ECO-FRIENDLY TRAINER

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Name of Degree Programme Abstract

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The thesis presents a final project for the Mechanical engineering degree consisting of 15 ECTS. The topic of this thesis is an eco-friendly trainer, it consists of the following aspects, which have to be reviewed and solved to some extent: introduction, literature survey, energy generation technologies, material selection, strength calculations, manufacturing methods and conclusion. The idea is to reform an existing gym machine to become more eco-friendly. The machine will be chosen by a target group of people through a survey. Other selection criteria are functionality and energy efficiency. The chosen machine will be analyzed, and a modern energy generator will be introduced into a trainer. Further, the material selection will be done, fulfilling all necessary requirements, such as safety, functionality, recyclability, etc. As much as possible engineering tools are planned to be used during the execution, such as formulas, 3D and stress analysis tools, comparison programs, etc. The readiness to obtain a new knowledge of engineering solution and innovative thinking approach is going to be used if required. After an execution and project’s hand-in, a brief, but clear view of the product shall be presented on the presentation.

Keywords Eco-friendly; leg press; environment; trainer; carbon footprint.
Pages 44 pages and appendices 18 pages

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Appendices

Glossary

3D – three-dimensional

CO2 – carbon dioxide

EU – European Union

USD – United States Dollar

USA – the United States of America

kWh – kilowatts per hour

MWh – megawatts per hour

HVAC – heating, ventilation and air conditioning

K – Kelvin

T – Tesla

η – energy conversion efficiency

Ω – Ohm

W – watts

Ws – watts per second

kWs – kilowatts per second

Wh – watts per hour

GPa – gigapascals

V – volts

A – ampers

kg – kilograms

EAF – electric arc furnace

BF or BOF – burst furnace

FRP – fiber reinforced polymers

PAN – polyacrylonitrile

CF – carbon footprint

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1 Introduction

Over the past century, the population of the Earth has been rapidly growing. The current population of our planet exceeds 7 billion people, the value, which has doubled over the past 50 years (Wikipedia, 2019). Along with the growth of the population, industrialization expanded as well; people merely needed more resources to satisfy their demands (JAMA Revisited,1970). However, due to the non-sustainable methods of production, a significant impact has been made on the environment and climate. According to the United Nations, if humanity could not do the changes in the ways they live and produce essential goods, by 2030 the climate changes caused by anthropogenic activities would become irreversible (United Nations, 2021).

In order to tackle the issue of the changing climate caused by people, the rate of impact must be quantified. The commonly agreed notion for that became «Green House Gases», the main element of which is CO2 – carbon dioxide (Puorakbari-Kasmaei et al, 2019). The global community has agreed to apply national and international measures aimed at dropping the amount of CO2 emissions in their respective countries. Such measures could be carbon taxation and carbon caps. Those policies aim to achieve carbon neutrality, though different countries set different deadlines for that. The European Union, for instance, made a bold goal to become carbon neutral by 2050 (European Commission, 2021). Still, even within the EU, progress is different state by state, though in total in a positive dynamic; the initial goal of dropping carbon emissions by 40 percent by 2030 has been changed to 55 percent for the same year deadline (BBC, 2020).

As it was mentioned, the progress on achieving carbon neutrality is not equal in the world, and even within the European Union. A closer look can be made at specific EU states. Finland and Denmark are such states, that can require special attention. Both countries, besides being EU member states, are also members of the Nordic Council, which has been applying one of the strongest actions to fight climate change in the world. Nordic Council countries have been applying joint and national measures: integrated electricity market, decarbonization of the transport sector, development of bioeconomy, reliance on sustainable and renewable means of electricity generation (Nordic Energy Research, 2019; Nordic Council of Ministers, 2017). Finland aims to become carbon neutral in 2035, 15 years faster than the EU plan (International Institute for Sustainable Development, 2020). Even though Denmark plans to reach neutrality by the same common deadline, it is rushing ahead to reduce 70 percent of its emission in 10 years (Danish Ministry of Climate, Energy and Utilities, 2020).

Various industries produce carbon emissions. However, electricity production and consumption are considered to be the main cause of pollution and climate change (Puorakbari-Kasmaei et al, 2019). Therefore, achieving carbon neutrality is an endeavour of every person, so that each of us needs to change our lifestyles and become more sustainable in our daily activities. Our life includes a number of aspects, one of which is health and well-being. This particular part of our life has been gaining momentum of popularity: more people have become concerned about their well-being and more well-being businesses, like gyms, are increasing profits (Smiljanic, 2021; Euromonitor, 2017). Between 2013 and 2017 the compound growth of gyms in Europe exceeded four percent annually (MarketLine, 2017). Gym businesses in Finland and Denmark have been excelling as well: companies like Fitness 24Seven and SATS concern, to whom Elixia chain of gyms belong, have been growing and expanding (Fitness 24Seven AB, 2021; ELIXIA,2021; SATS ASA, 2020). This growth is owed to the popularity of sports among the populace of Finland and Denmark, which is the highest in the whole Europe (Eurostat, 2020).

Gyms, like any facility or enterprise, consume energy to provide services to their customers (heating, facility illumination, etc.). Despite the fact, that the electricity consumption could vary gym by gym, due to their sizes, it is still possible to make simple estimations of the carbon footprint of such facilities. On average, gyms cost 65000 USD in electricity upkeep (Sage Group plc, 2021). The cost of one kWh in the USA is 0,106 USD (Hawkes, 2013). Therefore, annually, on average gyms consume 613 MWh. If the coal-based generation method of electricity is concerned (Figure 1), it can be concluded, that annually an average gym facility produces about 557000 tons of CO2.

Generation method	ADEME Carbon Inventory, low (1)	ADEME Carbon Inventory, high	PLC, Inc (2)	Oak Ridge National Labs (2)	Average
Coal	800	1,000	889	948	909
Natural gas	430	-	517	449	465
Oil/Diesel	-	-	894	748	821
Nuclear	6	-	-	-	6
Hydro-electric	4	-	-	-	4
Geo-thermal	-	-	-	-	-
Solar/PV	60	150	-	-	105
Wind	3	22	-	-	13
Wood/biomass	1,500	-	-	-	1,500

Figure 1. Grams carbon dioxide per kilowatt-hour by generation method (BlueSkyModel, 2021)

Due to the popularity growth of gyms in Finland and Denmark, and considering the assumed average carbon footprint of them, deduction regarding sustainability principles can be made. An adherence to sustainability principles in that business sector and reduction of electricity consumption by gyms could contribute to the common goal of the Finnish and Danish nations in achieving the carbon neutrality. There are various ways to apply sustainable approaches in the gym sector, one of which is a conversion of the human exercise energy into electricity for subsequent consumption by the facility. The industry already knows equipment solutions, that do such transformation, for instance, electricity-generating bicycles and treadmills. Nonetheless, it is crucial to explore new possible solutions of gym equipment, that can transform human exercise energy into electricity.

In this research, such new possibilities would be explored and studied, along with the existing market solutions. Different electricity generating solutions would be analyzed and modeled to determine the most efficient method. Along with materials carbon footprint assessment, an overall carbon reduction could be determined to assess the practical aspect of using electricity-generating equipment in a gym in terms of carbon reduction by such facilities.

2 Theory and literature survey

The use of sustainable measures in the gym business development is not an innovation. Many companies have already incorporated sustainable approaches in their businesses. Study what are those approaches to determine different practices and pinpoint the areas that are still not implemented is necessary for a current research.

Being an environmentally friendly business means actively choosing to take actions in the best interests of the environment. Furthermore, in the long-term strategy, not only the environmental care is presented in this business model, but also an effective way to save money and reduce fixed costs (Glofox, 2021).

After a thorough literature inspection ten ways of how to make a gym more ecofriendly can be brought out:

1. Pay attention to the recycling, waste sort

A simple understanding of waste in your own gym and granting a waste sorting possibility will help to properly use different categories of waste respectively. Likewise, customers of the gym will subconsciously pay more attention to waste sorting.

2. Eco-friendly gym's supply

Entrepreneur shall consider a use of the eco-friendly equipment before making a purchase solution. It is necessary to put thought into every detail of the gym supplies. For instance, using sustainably sourced yoga mats is a good idea. The material that is used for yoga mats can be various, but a lot of yoga teachers choose to fill out the studios with planet-friendly, non-toxic and biodegradable mats, that release less harmful dioxins into an environment.

3. Smart water use

Pipe isolation decreases the water heat loss; low-flow shower heads, toilets and faucets can help the gym to save up to 9.5 liters of water per minute; water filtering and greywater use are other ways to save drinking water.

4. Decrease plastic use

Nowadays it is hard to imagine our life without plastic, but on the other side, plastic garbage is one of the biggest wasting problems because of long-term decomposition. Taking this fact into consideration, the reduction of the plastics used in the gym and recycling the rest of the plastics, is important for the environment.

5. Efficient lightning and temperature control

Installation of the movement detectors, use of energy-efficient light-bulbs, and HVAC maintenance can help the gym to save up to 20 percent of the money, which is planned to be spent on energy.

A current aspect strongly depends on the gym's location. In the equatorial countries, the skylight can be used due to the 12 hours of sun time with the use of the real lighting tunnels instead of the artificial light. In the Nordic countries, this principle is efficient only in the summertime. The same situation with a temperature.

6. Paper use reduction, digitality

Nowadays, approximately 50 percent of the waste of the business fields is paper waste. At the same time, to produce one A4 piece five liters of water required. Offering the digital format of communication with customers through the application, for example, it is possible to reduce the noticeable amount of paper.

7. Energy-efficient technologies

Several companies have designed treadmills, bicycles, and elliptical trainers with energy-generation technology. The main idea of the devices is to produce a certain amount of energy and alternatively use it for the lighting and other gym demands to reduce the use of the non-ecofriendly energy, gained from the coal and fuel plants.

8. Use local area food sources to reduce the travel time and contamination

Opting for organic and sustainable products creates a possibility of investment in green business in your area and, in addition, reduces travelers' road time. If the distance between the farm, the sorting center is large, the risk of product contamination is high.

9. Build a sustainable network of companies in order to make a sustainability-care society

In an attempt to make an eco-friendly gym it is necessary to cooperate with companies with the same company policy and values. Companies, which make no effort ecology-wise, can have a serious impact on the reputation of your eco-friendly business concept. The world knows companies, who are producing their goods from recycled materials, such as plastic bottles and wetsuits.

10. Alternative energy generation and supply

The last, but not the least important way to make a gym more eco-friendly, which was mentioned partially, but not to the full extent, is alternative energy sources use. The use of solar panels, wind, and water generators can noticeably reduce the amount of needed electricity or even make a field totally independent from the electrical city-grid.

Summing up all the factors, two main principles can be concluded. Eco-friendship strongly depends on the community: the more society pays attention to various ways of planet safe, the more options for the entrepreneur to create a sustainable field. Another influencing factor is location. As it was mentioned above, counties, which are located close to the equator, have a better location to build a gym business in terms of food providence, amount of light annually, temperature.

Out of all the ten approaches listed above, only two can be linked to the engineering solution: energy-efficient technology and alternative energy supply. Alternative energy usage means using such devices as solar panels, windmills, and water turbines to reduce the amount of burnt fuel and, respectively, carbon footprint. These devices are important for the world and curious of the research, although, the idea of the project does not have a link to such devices. Energy-efficient technology will be considered in the research, because it was mentioned in the project description.

2.1 SportsArt™

SportsArt company was founded in 1977. Nowadays, the main production facilities are located in China and Taiwan. Likewise, it is one of the largest single-brand manufacturers in the world and it sells its products in over 70 countries worldwide. SportsArt manufactures almost all the components and parts for its exercise equipment by itself, without resorting to outside help. And many of their technical solutions and innovative developments are protected by patents.

Concluding information from a company’s website (SportsArt, 2021), SportsArt has several production lines. The only one production line presented by the company has an energy generation ability, because only this product’s line includes an energy generator in the machines’ mechanisms. It is ECO-POWR™, which consists of treadmills, ellipticals, cross trainers, upright cycles, indoor cycles, and recumbent cycles. Thus, ECO-POWR™ includes only cardio trainers. According to a piece of information of the SportsArt ECO-POWR™ description video (Turn Your Gym Into A Clean Energy Power Plant, 2018), the set of 30 cardio trainers can produce up to 41 kW of electrical energy daily. More information about the SportsArt equipment can be found in Appendix A (page 1).

However, the company does not share information about the mechanism, which is designed to gain electricity. After several tries of contacting the company and calling to some phone numbers, nobody gave a technical operation of the trainers' operation. This can be explained by the company's privacy policy, the protection of its technologies.

2.2 The Green Microgym

The Green Microgym was started up by entrepreneur Adam Boesel in 2008 in Portland, the USA. While he was writing a business plan, he came up with an idea of people exercising and generating electricity at the same time. Firstly, he had a conversation with some companies, who had already designed «green» trainers, although, at that point, none of those companies were able to provide a clean, affordable way for a small gym to go «green». Adam started making his own prototypes and, after several tries, he and his team designed the first spin bike retrofit that is grid-tied by simply plugging "out" into a normal wall outlet.
As it listed on the Green Microgym webpage (The Story of The Green Microgym, n.d.), it uses about 85% less electricity and their carbon footprint is about one-tenth that of a traditionally run gym. A member of The Green Microgym saves about a quarter of a ton of carbon compared to if they belonged to a traditional gym.

Videos, captured by Adam Boesel, show, that the main equipment in his Microgym are SportsArt treadmills and bicycles. The screenshots from the videos with SportsArt equipment can be found in Appendix A (pages 2-3).

In 2013 Elliot Hawks conducted a research about the Green Microgym in order to inspect Adam Boesel's reports. The result of the research revealed that the reports were misleading. The calculated annual human power output is 1400 kWh, while Adam reported, that it saved 37000 kWh in 2009 (Elliot Hawks, 2013).

2.3 Survey

A detailed review of the literature and internet sources was done on the question of the existing green technologies, which can be applied in the gym. Existing technology analysis shows, that the main trainers, that contains «green» solutions are cardio trainers. But what are the customers' favorite machines in the gym? In order to obtain an answer to this question, a small survey was conducted.

The main target of the gym's equipment is a group of people, who uses various machines while training. In order to see what types of machines are the most useful for people during the process of exercising in the gym, conducting a survey among the target audience is necessary. Microsoft Excel will be used to perform the survey analysis and results. Questionary will be conducted using the Google forms.

The survey will consist of two questions:

1) How often do you attend gym?

This question is important in terms of the interviewee's answer weight. The more often a person attends the gym, the greater the weight of her/his answer. The reason for this decision is that active people from the survey's point of view have more interaction and experience with machines in the sports hall. Five different options can be chosen as an answer: a person visits a gym 3 or more times in a week, 1-2 times in a week, 1-2 times in 2 weeks, 1-2 times in a month or less often. Respectively, the weight of an answer is reflected in the following way: from 1 for the most active interviewees to 0 for inactive people.

2) What is your favourite type of exercises to do in the gym (select a machine for it)?

This question allows a person to choose a trainer, which he or she likes more than others while doing exercises. The interviewee can select multiple trainers. Trainers are divided into two groups: cardio trainers and strength trainers. The Russian Telegraph (The Russian Telegraph, 2019) source was studied, selected machines for the survey are the most abundant in the typical sports halls.

The analysis of the obtained result is done in the following way: selected option marks as 1 and non-selected option – as 0. This number multiplies with an attendance coefficient and puts into the Excel table.

2.3.1 Survey's result

The survey was created on the second week of the project execution. Within the four days, 25 people (mostly in the 18-25 age group) completed the questionnaire. The outcome of the survey was transferred to the Excel table, which can be found in Appendix B (page 4).

The first question's result of the survey shows, how the target respondents are relevant for the survey. In order to perform better results of the survey, interviewees have to be actively attending sports halls. A pie chart below shows, how the target audience is divided in terms of activity.

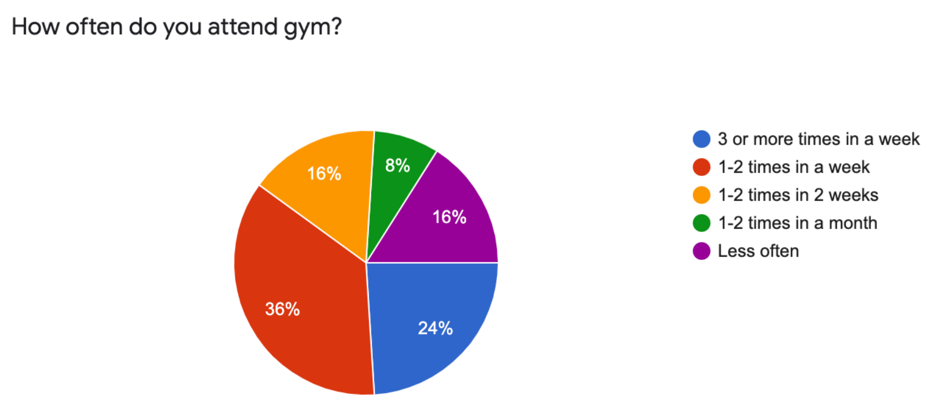


Figure 2. Gym attendance

A pie chart shows, that 60 percent of interviewed people are actively attending the gym and 16 percent moderately visiting sports halls. These facts mean, that questionnaire's audience is quite qualitative.

Further, the final results of the survey are performed in the next figure. Golden bar performs the first place machine, silver – the second and the third – bronze.

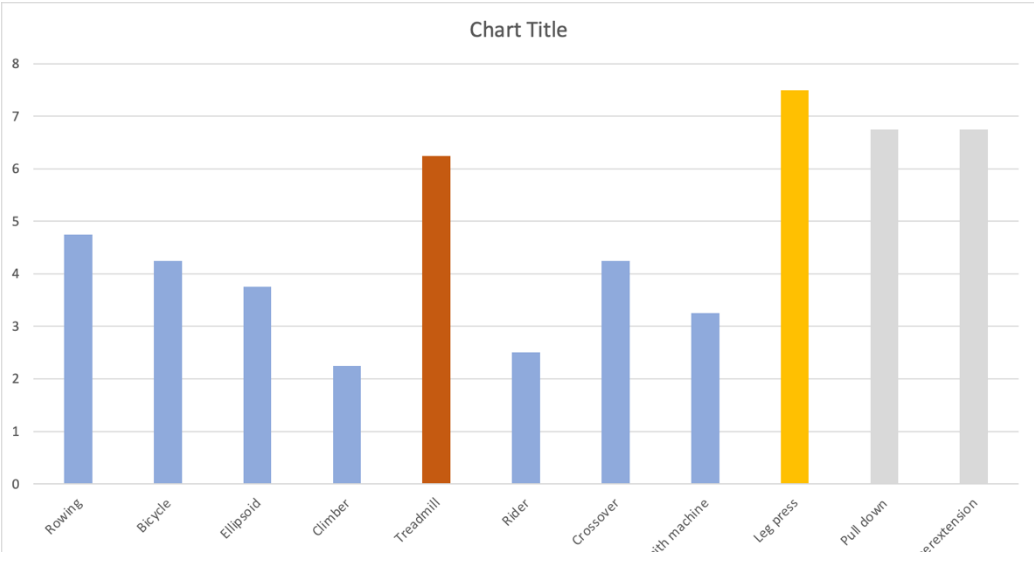


Figure 3. Survey results

As it is shown on Figure 3, the average popularity of the gym equipment on the strength trainers side, as they obtained more points among interviewees.

The survey tells that the favorite gym machine for interviewees is a leg press machine. Further research is going to be implemented around this machine.

3 Energy generation variety

The energy generation variety part consists of a brief review of the leg press - a machine, which was selected in the previous chapter by conducting a small survey. Further, potential ways of energy generators are presented, which were created, analyzed, and introduced to the trainer in order to reduce the carbon footprint of the gym. Finally, a comparison between an existing cardio treadmill and a designed generator is shown.

3.1 Leg press brief review

Leg press – a physical exercise, when a person has to press a certain weight up with his legs at 45 degrees angle. The schematic drawing of the exercise process is shown in Figure 4.

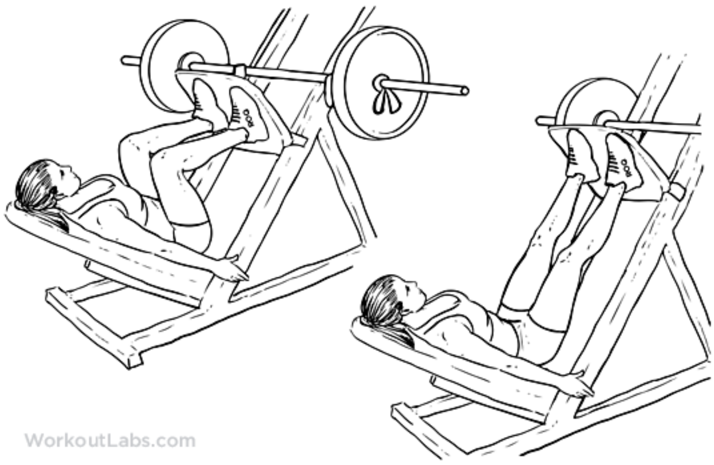


Figure 4. Leg press scheme

The machine for leg exercise is a triangular frame with an adjustable seat. The main moving block with adjustable weights is located on the inclined side of the frame. The angle, at which the main structure is located – 45 degrees. The main moving block traditionally has a bar from both sides of it, so applied weight can be regulated manually.

3.2 Design idea generation

The initial idea of the design idea generation part was to create the design of the energy generating technologies and calculate the amount of generated energy based on the mechanisms with principles of physics – electromagnetic induction. However, due to the lack of time and insufficient knowledge in the field, this part contains only one design, that was roughly calculated and other designs have only drawn designs of the mechanisms and description of the working principles. Deep dive into the electrical principles of the mechanisms seems to be a huge work, which can be considered in the separate research. Mainly, only components of the mechanisms with basic principles of operation are going to be described.

3.2.1 Flywheel with a constant resistance

Flywheel with a constant resistance – a simple electricity generator, which generates electric energy while the leg press is in operation. The actual design of the generator and integration of it in the trainers design is presented in Figure 5 and Figure 6 respectively. The design contains 2 electrical generators, but the actual calculations are going to be implemented around only one device.

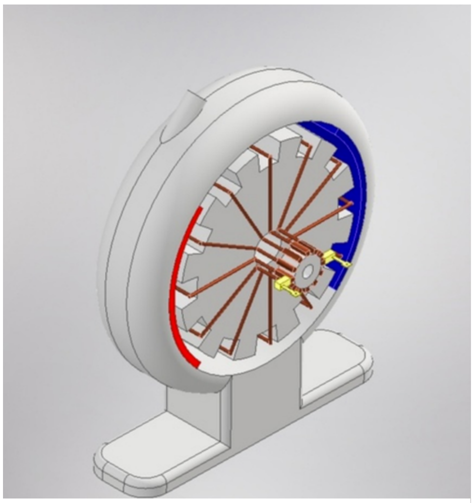


Figure 6. Energy generator design

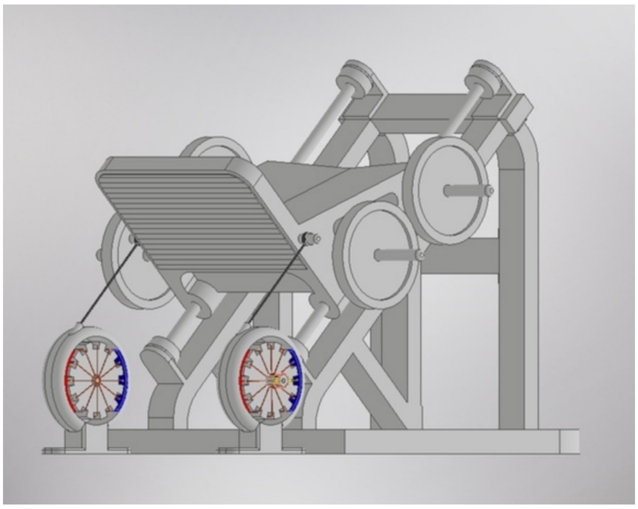


Figure 5. Generator integration into the trainer’s design

The principle of electrical energy generation is a rotational movement of the rotor in the mechanism, which rotates in the stator, and generates electricity. Rotor – a rotational part of the generator, which consists of the ferrite core, copper wiring, commutators, brushes, axle. Stator – a static part of the mechanism, which has constant magnets. Axle has a connection to the belt, which is attached to the main moving block of the trainer. While the block is moving upwards, the belt rotates an axle and, respectively, the whole rotor. According to the Faraday's law, the electromotive force around a closed path is equal to the negative of the time rate of change of the magnetic flux enclosed by the path. Thus, when the rotor rotates around the stator, the wiring gains a current flow.

While the wire frame makes a full turn in the magnetic field, the direction of the current changes, so the alternating current is generated. Figure 7 shows the occurred current in the frame in the time range.

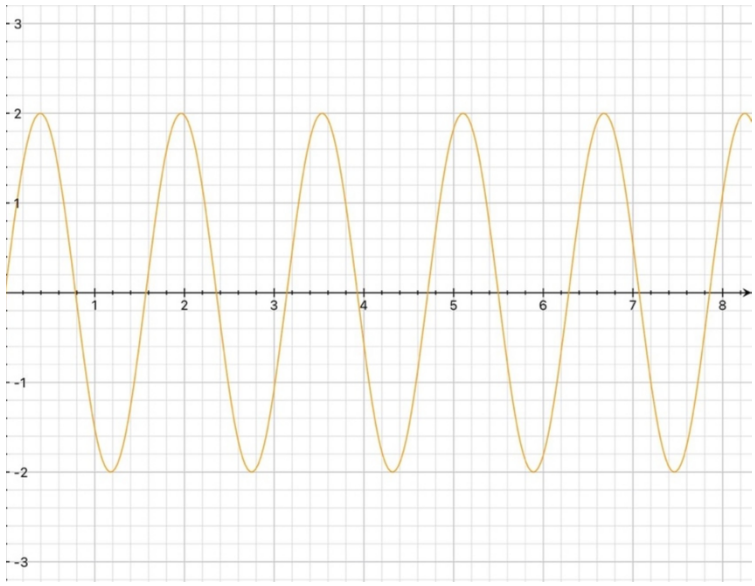


Figure 7. EMF/time graph in a one wire frame

The commutators do not allow the current to change the direction. If one fame has commutators, which are connected to the current receiving brushes, the current will not change the direction, although, the amplitude of the inductive current remains the same (Figure 8).

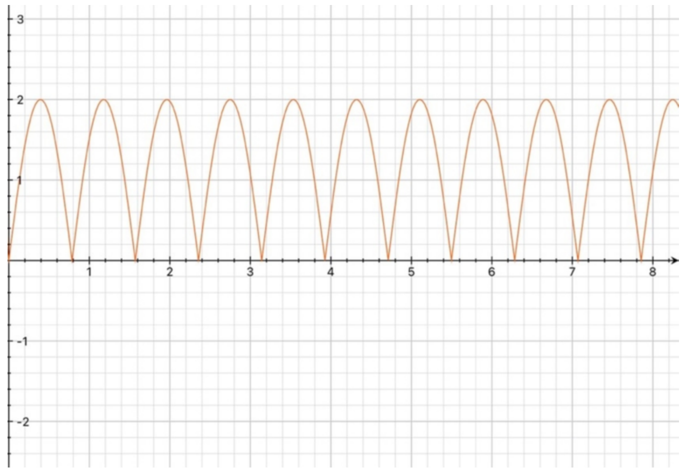


Figure 8. EMF/time graph in a one wire frame with 2 commutators

The big amount of frames and commutators leads to less current and electromotive force amplitude (Figure 9).

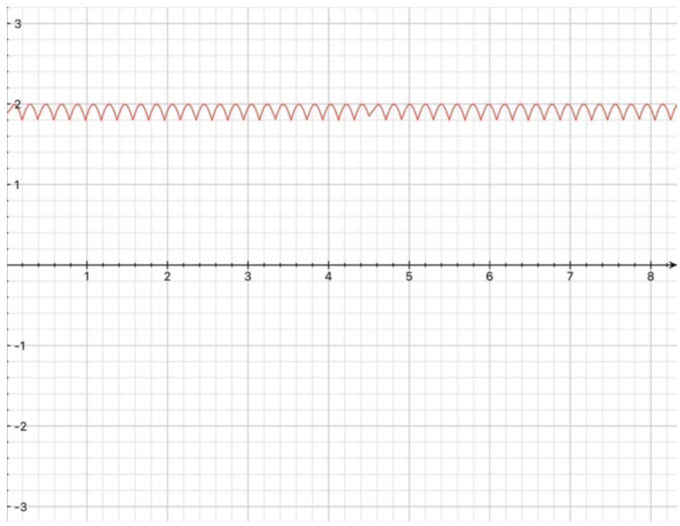


Figure 9. EMF/time graph in an electrical generator with a multiple frames and commutators

The amount of generated watts in the machine depends on the following indicators:

- The magnetic field magnitude
- The conductor's electrical resistivity
- The wire's cross-sectional area
- Number of turns of the inductor
- The area of the wire frame
- The speed of the rotor's rotation
- The core material

The whole operation process consists of 2 phase components (figure 10):

- Pushing the block upwards
- Returning to an initial position

Figure 10. Leg press operation steps

While the mechanism moves upwards, the acceleration and a constant speed occur, so the electromotive force in the circuit can be determined with the following formula:

$$\varepsilon_i = \eta \times N \times S \times B \times \omega$$

When the mechanism moves down, the rotor rotates in the same direction according to an impulse saving law and the occurring electromotive force can be calculated with the same formula, but the angular speed will decrease in time. Since the whole calculation based on the average speed, only the friction between the axle and generators frame decreases its speed.

Thus, the assumption that the electromotive force is 80 percent less when the block moves down:

$$\varepsilon_i = 0.8 \times \eta \times N \times S \times B \times \omega$$

Wire cross-sectional area was determined to be 3 square millimeters. A few sources were reviewed, the variety of wire cross section is huge. The decision to take a radius if the wire approximately 1 mm was done. The area, which was calculated, using a simple formula (shown below), is 3 square millimeters.

$$A = 3\ mm^2$$

The amount of turns of the wiring is calculated in the following way: the ferrite core has space for wire, which has to be calculated by reducing the area of the respective round sectors (shown in Figure 11). The calculation details can be found in Appendix C (page 5). Then the determined area for the wires is divided by the wire's cross-sectional area.

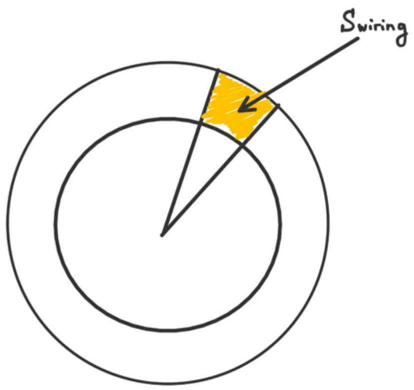


Figure 11. The area of the wiring in the rotor, one section

$$N = 202$$

In case of the wire's cross-sectional area increase, the number of turns decreases, because the area of the ferrite core for the wire remains.

The area of one frame is dependent on the energy generator dimensions. According to the designed model (in Appendix C (page 6) technical drawing of the rotor can be found) the average copper wiring area is:

$$S = 305\, mm \times\ 130\, mm = 39650\, mm^2$$

A magnetic field is determined to be 1,2 T. In order to obtain this value, several websites and shops were reviewed (The Magnets World, 2021; The Magnets Shop, 2021). The values vary from 0.6 to 1.8 T. The average number was decided to be taken into consideration.

$$B = 1.2\, T$$

Energy conversion efficiency is a ratio of the useful power of the generator to the whole power produced. The losses in the generator can occur in the friction of the axle with the frame, the drop of the electromotive force by the tiny angle between the frame and the magnetic field and other small factors. On average, electrical generators have an energy conversion efficiency coefficient of 0.9 (Wikipedia, 2020).

$$\eta = 0.9$$

It is crucial to calculate the exercising time range and the travel distance of the main moving block. Based on these variables, the average linear speed and an angular speed can be determined. The exercising time range was experimentally calculated in the gym. 3 first when a person was pushing the main moving block without the weight, then with a normal weight, and finally with a big weight. The results of the measurement are presented in the Excel table, which is attached in Appendix C (page 9). The results were obtained from the experiment are reflected below (t_1 – average travel time without load; t_2 - average travel time with a moderate load; t_3– average travel time with a big load):

$t_1 = 1.33\, s$ $\qquad$ $t_2 = 2.22\, s$ $\qquad$ $t_3 = 2.12\, s$

The travel distance of the moving block is equal to the humans' hip length, because in the lowest position the angle between the hip and shin is 90 degrees. The length of a person's hip, who conducted the experiment, was 46 centimeters, which is fortunately the same, as an average human's hip length (Appendix C page 7):

$$l_{hip} = 0.46\ m$$

Thus, the average speed can be calculated for each case by dividing the travel distance by the travel time (υ_0 – average speed without load; υ_1 - average speed with a moderate load; υ_1– average speed with a big load):

$$\upsilon_1 = 0.35\frac{m}{s} \qquad \upsilon_2 = 0.21\frac{m}{s} \qquad \upsilon_3 = 0.22\frac{m}{s}$$

The angular speed is determined by the division of the linear velocity by the wiring area central point radius:

$$\omega_1 = \frac{\upsilon_1}{R} = 2.258\ \frac{rad}{s} \qquad \omega_2 = \frac{\upsilon_2}{R} = 1.355\ \frac{rad}{s} \qquad \omega_3 = \frac{\upsilon_3}{R} = 1.419\ \frac{rad}{s}$$

Summing up all the variables, which are mentioned above, it is possible to determine an electromotive force of the generator:

$$\varepsilon_{i1} = 19.532\ V \qquad \varepsilon_{i2} = 11.719\ V \qquad \varepsilon_{i3} = 12.277\ V$$

A material for the wire was selected according to the material's electrical resistivity of the conductor and its affordability. The less the number of the electrical resistivity, the smaller the internal resistivity of the generator. The best electrical resistivity index is observed on silver and copper. While the price of the silver is 28 USD per unit, the copper price is 7 times lower (Stock Market Watch, 2021). The price is one of the indicators of carbon footprint. The carbon footprint value, which was indicated in the CES Edupack software, is 4 kg/kg for copper, while for silver is 26 times bigger (Appendix C page 8), so the choice was done for the copper material for the wire material. The electrical resistivity below is reflected, while the material is under 293 K temperature.

$$\rho = 1.68 \times 10^{-8}\ \Omega \times m$$

As it was mentioned earlier in the chapter, the cross-sectional area of the wire is:

$$A = 3\ mm^2$$

The whole length of the wire in the generator is determined in the following way: the length of one wire turn (in current design) is multiplied by the number of wire turns:

$$l = 870\ mm \qquad\qquad L = N \times l = 175.74\ m$$

The internal resistance of the generator on the generator can be determined with the following formula, which contains the wire's electrical resistivity, length of the wire and wire's cross-sectional area:

$$r = \frac{\rho \times L}{A} = 0.984\ \Omega$$

The inductive current is usually calculated with an electromotive force, which is divided by the sum of internal resistance and circuit resistance. Since the external resistance is involved only in plugging out wires, it can be neglected. Thus, the formula to calculate the inductive current for each case is:

$$I_{i1} = \frac{\varepsilon_{i1}}{r} = 19.847\ A \qquad I_{i2} = \frac{\varepsilon_{i2}}{r} = 11.908\ A \qquad I_{i3} = \frac{\varepsilon_{i3}}{r} = 12.475\ A$$

Finalizing all the steps, the generator's power can be calculated for each case – electromotive force is multiplied by the inductive current:

$$P_1 = \varepsilon_{i1} \times I_{i1} = 387.66\ W \quad P_2 = \varepsilon_{i2} \times I_{i2} = 139.557\ W \quad P_3 = \varepsilon_{i3} \times I_{i3} = 153.165\ W$$

Calculated cases were counted with a principle of the linear uniform motion, so the linear speeds of the moving block are considered as average and constant. Thus, the work of the generator in given periods of time can be obtained:

$$A_1 = P_1 \times t_1 = 0.516\ kWs \qquad A_2 = P_2 \times t_2 = 0.31\ kWs \qquad A_3 = P_3 \times t_3 = 0.325\ kWs$$

The whole calculation table was done using a Mathcad Prime 4.0, calculations can be found in Appendix C (pages 10-11).

The same calculation process is done for the downwards movement of the main block, while the flywheel continues to rotate in a previous direction.

Variables, which have changed, are the time of the execution and the emf value due to the friction. As a result, the following values for the power were obtained:

$$P_4 = \varepsilon_{i4} \times I_{i4} = 248.102\ W \qquad P_5 = \varepsilon_{i5} \times I_{i5} = 89.317\ W \qquad P_6 = \varepsilon_{i6} \times I_{i6} = 98.026\ W$$

Respectively, since the time of downwards movement is different, the work gained varies:

$$t_4 = 0.92\ s \qquad t_5 = 1.12\ s \qquad t_6 = 1.88\ s$$

$$A_4 = P_4 \times t_4 = 0.228\ kWs \qquad A_5 = P_5 \times t_5 = 0.1\ kWs \qquad A_6 = P_6 \times t_6 = 0.184\ kWs$$

Calculations are attached in Appendix C (pages 12-13).

The average power of the device can be taken into consideration for both cases (Appendix C page 15). Cases with weight plates have more weight in the calculation (without – 80%):

Average power estimation	Move upwards	Move downwards
First attempt, watts	387.66	248.102
Second attempt, watts	139.557	89.317
Third attempt, watts	153.165	98.026
Average, watts	200	130

Table 1. Average power estimation

The average time of repetition was calculated with exactly the same principle (Appendix C page 14):

Average time per repetition	Move upwards	Move downwards
First attempt, sec	1.33	0.92
Second attempt, sec	2.22	1.12
Third attempt, sec	2.12	1.88
Average, sec	1,80	1,25

Table 2. Average time per repetition

Assuming one attempt, where a person make 10 repetitions of the exercise, the amount of generated watts per hour is calculated:

$$A_{up} = P_{up} \times t_{up} = 200\ W \times\ 1{,}80\ s = 360\ Ws$$

$$A_{down} = P_{down} \times t_{down} = 130\ W \times\ 1{,}25\ s = 162{,}5\ Ws$$

$$A_{attempt} = (A_{up} + A_{down}) \times 10 = 5.225\ kWs$$

In order to achieve 1 kWh, it requires to do 689 attempts of 10 repetitions.

Returning to Adam Boesel's practical video (Appendix A, pages 4-5), using a treadmill, while he was walking with a 2 miles per hour speed for 46 seconds, jogging with a 5 miles per hour for 18 seconds and pushing a roller with a 3.5 miles per hour speed for 20 seconds, he obtained 1,27 Wh (4572 Ws) of electricity within 1 minute 24 seconds. Comparing it to the designed generation type of the generator, it makes 5225 Ws within 30.5 seconds, which is more, then a treadmill on a shorter time frame. It would generate 14390 Ws within 1 minute 24 seconds, which is more than 3 times more than a treadmill.

However, cardio trainers are presumed to be more energy-efficient, because the operation of these machines is a long-term operation and varies from 10 minutes to 2 hours of a constant operation. At the same time, strength trainers are in operation for at least 50 percent of a training time, because sportsmen take a rest while doing strength exercises. Likewise, sportsmen usually do 4-5 attempts on the trainer and then it can stay for a while without any movement.

3.2.2 Flywheel with a variable resistance

A flywheel with a variable resistance works with the same principle as the previously specified device. The main difference is the variable amount of force that has to be applied to the trainer in order to lift it. The current idea helps to exclude weight plates from the leg press's design and regulate the desired weight with flywheel's resistance. Likewise, the exclusion of weight plates and an additional geometry from the main block reduces the amount of production and, respectively, helps to reduce a carbon footprint. The design of the trainer with this type of generator is presented below (Figure 12).

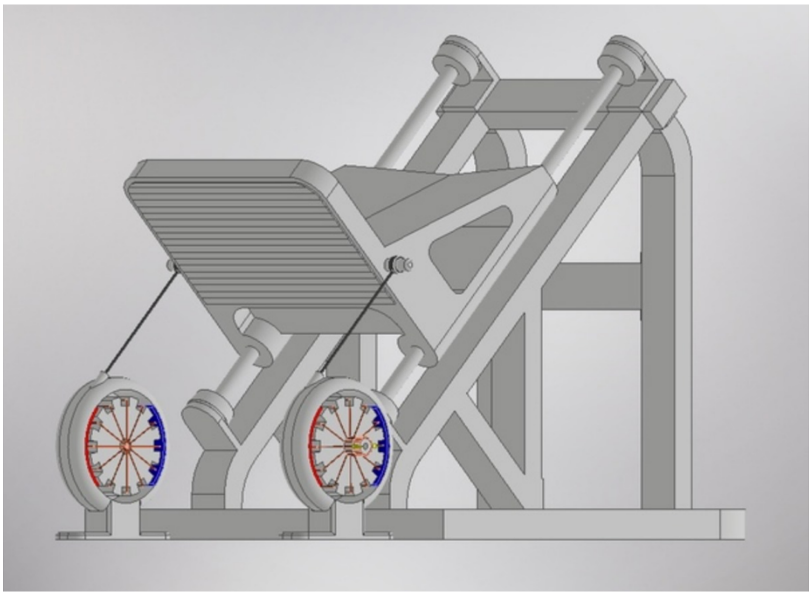


Figure 12. The second energy design (main block's geometry reduction)

The inspiration for the current design came from the SportsArt treadmill, which has 2 modes of operation:

- Run mode – when a treadmill uses electrical energy to operate itself and an applied force by a human generates instant watts to the grid.
- Push mode – when a person pushes a treadmill by himself only, without a treadmill's support.

In Adam Boesel's video, he walks and runs in a Run mode with a speed of 2 miles per hour and 5 miles per hour. Instant watt to grid values were 40 watts and 100 watts respectively. After turning on the Push mode on the device, he was pushing a machine having a speed of 3.5 miles per hour and generating 100 instant watts to the grid. The screenshot can be found in Appendix A (pages 2-3).

	Run mode (walk)	Run mode (run)	Push mode
Human's speed, miles per hour	2	5	3.5
Instant watt to grid, watts	40	100	100

Table 3. SportsArt treadmill values

As the table reflects, in a Push mode (without treadmill's support) human has to put more effort, but walk with a less speed to generate electricity. This case was an inspiring idea for the flywheel with a resistance variability.

On the other hand, the maximum possible electricity generation can be achieved in a Push mode with a treadmill, and in a Run mode, the amount of generated watts decreased because of the treadmill run support. Concluding, the increase of the resistance of the treadmill is limited by the operation mode of the treadmill.

One of the ways to increase the rotor's rotational speed is an introduction of a gearbox. The disadvantage of the design lays in the construction difficulty, adding another mechanism, consequently, the increase of a carbon footprint. Moreover, the main goal of the trainer's operation is to exercise. Considering the introduction of a classic gearbox into the operation, a trainee will have to switch the gear while pushing the weights. The gearbox's working principle shall be similar to a bicycle's type: the initially selected gear determines the resistance of the generator.

3.2.3 Copper frame and a constant magnet

A copper frame with a constant magnet movement can be considered a classic idea in the electromagnetic sphere of physics – its design contains a constant magnet and a copper wireframe. The detailed design is shown in Figure 13.

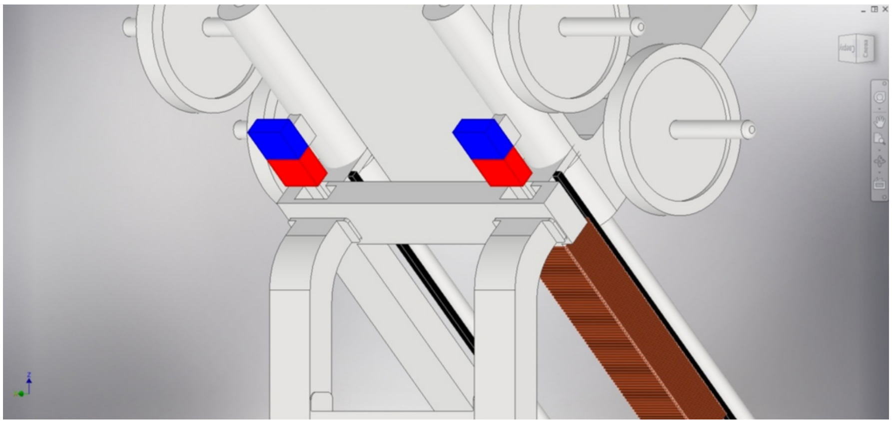


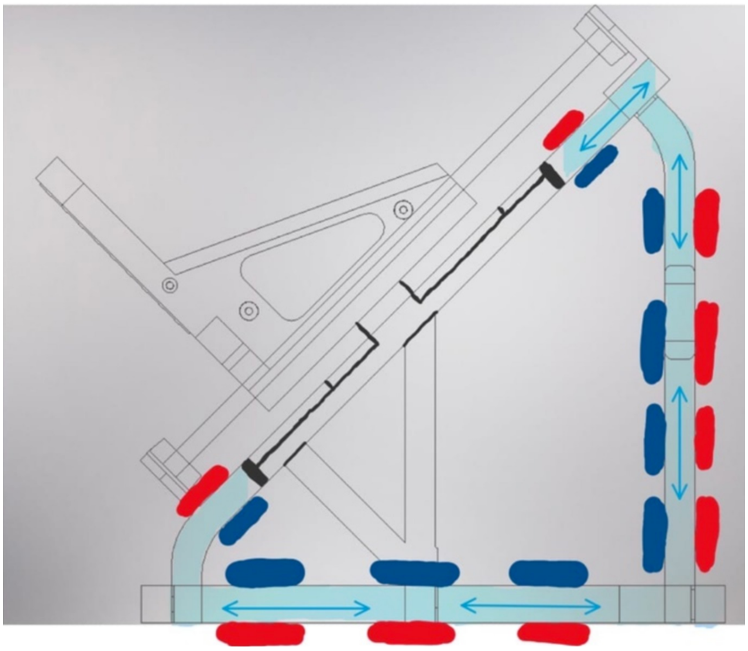
Figure 13. Energy generation using a magnet and copper frame design

As it can be seen on the figure 13, the frame has a cut geometry and the main moving block includes an attachment of a constant magnet. The magnet goes into the frame and, while the moving block is in up- and downwards movement, the inductive current occurs in frames. The copper wireframes have a form of a three-sided rectangle (non-close) and they are attached to the long commutators, which have the same length, as a bar, where the main moving block is based on. As a result, in the upward movement potential difference occurs between commutators, and the same result is obtained when the block moves downwards. Since the movement is reciprocating, the alternating current occurs in the frame.

3.2.4 Hydraulic frame with an MHD generator

A principle of the hydraulic frame with magnetohydrodynamic energy generation is described in the following sentences. The closed triangular frame of the leg press contains an electrolyte. The main moving block of the trainer has a connection to the piston. The piston moves up and down in the frame while the main moving block is in operation. It pushes the liquid in the frame and creates an electrolyte flow, which flows clockwise and counterclockwise in respect to the block movement. The whole frame is surrounded by constant magnets, which create the magnetic field. The electrolyte flows through the magnetic field and creates electricity. The schematic drawing of the design is shown in Figure 14.

Figure 14. MHD generation schematic design



A hydraulic frame of the leg press with a magnetohydrodynamic power generation principle was created after a trainers design implementation. Thus, the designed device is not sufficient for this idea, because it does not have a triangular closed frame.

The main parameters, which are considered in the current generation process, are:

- The electrolyte flow speed
- The cross-sectional area of the frame
- The magnetic field magnitude
- The chemical composition of the electrolyte

4 Material selection

The material selection chapter contains the review of the materials, that are going to be used for the trainer's manufacturing. The special software, which makes a material assessment structured, referred and accurate, CES Edupack, was used. Out of the database of materials in the program, elastomers and foams cannot be considered due to their low Young modulus value, ceramics – high brittleness probability, composites – relatively high carbon footprint and recycling impossibility. Therefore, metals, polymers and natural materials are planned to be researched.

The main parameters, which are going to be considered in the material choice, compared and analyzed, are:

- Price per kilogram – bring impact on the net cost of the manufactured details and final product, respectively, on the product's market price.
- Young modulus – the parameter, which is considered in strength calculations. It will play a key role in allowable displacement and materials buckling.
- Yield strength – the elastic limit for the selected materials, it is a crucial parameter, because an elastic deformation cannot be exceeded due to the product's initial form loss and a fail in its operation (displacement of the main bar can cause an impossibility of a trainer's operation).
- CO2 footprint, primary production – the crucial parameter due to the project's purpose – the carbon footprint assessment. The value consists of the amount of burnt fuel, the transportation, the production impact and maintenance.
- Recycle – another important aspect of a sustainability principle. The CES Edupack simply shows material's recyclability if it is applicable. In the current project, only materials with recyclability ability are going to be compared.

4.1 Metals

Metal is one of the primary materials in the big variety of manufacturing. One of the metals – steel, is a durable and strong material. It is able to save its properties' values even after many recycling processes. The recycling of steel has a positive impact on a carbon footprint reduction of the steel industry. Steel production accounts for 7-9% of world emissions. Extraction and purification of iron ore produce the most share of emissions. But different processes have different environmental impacts. The manufacturing of steel produces the most amount of emissions in steel's lifecycle. Electric arc furnaces (EAF) produce less emission than blast furnaces (BF or BOF), though they need an immense amount of electrical power input. There is a prediction that emissions linked to steel manufacturing would continuously reduce in the future. (Berki E, 2020).

4.2 Polymers

Polymers include thermoplastics and composites. In comparison to metals, plastics have a high carbon footprint, so the first priority material for the trainer is going to be a metal. Polymers have a great group of materials - fiber reinforce. Fiber-reinforced polymers (FRP) – strong, stiff, durable, light. Some FRPs can be stronger than mild steel. Carbon FRP is one of the strongest types. It is also resistant to moisture and other environmental attacks. It is also fatigue resistant. The price per kilogram is much higher than a metals data – 14,64-16,11 €/kg. The carbon footprint for the CFRP is 33-36.4 kg/kg and it is not recyclable according to the CES Edupack.

4.3 Natural materials

Natural materials are great materials (with the right attitude) in terms of carbon footprint. Wood can be considered renewable material only if it was grown and sourced sustainably. Unfortunately, often that is not a reality.
Engineering wood products are hard to recycle. This wood is either burnt, which adds up the CO2 emission, or left to decay, which results in the production of methane, 25 times more potent than CO2 as a greenhouse gas. (Webster, M. D., 2017). These arguments exclude natural materials from the main material choice aspect.

5 Strength of materials analysis

The strength of materials is an engineering sphere, which is focused on loads and stresses and construction reactions on them. In this subchapter, the relations between the Young modulus and a maximum allowable load and a buckling issue are going to be reflected.

5.1 Young modulus

In order to get a range for a Young modulus value, an approach of an available displacement is done. According to the Materials and Design source, the yield strength offset is 0.2 percent from the specimen length for the metals and 3 percent for polymers (Materials and Design, 2021).

Further, the Mathcad Prime 4.0 was used to calculate the maximum allowable load for the trainer. The maximum weight, which has been lifted by a human, is 1118 kilogram (Record Setter, 2021). So, with a safety limit, the 1200 kilogram limit is considered. During the program execution, a strong dependence on the bar diameter was noticed. The initially designed bar was 50 mm in diameter, so for the 1200 kg value the Young modulus value had to be huge, and the only one material was suitable for the design. Thus, the decision of changing the diameter to 60 mm was done. The calculation of the maximum allowable weight depending on the Young Modulus value is attached in Appendix D (page 15).

$$E = 157\ GPa \qquad\qquad m_{max} = 1207\ kg$$

Further, the same calculation principle was applied to the FRP material. The calculation principle is the same: with a young modulus adjustment the maximum allowable weight is calculated, and this Young modulus value can be considered as a minimum (calculations in Appendix D page 16).

$$E = 10.41\ GPa \qquad\qquad m_{max} = 1200\ kg$$

However, in the second case (CFRP calculation) the maximum allowable displacement is 2.7 cm, which is noticeably big and it can interfere with a trainer’s operation. An assumption of the available displacement is done, that it shall not exceed 10 millimeters. Thus, the E value is 28.13 GPa (Appendix D page 16).

$$E = 28.13\ GPa$$

5.2 Buckling

Buckling is a sudden change of the material's shape under a certain load. Numerically, it depends on the young modulus of the material, profile shape and length of the specimen.

$$F_{cr} = \frac{\pi^2 \times E \times I}{L^2}$$

Determining the required second moment of inertia, the following number was reached in the metal case (Appendix D page 17-18):

$$I_{req} = \frac{F_{cr} \times L^2}{\pi^2 \times E} = 1.49\ cm^4$$

The same formula was used for polymers:

$$I_{req} = \frac{F_{cr} \times L^2}{\pi^2 \times E} = 8.31\ cm^4$$

6 Material choice

After applying all the parameters in the CES Edupack, the following list of materials remained:

- Cast iron, ductile (nodular)
- High carbon steel
- Low alloy steel
- Low carbon steel
- Medium carbon steel
- Stainless steel

The comparison table of the materials is shown below:

	Price per kg, €/kg	Young Modulus, GPa	Yield strength, MPa	CO2 footprint, kg/kg	Recyclability
Cast iron, ductile (nodular)	0.24-0.26	165-180	250-680	1.7-1.8	Yes
High carbon steel	0.28-0.30	200-215	400-1160	1.71-1.89	Yes
Low alloy steel	0.33-0.36	205-217	400-1500	1.93-2.13	Yes
Low carbon steel	0.24-0.27	200-215	250-395	1.72-1.9	Yes
Medium carbon steel	0.26-0.28	200-216	305-900	1.72-1.9	Yes
Stainless steel	3.02-3.32	189-210	170-1000	4.73-5.23	Yes
Cast iron, ductile (nodular)	High carbon steel	Low alloy steel	Low carbon steel	Medium carbon steel	Stainless steel

Table 4. Various metals comparison table

The high carbon steel is the first priority option after a characteristics analysis.

In order to achieve the customer’s appeal, a CFRP material can be used for the external design. However, it should be detachable and leave a recycling ability for the high carbon steel.

	Price per kg, €/kg	Young Modulus, GPa	Yield strength, MPa	CO2 footprint, kg/kg	Recyclability
CFRP	14.64-16.11	69-150	550-1050	32.9-36.4	No

Table 5. Carbon fiber reinforced polymer parameters

7 Manufacturing methods

In the manufacturing methods part, the main worldwide principles and technologies are going to be researched and described. As far as the determination of the material has been done, the manufacturing methods will be reviewed around steel and carbon fiber-reinforced polymer. The subgoal of the chapter is to have a vision of the carbon footprint and cost of processes in order to get an understanding and insert the data into the overall analysis.

7.1 Steel

The whole plant's structure is complicated; various processes are intersecting each other. The exact operation of the plant can be seen in Figure 15. Mined iron ore and sorted metal waste (ferrous/non-ferrous) are going to the EAF or BF by adding limestone and coke (coal with removed volatiles, pure carbon). High carbon steel is typically in the range of 0.3% to 1.7% carbon. Low – from 0.1% to 0.3%.

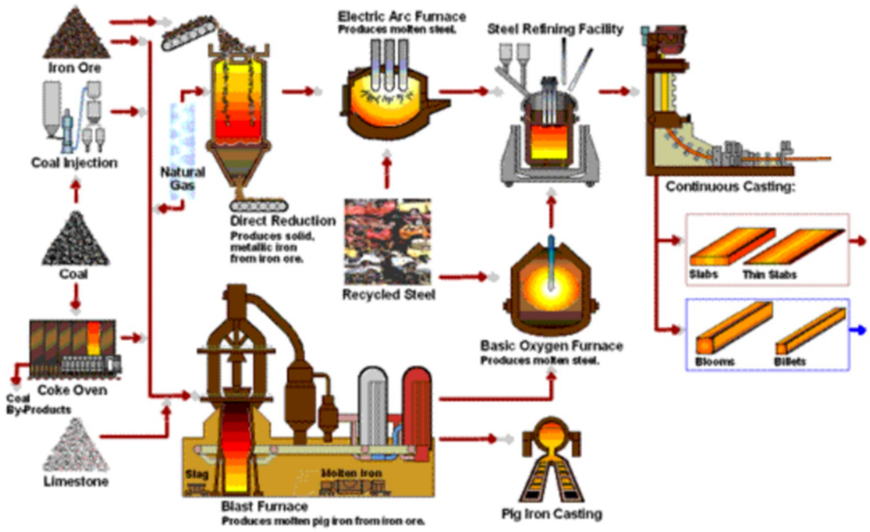


Figure 15. Steel production plant's operation

Finally, molten steel goes to the steel refining facility (where the desired carbon level is reached by blowing a liquid with oxygen) and further to continuous casting, where special shapes are designed and go to the manufacturing facilities.

The manufacturing facilities can involve robotic or human mechanical operations on the specimens. Human work is usually more expensive and not as precise as the robotic one. Definitely, to make mass production, a robotic line shall be used to produce various design shapes.

7.2 Carbon fiber-reinforced polymer

Carbon fiber production lines consist of 6 main steps:

- Polymerization

The first stage of the process is a polymeric feedstock (precursor), after which fibers' molecular backbone occurs. 90% of carbon fiber is of polyacrylonitrile (PAN). The quality of a CF is directly dependent on that of the precursor. Attention to precursor quality minimizes variation in the yield, or length per unit of fiber weight.

- Precursor production

The process starts with an acrylonitrile monomer, which is combined in a reactor with plasticized acrylic co-monomers and a catalyst, sulfur dioxide acid for instance. Continuous stirring blends the ingredients, ensures consistency and purity, and initiates the formation of free radicals within the acrylonitrile's molecular structure.

- Spinning

PAN fibers are formed by a process called wet spinning. The dope is immersed in a liquid coagulation bath and extruded through holes in a spinneret made from precious metals. The spinneret holes match the desired filament count of the PAN fiber (for example, 12,000 holes for 12K carbon fiber). Before the oxidation process, a finishing oil, that prevents tacky filaments from clumping, is applied in a PAN precursor fiber formation.

- Oxidation

Before they enter the first oven, the PAN fibers are spread flat into a tow band or sheet referred to as warp. The oxidation oven temperature ranges from 200°C to 300°C. The process combines oxygen molecules from the air with the PAN fibers in the warp and causes the polymer chains to start crosslinking. Oven manufacturers use a variety of airflow designs to help dissipate heat and control temperature to avoid runaway exotherm.

- Carbonization

Carbonization occurs in an inert (oxygen-free) atmosphere inside a series of specially designed furnaces that progressively increase the processing temperatures. At the entrance and exit of each furnace, purge chambers prevent oxygen intrusion because every oxygen molecule that is carried through the oven removes a portion of the fiber. In the absence of oxygen, only noncarbon molecules, including hydrogen cyanide elements and other VOCs and particulate, are removed and exhausted from the oven for post-treatment in an environmentally controlled incinerator. Carbonization begins in a low-temperature furnace that subjects the fiber to 700-800°C and ends in a high-temperature furnace at 1200-1500°C. Fiber tensioning must be continued throughout the production process.

- Surface treatment and sizing

Producers use different treatments, but a common method involves pulling the fiber through an electrochemical or electrolytic bath that contains solutions, such as sodium hypochlorite or nitric acid. Next, a highly proprietary coating, called sizing, is applied. At 0.5 to 5% of the weight of the carbon fiber, sizing protects the carbon fiber during handling and processing (e.g., weaving) into intermediate forms, such as dry fabric and prepreg. When the sizing dries, the long process is complete. (Composite World, 2021).

Due to the high cost and carbon footprint of the CFRP, it can be only used for the additional design attachments of the trainer in order to gain a consumer’s appeal.

8 Final design

The final design of the trainer is presented in Figure 16.

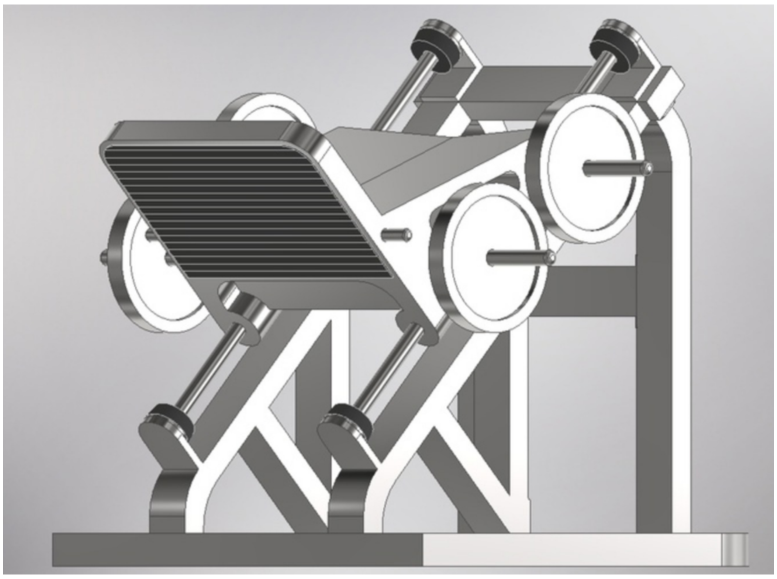


Figure 16. The final design of the leg press

As it can be seen, the design mainly consists of high carbon steel and only small parts, such as cork protections and the main cover, produced from other materials. The total weight of the design is assumed to be 287.6 kilograms. The carbon footprint of the design – around 517,7 kg/kg. The market price for the trainer with integrated generators from both sides – 2500 USD.

9 Conclusion

Nowadays, the question of environmental pollution is a serious issue for humanity, because the people's life quality is in direct dependence on the statement of the Earth's biosphere. The whole European Union pursuing environmental protection policies, the Nordic Council does the strongest positive influence on the environment among other EU members.

The main goal of the project was to do research on a trainer, which has the least destructive impact on the environment. This research aimed at finding an alternative energy generation method by converting a human's exercising energy into an electrical one. At the same time, the research reviewed materials that have the least carbon footprint value and relatively strong mechanical properties.

The research results revealed that cardio trainers are more efficient than strength trainers due to their constant and long-term operation. However, with theoretically designed energy generators, it is possible to achieve a noticeable value of a generated energy while the trainer is in operation. In the material research part, the main group of materials was defined and studied. Based on them, the structural analysis with allowable loads and safety factors were obtained. The final price of the product consists of the net cost of materials, the labor cost, the transportation cost, the plant consumption cost, the value-added tax and a profit. The same positions were considered during the carbon footprint assessment. The final values were easily obtained from the CES Edupack software, the highest numbers out of a given CO2 footprint and a price per kilogram range were considered.

The energy generation technologies, which are presented in the work, can be calculated and applied to the other types of trainers, because such mechanisms are versatile.

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1 Appendix A – Literature Survey

SportsArt video

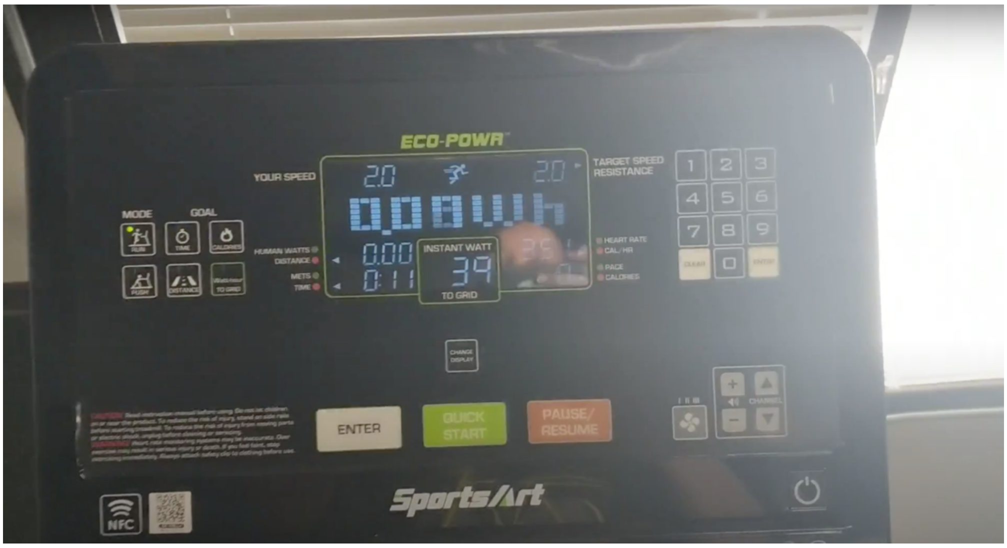
Link: https://www.youtube.com/watch?v=pHUXd86hI_g&ab_channel=SportsArt

Adam Boesel's video files

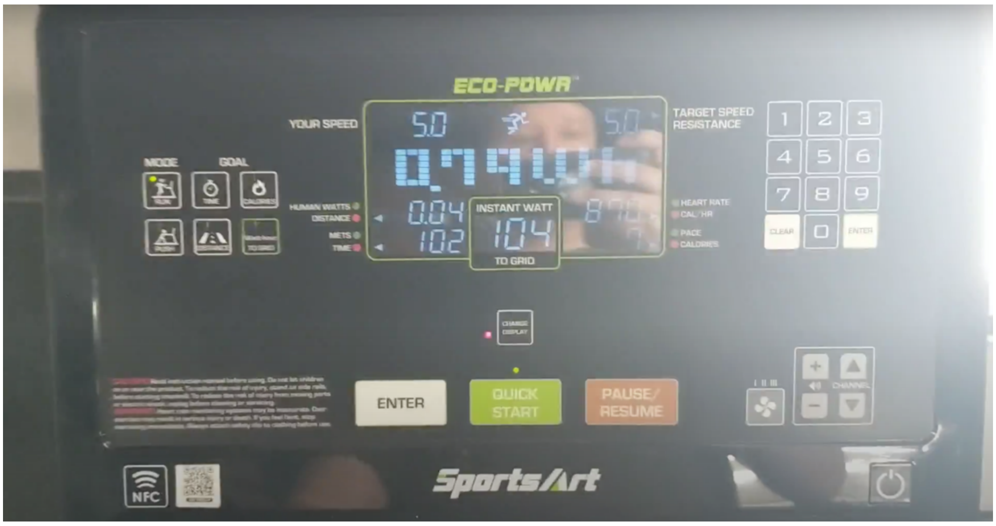
Link:

https://www.youtube.com/watch?v=tajBlef5edQ&t=143s&ab_channel=AdamBoeselAdamBoesel

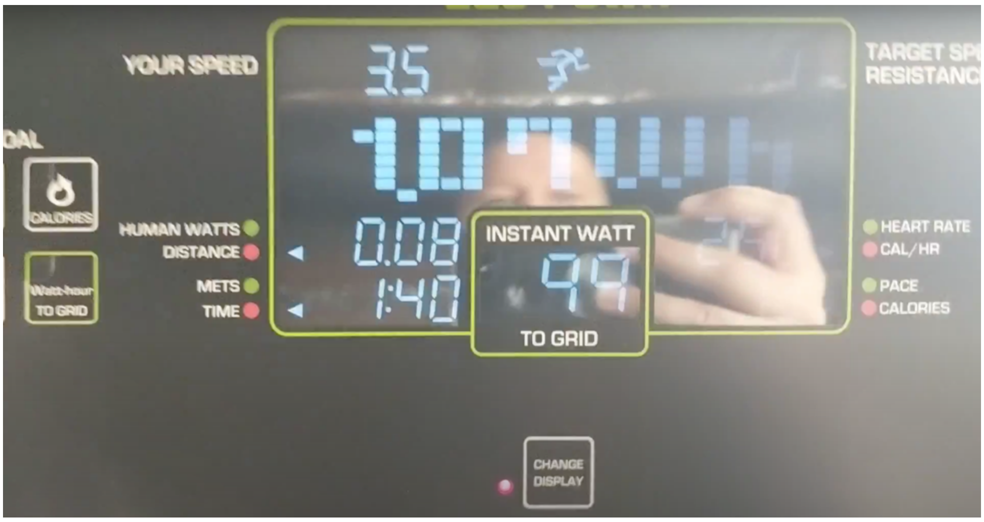
Run mode of the SportsArt treadmill with a 2 miles per hour velocity



Run mode of the SportsArt treadmill with a 5 miles per hour velocity



Push mode of the SportsArt treadmill with a 3.5 miles per hour velocity



2 Appendix B – Gym attendance survey

Survey’s result excel file

Person	Gym's attendence	Rowing	Bicycle	Ellipsoid	Climber	Treadmill	Rider	Crossover	Smith machine	Leg press	Pull down	Hyperextension
1	0	0	0	0	0	0	0	0	0	0	0	0
2	1	0	0	0	0	1	0	0	1	0	1	0
3	0,75	0	0	0,75	0	0,75	0,75	0	0	0,75	0	0
4	0,75	0	0	0,75	0	0,75	0	0	0	0,75	0	0
5	0,75	0	0,75	0	0	0	0	0	0	0,75	0	0
6	0,5	0	0	0	0,5	0,5	0	0	0	0	0,5	0,5
7	0,5	0	0	0	0	0	0	0	0	0	0,5	0
8	0,75	0	0,75	0,75	0,75	0,75	0,75	0,75	0	0	0	0
9	1	0	0	0	0	0	0	0	0	0	0	1
10	0,75	0,75	0	0	0	0	0	0,75	0	0,75	0	0
11	0,75	0	0	0	0	0	0	0	0	0	0	0,75
12	1	0	0	0	0	0	0	0	1	1	1	0
13	0	0	0	0	0	0	0	0	0	0	0	0
14	0	0	0	0	0	0	0	0	0	0	0	0
15	0,25	0	0,25	0,25	0	0	0	0	0	0	0	0,25
16	0,25	0	0	0	0	0,25	0	0	0,25	0	0	0,25
17	1	0	0	0	0	0	0	0	0	0	1	0
18	0,5	0	0,5	0	0	0,5	0	0,5	0	0,5	0,5	0
19	0,75	0	0	0,75	0	0	0	0	0	0	0	0,75
20	0,75	0,75	0	0	0	0	0	0	0	0,75	0,75	0
21	1	1	1	0	1	0	0	0	0	0	0	1
22	0,75	0,75	0	0	0	0,75	0	0,75	0	0,75	0	0,75
23	0,5	0,5	0	0,5	0	0	0	0,5	0	0,5	0,5	0,5
24	1	1	1	0	0	1	1	1	1	1	1	1
25	0	0	0	0	0	0	0	0	0	0	0	0
		Rowing	Bicycle	Ellipsoid	Climber	Treadmill	Rider	Crossover	Smith machine	Leg press	Pull down	Hyperextension
		4,75	4,25	3,75	2,25	6,25	2,5	4,25	3,25	7,5	6,75	6,75

Gym attendance coefficient is written based on the frequency of the gym attendance of a person. Further, green cells are the ones, which were selected by a person and the red ones are the ones that were not selected. The number is multiplied by the gym’s attendance coefficient. Finally, vertically numbers are summed together and the ranking can be seen at the bottom of the table.

3 Appendix C – Methods

The wiring area calculation

Determination of number of turns in inductor

$D := 325\ mm \qquad d := 295\ mm \qquad \alpha := 15° \qquad \beta := 360°$

$R := \frac{D}{2} = 162.5\ mm \qquad r := \frac{d}{2} = 147.5\ mm$

$$S_{sec1} := \frac{\pi \cdot R^2}{\beta} \cdot \alpha = \left(3.457 \cdot 10^3\right)\ mm^2$$

$$S_{sec2} := \frac{\pi \cdot r^2}{\beta} \cdot \alpha = \left(2.848 \cdot 10^3\right)\ mm^2$$

$$S_{wiring} := S_{sec1} - S_{sec2} = 608.684\ mm^2$$

Cross sectional area of the wire

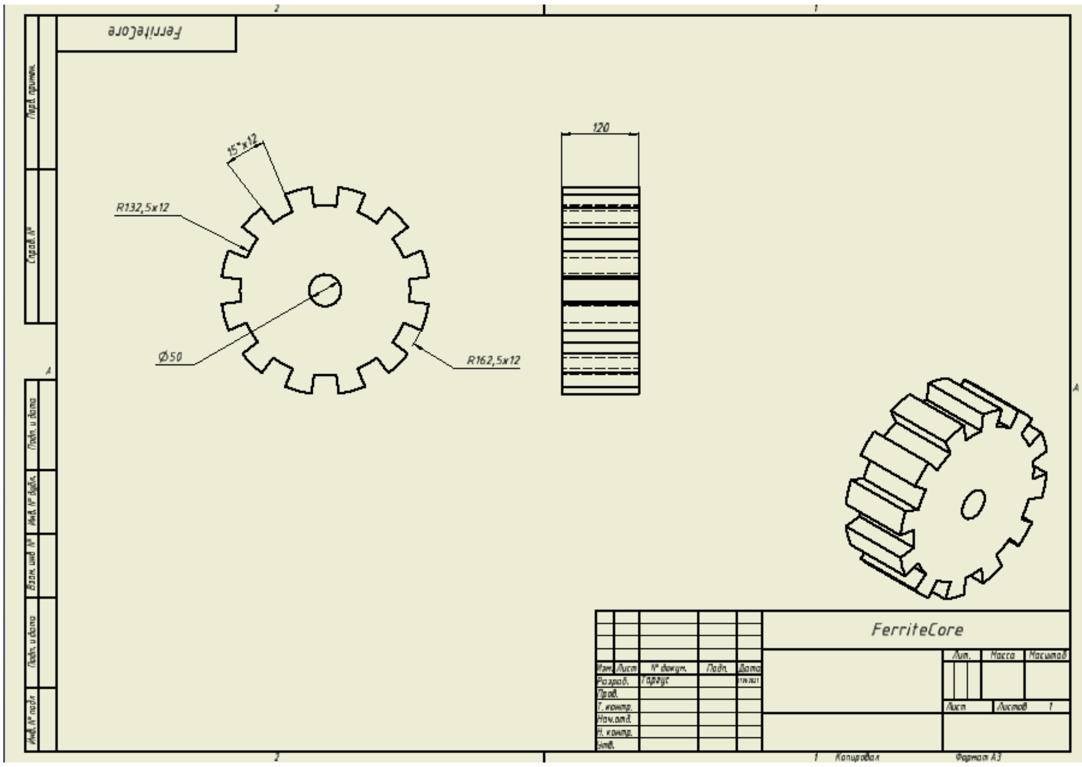
$A := 3\ mm^2$

Number of turns of inductor

$$N := \frac{S_{wiring}}{A} = 202.895$$

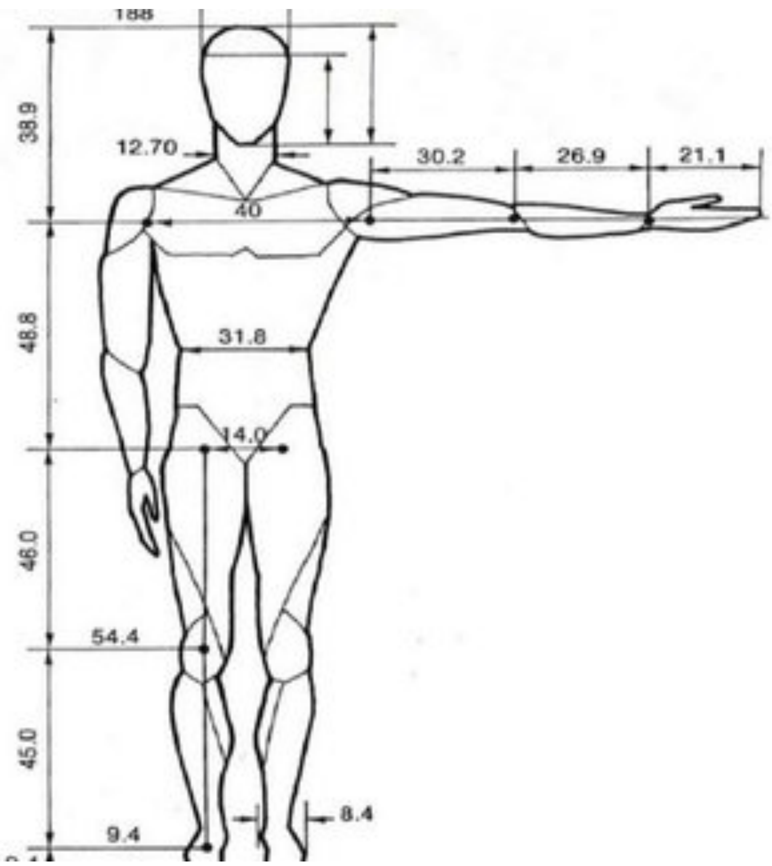
The area of the outer sector is reduced by the area of the internal sector.

Ferrite core technical drawing

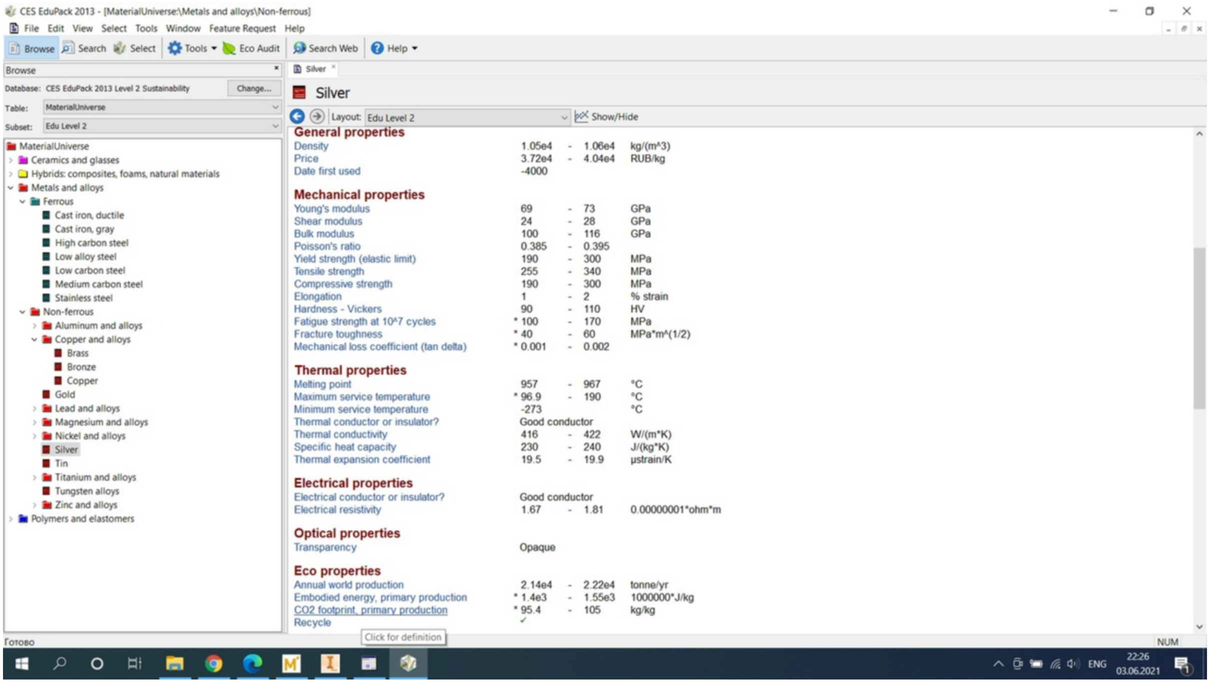


The outer diameter is equal to 325 mm and the internal diameter is equal to 295 mm.

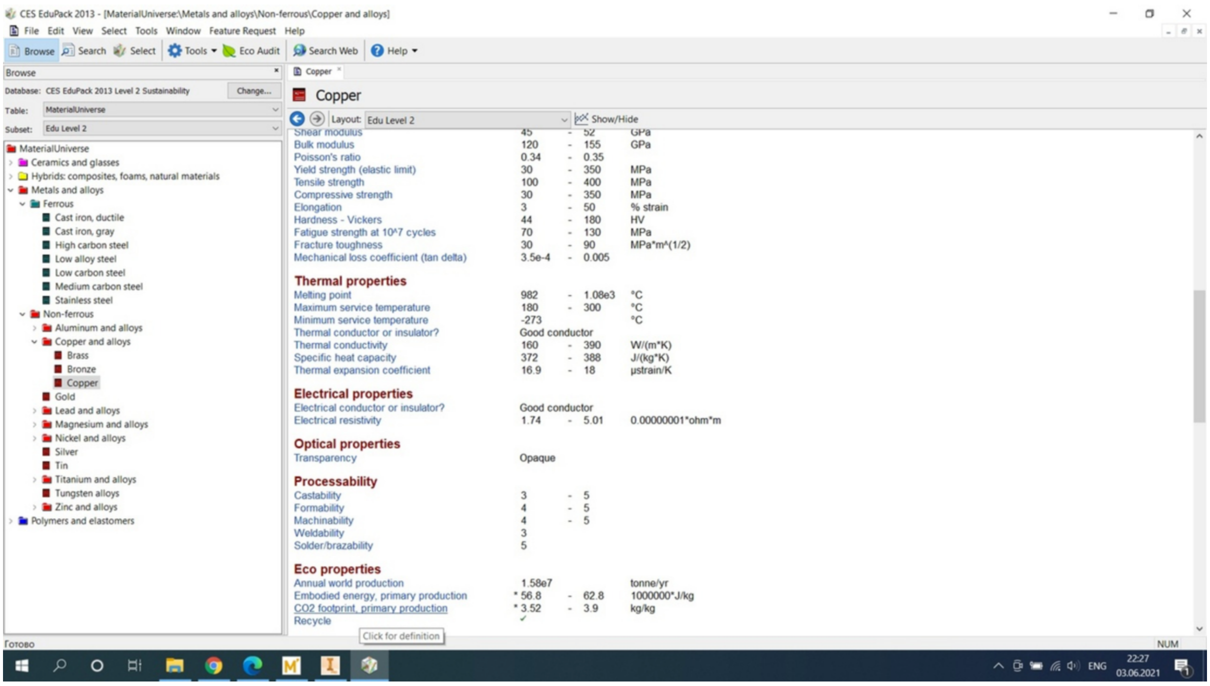
Human dimensions



CO2 footprint for silver (underlined)



CO2 footprint for copper (underlined)



Gym experimental average velocity measurement

First attempt		Time					Second attempt		Time			
	Move up	1,30	s	Move up average time				Move up	1,90	s	Move up average time	
	Move down	0,90	s	1,33	s			Move down	1,18	s	2,22	s
	Move up	1,59	s					Move up	1,87	s		
	Move down	0,85	s					Move down	1,16	s		
	Move up	1,34	s	Move down average time				Move up	2,38	s	Move down average time	
	Move down	1,14	s	0,92	s			Move down	1,06	s	1,12	s
	Move up	1,33	s					Move up	2,03	s		
	Move down	0,78	s					Move down	1,26	s		
	Move up	1,28	s	Leg length				Move up	2,41	s	Leg length	
	Move down	1,14	s	0,46	m			Move down	1,09	s	0,46	m
	Move up	1,45	s					Move up	2,13	s		
	Move down	0,88	s					Move down	1,01	s		
	Move up	1,44	s	Speed of move up				Move up	2,49	s	Speed of move up	
	Move down	0,90	s	0,35	m/s			Move down	1,23	s	0,21	m/s
	Move up	1,16	s					Move up	2,21	s		
	Move down	0,98	s					Move down	1,08	s		
	Move up	1,10	s	Speed of move down				Move up	2,60	s	Speed of move down	
	Move down	0,73	s	0,50	m/s			Move down	0,98	s	0,41	m/s

Third attempt		Time			
	Move up	1,89	s	Move up average time	
	Move down	1,38	s	2,12	s
	Move up	2,15	s		
	Move down	2,03	s		
	Move up	2,28	s	Move down average time	
	Move down	1,98	s	1,88	s
	Move up	2,38	s		
	Move down	2,18	s		
	Move up	2,33	s	Leg length	
	Move down	2,26	s	0,46	m
	Move up	2,10	s		
	Move down	1,90	s		
	Move up	2,02	s	Speed of move up	
	Move down	1,84	s	0,22	m/s
	Move up	1,86	s		
	Move down	1,83	s		
	Move up	2,04	s	Speed of move down	
	Move down	1,51	s	0,24	m/s

Each attempt contains 9 repetitions. Firstly, the average time is calculated. Then, taking the human's hip length into consideration (Appendix C page 9), the average speed is calculated.

Electromotive force calculation for the upward movement

EMF calculation upwards

$N := 202 \qquad S := 305\ mm \cdot 130\ mm = \left(3.965 \cdot 10^{4}\right)\ mm^{2}$

$\eta := 0.9 \qquad B := 1.2\ T \qquad R := 155\ mm$

$v_1 := 0.35\ \frac{m}{s} \qquad v_2 := 0.21\ \frac{m}{s} \qquad v_3 := 0.22\ \frac{m}{s}$

$\omega_1 := \frac{v_1}{R} = 2.258\ \frac{rad}{s} \qquad \omega_2 := \frac{v_2}{R} = 1.355\ \frac{rad}{s} \qquad \omega_3 := \frac{v_3}{R} = 1.419\ \frac{rad}{s}$

$\varepsilon_{i1} := \eta \cdot N \cdot S \cdot B \cdot \omega_1 = 19.532\ V$

$\varepsilon_{i2} := \eta \cdot N \cdot S \cdot B \cdot \omega_2 = 11.719\ V$

$\varepsilon_{i3} := \eta \cdot N \cdot S \cdot B \cdot \omega_3 = 12.277\ V$

Current, power and work calculations for the upward movement

Current calculation

$A:=3\ mm^2$ $\quad \rho:=1.68\cdot10^{-8}\ \Omega\cdot m$ $\quad l:=870\ mm$ $\quad L:=l\cdot N=175.74\ m$

$$r:=\frac{\rho\cdot L}{A}=0.984\ \Omega$$

$$I_{i1}:=\frac{\varepsilon_{i1}}{r}=19.847\ A \qquad I_{i2}:=\frac{\varepsilon_{i2}}{r}=11.908\ A \qquad I_{i3}:=\frac{\varepsilon_{i3}}{r}=12.475\ A$$

Power calculation

$$P_1:=I_{i1}\cdot\varepsilon_{i1}=387.66\ W \qquad P_2:=I_{i2}\cdot\varepsilon_{i2}=139.557\ W \qquad P_3:=I_{i3}\cdot\varepsilon_{i3}=153.165\ W$$

Work calculation

$t_1:=1.33\ s$ $\quad t_2:=2.22\ s$ $\quad t_3:=2.12\ s$

$$A_1:=P_1\cdot t_1=0.516\ kW\cdot s$$

$$A_2:=P_2\cdot t_2=0.31\ kW\cdot s$$

$$A_3:=P_3\cdot t_3=0.325\ kW\cdot s$$

Based on the electromotive force calculation (Appendix C page 10), the calculation of current, power and work are implemented.

Electromotive force calculation for the downward movement

EMF calculation downwards

$N := 202 \qquad S := 305\ mm \cdot 130\ mm = \left(3.965 \cdot 10^{4}\right)\ mm^{2}$

$\eta := 0.9 \qquad B := 1.2\ T \qquad R := 155\ mm$

$v_1 := 0.35\ \frac{m}{s} \qquad v_2 := 0.21\ \frac{m}{s} \qquad v_3 := 0.22\ \frac{m}{s}$

$\omega_1 := \frac{v_1}{R} = 2.258\ \frac{rad}{s} \qquad \omega_2 := \frac{v_2}{R} = 1.355\ \frac{rad}{s} \qquad \omega_3 := \frac{v_3}{R} = 1.419\ \frac{rad}{s}$

$\varepsilon_{i4} := 0.8 \cdot \eta \cdot N \cdot S \cdot B \cdot \omega_1 = 15.626\ V$

$\varepsilon_{i5} := 0.8 \cdot \eta \cdot N \cdot S \cdot B \cdot \omega_2 = 9.376\ V$

$\varepsilon_{i6} := 0.8 \cdot \eta \cdot N \cdot S \cdot B \cdot \omega_3 = 9.822\ V$

Current, power and work calculations for the downward movement

Current calculation

$A := 3\ mm^2$ $\quad \rho := 1.68 \cdot 10^{-8}\ \Omega \cdot m$ $\quad l := 870\ mm$ $\quad L := l \cdot N = 175.74\ m$

$$r := \frac{\rho \cdot L}{A} = 0.984\ \Omega$$

$$I_{i4} := \frac{\varepsilon_{i4}}{r} = 15.878\ A \qquad I_{i5} := \frac{\varepsilon_{i5}}{r} = 9.527\ A \qquad I_{i6} := \frac{\varepsilon_{i6}}{r} = 9.98\ A$$

Power calculation

$$P_4 := I_{i4} \cdot \varepsilon_{i4} = 248.102\ W \qquad P_5 := I_{i5} \cdot \varepsilon_{i5} = 89.317\ W \qquad P_6 := I_{i6} \cdot \varepsilon_{i6} = 98.026\ W$$

Work calculation

$t_4 := 0.92\ s$ $\quad t_5 := 1.12\ s$ $\quad t_6 := 1.88\ s$

$$A_4 := P_4 \cdot t_4 = 0.228\ kW \cdot s$$

$$A_5 := P_5 \cdot t_5 = 0.1\ kW \cdot s$$

$$A_6 := P_6 \cdot t_6 = 0.184\ kW \cdot s$$

Based on the electromotive force calculation (Appendix C page 12), the calculation of current, power and work are implemented.

Average power of the generator calculation

Power	Move up	Move down
First attempt	387,66	248,102
	0,8	0,8
Second attempt	139,557	89,317
Third attempt	153,165	98,026
Average	200,95	128,61

The first attempt was multiplied by 0.8, because rarely sportsmen use the trainer without an additional weight.

Average time calculation

Time	Move up	Move down
First attempt	1,33	0,92
	0,8	0,8
Second attempt	2,22	1,12
Third attempt	2,12	1,88
Average	1,80	1,25

The first attempt was multiplied by 0.8, because rarely sportsmen use the trainer without an additional weight.

4 Appendix D – Material selection

Young modulus and maximum allowable weight calculation for metals

Allowable displacement metals

$E := 157\ GPa \qquad L := 900\ mm$

$g := 9.81\ \frac{N}{kg} \qquad d := 60\ mm$

$r := \frac{d}{2} = 30\ mm \qquad \delta_{max} := 0.2\% \cdot L = 1.8\ mm$

$I := \frac{\pi \cdot r^4}{4} = 63.617\ cm^4$

$E = \frac{F_{max} \cdot L^3}{48 \cdot I \cdot \delta_{max}} \qquad F_{max} := \frac{48 \cdot E \cdot I \cdot \delta_{max}}{L^3} = 11.838\ kN$

$m_{max} := \frac{F_{max}}{g} = \left(1.207 \cdot 10^3\right)\ kg$

Young modulus and maximum allowable weight calculation for polymers

Allowable displacement polymers

$E := 10.41\ GPa \qquad L := 900\ mm$

$g := 9.81\ \frac{N}{kg} \qquad d := 60\ mm$

$r := \frac{d}{2} = 30\ mm \qquad \delta_{max} := 3\% \cdot L = 27\ mm$

$I := \frac{\pi \cdot r^4}{4} = 63.617\ cm^4$

$E = \frac{F_{max} \cdot L^3}{48 \cdot I \cdot \delta_{max}} \qquad F_{max} := \frac{48 \cdot E \cdot I \cdot \delta_{max}}{L^3} = 11.773\ kN$

$m_{max} := \frac{F_{max}}{g} = \left(1.2 \cdot 10^3\right)\ kg$

Young modulus and maximum allowable weight calculation for polymers with a 10 mm displacement consideration

Allowable displacement polymers

$E := 28.13\ GPa \qquad L := 900\ mm$

$g := 9.81\ \frac{N}{kg} \qquad d := 60\ mm$

$r := \frac{d}{2} = 30\ mm \qquad \delta_{max} := 1.11\% \cdot L = 9.99\ mm$

$I := \frac{\pi \cdot r^4}{4} = 63.617\ cm^4$

$E = \frac{F_{max} \cdot L^3}{48 \cdot I \cdot \delta_{max}} \qquad F_{max} := \frac{48 \cdot E \cdot I \cdot \delta_{max}}{L^3} = 11.771\ kN$

$m_{max} := \frac{F_{max}}{g} = \left(1.2 \cdot 10^3\right)\ kg$

Buckling calculation for metals

Buckling metal

$E := 157\ \mathbf{GPa}$ $\quad L := 1400\ \mathbf{mm}$ $\quad m := 1200\ \mathbf{kg}$

$g := 9.81\ \dfrac{\mathbf{N}}{\mathbf{kg}}$ $\quad d := 60\ \mathbf{mm}$ $\quad F_{cr} := m \cdot g = 11.772\ \mathbf{kN}$

$$F_{cr} = \frac{\pi^2 \cdot E \cdot I}{L^2}$$

$$I_{req} := \frac{F_{cr} \cdot L^2}{\pi^2 \cdot E} = 1.489\ \mathbf{cm}^4$$

$b_o := 150\ \mathbf{mm}$ $\quad h_o := 80\ \mathbf{mm}$ $\quad t := 1\ \mathbf{mm}$

$b_i := b_o - 2 \cdot t = 148\ \mathbf{mm}$ $\quad h_i := h_o - 2 \cdot t = 78\ \mathbf{mm}$

$$I := \frac{b_o \cdot h_o^{\,3} - b_i \cdot h_i^{\,3}}{12} = 54.719\ \mathbf{cm}^4$$

The actual second moment of inertia for the 1 mm wall thickness is bigger, than a required one, buckling will not occur.

Buckling calculation for polymers

Buckling polymer

$E := 28.13\ GPa \qquad L := 1400\ mm \qquad m := 1200\ kg$

$g := 9.81\ \frac{N}{kg} \qquad d := 60\ mm \qquad F_{cr} := m \cdot g = 11.772\ kN$

$$F_{cr} = \frac{\pi^2 \cdot E \cdot I}{L^2}$$

$$I_{req} := \frac{F_{cr} \cdot L^2}{\pi^2 \cdot E} = 8.311\ cm^4$$

$b_o := 150\ mm \qquad h_o := 80\ mm \qquad t := 1\ mm$

$b_i := b_o - 2 \cdot t = 148\ mm \qquad h_i := h_o - 2 \cdot t = 78\ mm$

$$I := \frac{b_o \cdot h_o^{\ 3} - b_i \cdot h_i^{\ 3}}{12} = 54.719\ cm^4$$

The actual second moment of inertia for the 1 mm wall thickness is bigger, than a required one, buckling will not occur.