01	91	1.092	2.66	0.03192	Landfill
Pedal Cranks	Stainless Steel	1.40E-04	7850	1.10	56.7	62.3133	6.145	6.753355	Recycled
	Carbon Fiber	1.40E-04	1600	0.22	315	70.56	1.2	0.2688	Recycled
	Aluminium	1.40E-04	2700	0.38	155	58.59	8.2561	3.1208058	Recycled
Pedals	Poly Vinyl Chloride	1.00E-04	1380	0.14	77.2	10.6536	2.61	0.36018	Reused
Chair	High Density Polyethylene	2.00E-02	970	19.40	76.7	1487.98	1.57	30.458	Reused
	Fiber Glass	2.00E-02	1500	30.00	100	3000	8.1	243	Reused
Chair Padding/ surface	Rigid Rubber	1.00E-02	1200	12.00	91	1092	2.66	31.92	Reused
Plate Housing	Poly Vinyl Chloride	4.00E-03	1380	5.52	77.2	426.144	2.61	14.4072	Recycled
	Fiber Glass	4.00E-03	1500	6.00	100	600	8.1	48.6	Recycled
Bearings	Bronze	3.00E-05	8500	0.26	69	17.595	3.73	0.95115	Recycled

ANNEX D

Warranty, cost and max user weight information for various recumbent bikes.

	Livestrong LS6.0R	Xterra SB4.5R	Nautilus R514c Recumbent	Phoenix 99608 Recumbent	Stamina 1350 Recumbent
Frame Warranty (yrs)	10	Lifetime	10	1	1
Parts Warranty (yrs)	1	3	2	90	90
Electronics Warranty (yrs)	1	Incl. in parts	1	-	-
Max User Weight (kg)	136	136	136	113	113
RRP Cost ($)	999	899	699	219.99	250
Res Mechanism	Magnetic	Magnetic	Magnetic	Magnetic	Magnetic

MTBF Derivation:

The formula is quite simple to derive. It is merely the average of the lifetimes of two components, ie MTBF = (LifetimeA + LifetimeB)/2.

The lifetimes, with respect to monetary investment, are then assumed to follow a logistic curve, where lifetime increases exponentially with investment up to a certain point, before becoming logarithmic as diminishing returns become a factor. The logistic curve for a single variable is $\frac{M}{1+\frac{M-P}{P}*e^{-ka}}$ (Weisstein, 2014) and we thus plug this expression in for the LifetimeA and LifetimeB variables to obtain the final expression, ie:

$$MTBF(a,b) = \left[\frac{M}{1+\frac{M-P}{P}*e^{-ka}} + \frac{N}{1+\frac{N-Q}{Q}*e^{-vb}}\right]/2$$

The value of P is taken as 0.1 to allow us to use the model. This is termed the starting value as logistic curves are often used to model population growth.