TÉCNICO LISBOA

Project of an electrically assisted bicycle adapted to the urban mobility

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I would like to dedicate this thesis to my family, specially my parents and brother. For the unconditional support and trust and for all the sacrifices made through out my academic career.

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Resumo

O presente trabalho tem como objetivo estudar e criar uma solução para ser usada como meio de transporte em ambientes urbanos. A solução encontrada passa por projetar e construir uma bicicleta assistida eletricamente, adaptada e direcionada para ser usada em torno do conceito de “Last mile”.

Foi feito um estudo para perceber a legislação em torno deste tipo de veículo, para assim compreender as várias classificações que lhe podem ser atribuídas e quais as limitações no que diz respeito à lei. Foi feita uma análise do mercado, a qual mostrou que a venda de bicicletas elétricas tem experienciado um grande crescimento nos últimos anos.

Os componentes que compõem bicicletas foram analisados e comparados, desta forma podemos fazer uma escolha correta e pensada dos componentes a utilizar no projeto. Uma vez que o mercado apresenta já bastantes soluções em volta deste conceito, foi feita uma análise de várias alternativas e consideradas as suas vantagens e desvantagens.

Foram estabelecidos vários requisitos para o projeto, os quais constituem os pontos de maior importância para um veículo com este tipo de aplicação. Devido a alguns constrangimentos do projeto, como o orçamento disponível, tempo, acesso a materiais e métodos de construção entre outros, foram projetados dois designs diferentes. Um totalmente criado de raiz, concebido tendo em conta os requisitos do projeto. O segundo design será destinado a construir um protótipo totalmente operacional. Este protótipo usa componentes de bicicleta disponíveis no mercado e foi construído com o objetivo de manter as características principais do modelo criado inicialmente. Ambos os modelos foram analisados à estática e frequência de vibração, usando o método de elementos finitos. Para cada um dos designs foi feita também uma escolha de componentes e uma análise de custos.

Palavras-chave: Bicicleta assistida eletricamente, ambientes urbanos, protótipo, ”Last mile”.

Abstract

The present work intends to study and create a solution to be used as a means of transportation adapted to the metropolis environment. This solution lies in projecting and building a prototype of an electrically assisted power cycle, mainly directed to be used around the ”Last mile” concept.

It was made a survey to perceive the legislation that concerns this type of vehicle, this was in order to understand the several different classifications that it can have and what were our constraints regarding the law. The market was also researched which showed that e-bike sales have experienced a massive growth in sales in the last years.

The components of bicycles and electrical bicycles were studied and compared, this way we could do a correct and wise choice of components to be used in the project. Since the market already presents several different solutions in terms of this concept, it was made a study regarding some of the market available models, considering its vantages and disadvantages.

Prior to the creation of the design, we established some main requirements, these constitute the points with major importance concerning a vehicle for this specific range applications.

Due to some project constraints as time, capital available, access to building methods and materials, among other, it were developed two different models. One totally conceived from scratch, and design taking in consideration the requirements established for the project. The second design was intended to be build, creating a fully working prototype. This last was made from already produced bicycle components and was thought so that it would be similar to the conceived project and to maintain its must important features. Both models were structurally validated using the finite element method with a static and frequency of vibration analysis. For each of the models was also chosen the best component configuration, this was made comparing each of the alternatives that each component presents and the advantages that they would provide. A cost analysis was also made for both designs, which showed the different cost rates of the two designs.

Keywords: Electrically assisted power cycle, metropolis environment, prototype, last mile.

Contents

List of Tables

List of Figures

Glossary

BMS	Battery management system
CAD	Computer-aided design
CPSC	Consumer Product Safety Commission
DC	Direct current
EAPC	Electrically assisted power cycle
EN	European normative
EU	European Union
FEA	Finite element analysis
FEM	Finite element method
NHTSA	National Highway Traffic Safety Administration
PAS	Pedal assist system
Pedelec	Pedal electric cycle
SLA	Sealed lead acid
USDOT	United States Department of Transportation

Chapter 1

Introduction

1.1 Motivation

The search and evolution of electrical vehicles is growing more and more as the days go by. New technological breakthroughs allied with growing concerns with the environment and physical health had led to huge developments around this concept. Electrical vehicles are claiming a place in several industries, especially in the fields of transportation. The application of electrical motors in bicycles and cars opens up new possibilities and a large number of advantages. Electric motor vehicles are a concept to take into account in the present and even more in the future, as they can open new possibilities or even replace the possibilities given nowadays by the common internal combustion engines. In the current days, fully electrical cars can already directly compete with an internal combustion car or even overcome and make them look obsolete in several aspects.

The application of electrical motors in bicycles has several benefits linked to it. It can provide assistance to the rider through tough climbs, to help rapidly achieve higher speeds or just to let the rider rest along the way, allowing him to do longer and tougher routes with less effort. This concept can reveal to be also very beneficial to people with locomotion difficulties, as it can transform and upgrade a common bicycle or similar vehicle to meet people's needs, helping them on transportation and increasing its mobility.

A foldable electrically assisted power cycle has many advantages, it doesn't pollute the environment, it's good for the health, allowing to exercise and to manage the effort with the amount of power produced by the motor. In a metropolis environment it represents great mobility, it can be folded up and carry it into public transportation to get near the destiny. Or otherwise, to ride it to the destiny, with the electrical motor assisting through the route. As a bicycle, it is very advantageous in traffic jams, as it allows to pass by stopped traffic and reach the destiny possibly even faster than in a car or public transportation.

It presents a very small ecological footprint, specially comparing with cars, once that they are less or virtually non-pollutant. Another feature that increases this variation are the considerable different occupation rates. Cars usually present occupation rates around 1 and 2 persons, representing 20 to 40 percent of its total capacity while bicycles employ all its capacity rate, increasing efficiency and reducing the footprint.

One usual problem associated with the use of bicycles in big cities are the robbery's, leaving the bike chained in the outside it's always a risk, even the best locker can be overcome. With a folding bicycle, this problem doesn't exist anymore as it can just be folded and taken inside with the rider, ensuring its safety. Comparing with a moped or motorcycle, it's cheaper to buy in most of the cases and cheaper to maintain. You don't need any kind of documentation or requirements to apply and they have very similar mobility characteristics through traffic and in a metropolis environment in general.

1.2 Objectives

This thesis has the objective to consider the best alternatives to be used as a daily mean of transportation to commute to work. We should come up with a solution able to solve the problems inherent to the common urban means of transportation, as public transports, private cars or common bicycles and thus create a better alternative for this specific purpose. For such, we will be considering and study the best alternatives from the several hypothesis for an electrically assisted bicycle. This thesis also has the end of building a fully working prototype within the possibilities that are given, this is, taking into consideration the time, capital available, access to building methods and materials among other constraints.

This bicycle or, electrically assisted power cycle, is meant and designed for a very specific use and application: it is designed to be used as a daily mean of transportation to cover the distance between house to work and vice versa. It should be adapted to urban transportation, creating an alternative to other usual and less attractive means of transportation in a metropolis environment. It should be the perfect choice to be applied in the ”last mile” concept. This is a concept that refers to the last section of your daily work route. Whether it is directly from house to work or from the public transport or private car. The bicycle has the objective of making your way to work easier, effortless and eliminating the problems inherent in the use of a common bicycle. Nowadays we also have a growing concern with the environment and the pollution, by using an electrical vehicle, you would have a vehicle with virtually no pollution inherent to it, making the way to work cleaner and greener and thus reducing the ecological footprint both of the rider as of the city itself.

Let's envisage the following scenario where you live relatively near to your workstation (about 5 km or more). This would leave you with a small distance to cover to go to work but still a large distance to cover by foot. Therefore the common alternatives would be a public transport, a common bicycle or a private car, but all these alternatives can represent problems. Using the public transportation, more likely a bus in this situation, you would always have variables that you can't and won't control or overcome and that could lead to make you arrive late to the destiny. Variables such as the schedule of the bus, possible but still common delays or even just the traffic, which is quite usual in big cities. With public transportation you also would have more expenses, just to go to work. The common bicycle would be a good alternative as it has more maneuverability and can easily overcome traffic or other urban obstacles. Even so, using a common bicycle with hot weather or in hilly paths can be exhausting, tiring down the rider and making him sweat and uncomfortable, even before arriving to the workstation. This probably would have a negative effect on the performance and well-being throughout the work day. Another problem inherent to the use of bicycles in city environments is the safety, daily dozens of bicycles are stolen and never retrieved. Taking your private car would also be a good alternative but this also raises practical problems. Problems such as traffic or finding a spot to park. Another common scenario, is the one of people that work in a big city but live in its surroundings. These often take the public transport to get to the city, as a train, boat or bus, but this transport doesn't take them to the final destination. Therefore they still have a distance to cover within the city. The alternatives to this last part of the route, or "last mile", would be taking a second public transport, to near the destination or to use a common bicycle, preferably foldable so that you could take in the public transport with any problems. These alternatives would raise problems, just like the ones described before.

A foldable electrically assisted bicycle would solve all these problems. Traffic wouldn't be a problem, as a bicycle, it can easily overtake stopped traffic or go to an alternative route where cars or public transports can't go. Comparing to a common bicycle, it would keep its main features as its maneuverability and practicability, but would make the route easier and requiring less effort from the rider, as the motor would do most of the work, allowing him to arrive to work fresh and rested. Such problems as robberies wouldn't be a problem once the bicycle can be foldable and taken into the inside of the building or workstation. This work intends therefore to create an alternative mean of transportation. One alternative that is better in most aspects than the common transports and able to solve and overcome the problems and obstacles that can often be found in a metropolis environment.

1.3 Methodology

1.3.1 Frame project

The frame is the main component of a bicycle, it's the component that connects all the other bicycle parts and where these are fitted in. But it isn't just the component that connects all the parts, as it has extreme influence in the bicycle performance, safety and nearly all aspects of the bicycle. There are several alternatives to the shape and size, but the most common is known as the diamond frame, composed by two triangles as can be seen in the figure.

Figure 1.1: Bicycle diamond frame

There are several aspects to consider in the design and conception of a bicycle frame, essentially the weight, strength and stiffness. Also, and in this project in particular, the compactibility is very important factor, once a foldable bike, when folded, has to became as compact and easy to store as possible. These are then the main features that should be given more importance, as they heavily influence the final product and translate into the main characteristics of a foldable bicycle.

Regarding the material for the frame, the most common and used from the beginning of the bicycle history is the steel, but there are several other ordinary alternatives as aluminum alloys, titanium, carbon fiber and other composite materials. All the materials present its own advantages, but it is steel the most used one, as it is strong, relatively easy to work, cheap and reliable, which makes it one of the better alternatives for this specific purpose. Aluminum, despite its lower density compared to steel, is more difficult to work with and more expensive, both the raw material and the tools needed. Titanium, despite having a high strength to weight ratio and excellent corrosion resistance its even more expensive and difficult to machine than both steel and aluminum. Regarding the carbon fiber, it has the advantage that can adapt to virtually any shape but it needs constant care and maintenance.

1.3.2 Finite Element Method

The finite element method (FEM), also known as finite element analysis (FEA) is a numerical technique, well suited to digital computers, it can be applied to solve problems in solid mechanics, fluid mechanics, heat transfer or vibrations. The procedures to solve the problems in each of these fields is very similar but in this work we will focus in solid mechanics problems.

Finite element method is a numerical technique for finding approximate solutions to boundary value problems for partial differential equations. The basic concept is the subdivision of the mathematical model into a finite number of parts with smaller and simpler geometries called finite elements. These elements are connected at points called nodes. The finite element method chooses the nodal displacements so that the stresses are in equilibrium with the applied loads and the constraints of the structure. The response of each element is then expressed in terms of a finite number of degrees of freedom, these represent the conditions of equilibrium of each element and are converted into a set of linear algebraic equations. These simple equations are then assembled into a larger system of equations that models the entire problem and that can be solved using basic algebra techniques. The global system of equations has a known solution and can be calculated from the initial values of the original problem to obtain a numerical answer, which shows the actual strains and stresses in all the elements that compose the component.

The method emerged from the need to solve complex elasticity and structural analysis problems in civil and aeronautical engineering. The first developments were around 1940, by A. Hrennikoff [1] and R. Courant [2]. Despite both scientists had different perspectives, both had one common and essential characteristic, mesh discretization of a continuous domain into a set of discrete sub-domains, usually called elements. Another important contribution was brought into FEM development by the papers of Argyris [3], Turner [4], Martin [5] and several others. The finite element method obtained its real impetus in the 1960's and 1970's by the developments of J. H. Argyris [3], the main reason why the method only spread years later was mostly due the possibility to use computers to make the calculations, once the method has a big volume of computations required. The first book on FEM was published in 1967 by Zienkiewicz and Cheung [6] and called "The finite element method in structural and continuum mechanics".

In the 1970's emerged the computer-aided design (CAD) which made the implementation of FEM much easier. In the current days there are several programs that use this method like ANSYS, Solid-Works, NX and many others, making the method application much easier, practical and cheaper. In the present it is a method widely used, specially in engineering.

1.3.3 Decision Method

In order to be able to make decisions in a less subjective way, we opted to use a decision method. The Pugh method or decision-matrix [7] method is a quantitative technique widely used in engineering. The method was developed by Stuart Pugh, a British professor that worked in the University of Strathclyde, Scotland, in the fields of product design and development, engineering and management. The Pugh method relies upon a series of pairwise comparisons between the design candidates. It allows the comparison of the different alternatives through a wide number of criteria, even more, it manages to attribute different weights to the different criteria, enabling more or less importance to a specific criteria. This allows to take in consideration the importance of each of the criteria individually, taking in account our designed objective and purpose.

To apply the method, first it is necessary to grade (from 1 to 5 for example) each of the criteria, this is made by taking in account the importance that it has on the decision making. This is, a very important criteria, that has a big influence in the choice, would be graded with a five, in contrast, a criteria with little importance would be graded with a one and so on. This is referred as the criteria weight, by other words, how important and how influential this specific criteria will be on the decision making. After the criteria selected and graded according to its importance, it's time to grade how good or bad each option fulfills the criteria. This means that if an option is a good option taking in account only this specific criteria, it should be highly graded. On the other hand, if an option doesn't suits the criteria at matter, it should be poorly graded. This value thus represents how each of the options classifies in accordance with a criteria in particular. Then, with the matrix all filled up and graded proportionally, the results can be calculated. This calculation is made by multiplying the criteria weight by the grade that the option at issue got. To obtain the final result, it is necessary to sum the multiplication results from each of the criteria. Comparing the results of the sums of each option we can easily make a decision, a decision that resulted from a comparison between all the options and taking in account all of the criteria as well as its individual importance.

1.4 Thesis Outline

The present document is divided in 6 chapters, introduction included, and it is structured as it follows:

- Chapter 2 - State of art - Presents a review of electrical bicycles and its main components. It approaches the legislation that concerns electrical bicycles and a quick analysis regarding the market of the concept. It also explores and compares the models existent in the actual market.
- Chapter 3 - Electrical bicycle project - Gives an inside of the project requirements. It is made an analysis and selection of the better suited components to be used in both designs. The models are described and its production costs estimated.
- Chapter 4 - Structural analysis - First are established the load cases to be used for the analysis. Both models are structurally validated with a static, a fatigue and a frequency analysis and the results analyzed.
- Chapter 5 - Prototype construction - Presents the difficulties and building processes used to build the prototype and shows the final result.
- Chapter 6 - Conclusion and future work - Summarizes the work and explains how it could be improved in the future.

Chapter 2

State of art

2.1 Electrical bicycles

Bicycles have been around for more than two hundred years now and since then they have been one important and one of the most used means of transportation. Who invented the concept is a very controversial question and can not be known for sure. What is certain is that they evolved a lot since its creation and still have a very important role in today's society. In 2003, more than 1 billion bikes had already been produced worldwide twice as many as the number of automobiles [8]. They not only provide a viable mean of transportation but also a very popular form of recreation. They had been adapted to lots of applications as children toys, general fitness, military and police applications, courier services, bicycle racing and several others.

An electric bicycle is a bike with an electric motor integrated used to assist the rider propelling the bike. There are two main types of electrically assisted power cycles: pedelecs and E-bikes, the difference is the way which the motor is actuated. Pedelecs use a PAS, the motor automatically assists the driver as long as he keeps on pedaling and if the driver stops pedaling the motor will stop. The amount of assistance given by the motor is automatically adjusted in accordance with the sensors integrated in the motor, which usually measure the pedaling rate, bike speed or torque applied by the driver. Not all the designs have these three types of sensors, but the recent designs have the three types of sensors working together, which results in a more controlled driving experience and in the improvement on some main characteristics of an EAPC, as the range and comfort. In E-bikes, or as they are commonly referred "power-on-demand" or "twist-and-go" bikes it's used a trigger or throttle which the driver actuates to propel the bike. There are also some designs that present both operating modes.

The first known patent for an e-bike was published at 31 December of 1895 by Ogden Bolton Jr. in the United States [9]. It was a simple design ant it used a direct current (DC) brushed hub motor mounted in the rear wheel. It had no gears and the motor could draw up to 100A from a 10V battery fixed in the frame . As it can be seen from the figure, this design is quite similar to the models that we have nowadays.

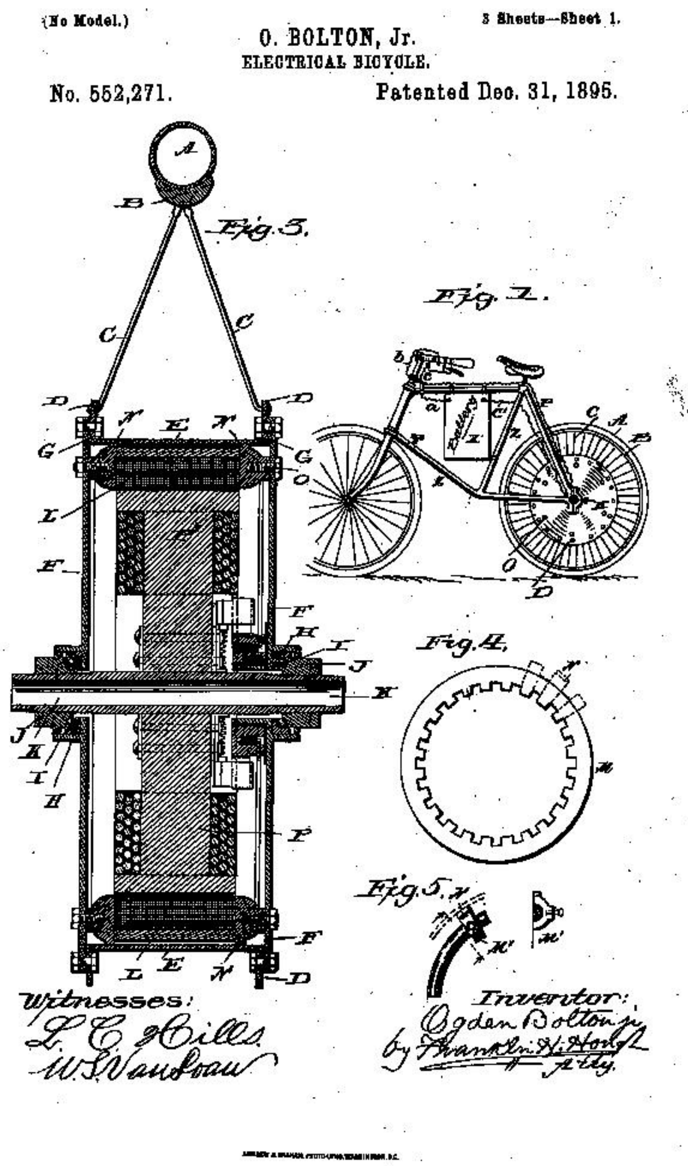


Figure 2.1: Patent US552271-0 [9]

With the objective to increase the power and efficiency of the hub motors, and just one year later, appeared the first brushed planetary-geared hub-motor with a total RPM reduction of 5.6:1[10]. Surprisingly, and just another year later surged the first electric bicycle with a mid-drive motor. The patent was filed again in the United States and by Hosea W. Libbey [11], however this particular mid-drive only spinned at the same RPMs of the bike wheel, which doesn't took much advantage from the use of the mid-drive motor .

Despite the first patents referring to bicycles with electric motors integrated appeared in the 1890s, was not until the late 1990s that EAPC's started to became popular. New technologies allowed the manufacturers to build better, more consistent and more reliable electrical bicycles. The concept of electrically assisted powered cycle started to grow in a considerable scale and these started to be seen as a proper mean of transportation, starting to compete against common bicycles, mopeds, motorcycles or even cars. Even so, the highest growth was in the last ten years or even recently in some countries. The legislation referring to this recent category of vehicle is therefore a little premature and is still adapting and trying to respond to the frequent changes and innovations of the market. The EU conceived directives and standards, in order to try to harmonize the laws and safety around this concept all over Europe, which in nowadays it's almost achieved. One of the main concerns of the EU is the safety concept, once the EAPCs are designed to be used in environments with various parts involved as cars, pedestrians, other bicycles and several other types of obstacles.

New technology developments allied with new and ”sexier” designs took an important role in the growth of the market but not only, a growing concern with the environment had led to even bigger search and demand of electrically assisted power cycles. Some of the main and latest inventions that took an important part in the EAPC industry were components like the torque sensors, batteries, power sensors and the motor itself. The creation and improvement of these parts allowed the industry to progress even more and to get the recognition that it didn't had before. These breakthroughs had extreme importance in the industry as they perfected the concept, allowing more fun and control driving the bike. The electrical bicycles became more reliable, cheaper, with a more controlled energy consumption,with bigger ranges which opened up doors to new applications. Nowadays the search for electric bicycles is still growing and in a level never seen before, as people recognize the several advantages that this type of vehicles have in a metropolis environment in comparison with a car, a common bicycle or a moped or motorbike. Electric bicycles are also starting to be used industrially, in company's like post-mails and several urban transportation and courier services.

It is expected that in a few years the electric bicycle industry will overcome mopeds and low power motorcycles, as they show several advantages and are emerging new, better and innovative designs. There are already new designs with incredible features, allowing you to connect the bike with your smart phone, enabling you to manage the electrical bicycle features or to charge up the phone. There are also surging new kind of electrical bicycles, like hybrid electrical bicycles, in which the rider pedals just to charge the motor as the crankset isn't connected to the wheel or retrofit kits, which are also getting very popular, as they evolve and present better efficiency rates, which translates into a significantly enlargement of the bicycle range, as they use the bicycle motion to recharge the batteries. As technology keeps on advancing, new improvements and refinements are expected to occur in the electrical bicycle industry, propelling the concept and resulting in better and more versatile designs, creating new applications for electrical bicycles and a continuous growth of the market.

Currently, the main down side of this type of vehicle are the costs inherent to it. Buying an electrically assisted bicycle or converting a common bicycle into an electrical one can reveal to be very expensive, essentially due to two main components, the motor itself and the battery. Despite the market is showing more and more different hypothesis, with different cost rates and power outputs, the concept has always a big investment linked to it, specially in comparison with common bicycles. This is a problem that can only diminish with time and a competitive market between the major brands of the industry. Luckily, and as it will be explained further, the electrically bicycle industry is experiencing a fast evolution with growing designs and innovations. Therefore, it is expected that prices will get lower and more appealing for this type of vehicle, as the main components that enlarge the costs are getting more common and easier to acquire.

2.2 Legislation

Electrically assisted power cycles are a relatively new concept and are in constant upgrade and evolution, therefore the legislation regarding this concept is still a little premature and continuously adapting to the frequent changes and to the new dangers linked to the concept. Nevertheless, there is legislation distinguishing this mean of transportation from the others.
It's hard to establish legislation for EAPC as there are a wide variety of different bicycles, with different powers rates, different work modes, different applications and present different dangers to the riders and to the surrounding environments. As the days go by, more and more designs with different and new features arise, this compels the legislation to be in continuously update. In this section we will be a making short description of the legislation surrounding this type of vehicles, more specifically in Europe, Portugal and in some of the main producers and users of this technology like the United Kingdom, Netherlands, China and the United States of America.

Europe

The European Directive 2002/24/EC makes the distinction between which bicycles keep being treated by the law as common bicycles and the ones that, because of the assistive motor, have to be treated otherwise, similarly to mopeds or motorcycles. The directive defines the main technical features for electrical bicycles as: "cycles with pedal assistance which are equipped with an auxiliary electric motor having a maximum continuous rated power of 0,25 kW, of which the output is progressively reduced and finally cut off as the vehicle reaches a speed of 25 km/h, or sooner, if the cyclist stops pedaling," [12]. If a bicycle is within this parameters, the laws applied are the same as with a common bicycle without any kind of assistive motor.
In the case of bicycles with more powerful motors or with different operating systems, directive 2002/24/EC states that they are considered mopeds or motorcycles. In these categories the driver has different rules to obey. It has an age limit, which depends from country to country, the use of helmet is mandatory for the driver, as a driver license. The vehicle has to have a license plate and insurance. In this case the vehicle has also to be subjected to a type-approval by an authorized entity which verify if the vehicle respects the respective standards for the category that it is inserted on.

The bicycles that are not covered by the European Directive 2002/24/EC (maximum of 0,25kW, and maximum output of 25Km/h which is progressively reduced and finally cut off as the vehicle reaches a speed or the rider stops pedaling) are the ones in focus in this work. To provide a standard for this category of electrically assisted powered cycles it has been developed the European standard EN15194 [13]. The aim of this standard is "to provide a standard for the assessment of electrically powered cycles of a type which are excluded from type approval by Directive 2002/24/EC"[13]. It concerns mostly with the electric part of the vehicle and it is valid across the whole EU and has also been adopted by some non-EU nations and some jurisdictions outside of Europe. Even so there is no legal obligation to this standard in most of the member states. On the other hand, all manufacturers throughout the EU do however have a legal obligation to comply with the General Product Safety Directive, 2001/95/EC [14]. In short, this law states that the manufacturers must be sure that the products they put out on the market are safe and reliable for use. In most of the member states it's allowed for the manufacturers to self-certificate their products, testing the product in their own facilities or having them tested by professional testing organizations.

EN15194 distinguishes EAPC in two distinctive groups. Both classifications are inserted in the category previously referred: motors up to 0.25kW and which the output is progressively reduced and finally cut off as the vehicle reaches a speed of 25 km/h, or sooner. This distinction is due to the comparatively different modes of actuating the motor:

- Pedelec: In this type of bicycles, the motorized assistance only engages when the rider is pedaling. When the driver stops pedaling, the motor switches off. Usually these bicycles have a mid-drive motor system mounted on the crank and connected to the bicycle own gearbox.

- E-bike: Oppositely these bicycles have a motor than can propel the vehicle by it self, this is, without the need for the driver to pedal. Normally seen with hub-motors inserted in the front hub, rear hub or in both. They are commonly referred as "twist-and-go" bicycles and the legislation is quite different for these in some countries, because of the similarities with mopeds or low-powered motorcycles.

EN15194 concerns, as said before, with the electrical components of the bicycle. The safety and performance of the bicycle, as the tests that it has to go through to be considered safe for use, are specified in EN14764 [15]. The aim of this standard is to ensure the strength and durability of individual parts as well as the bicycle as a whole, demanding quality products and high safety requirements. The standard was developed to ensure that the bicycles manufactured in EU would be as safe as possible.

Portugal

Portuguese legislation is in conformity with the European Directive for bicycles with motors under 25kW. The last modifications in the Portuguese legislation were made in 2012, updating *Artigo 112 do Código da Estrada* [16] and placing agreement with the European standards. Even so, for motors with higher capacities, above 25kW, the Portuguese regulation is not clearly defined.

Regarding the public transportation, it's allowed to take the bicycle to ride the Metro as long as it doesn't disturb its normal operation mode or if there is not a large amount of people riding the train. With respect to the buses in Lisbon, there are only some of the routes that allow transporting bicycles (708, 723, 724, 725 and 731).

United Kingdom

The last updates that entered into force in the United Kingdom were on 1 of January of 2016, where until this date the law didn't specify precisely what was either legal or illegal, concerning bicycles assisted by electric motor. Nevertheless even with the last updates, there are still some lack of conformance between the national and the European standards. The current Legislation for an electrically assisted pedal bicycle states that a bicycle doesn't need to be licensed and registered if within the limits: the continuous rated power of the motor must not exceed 200 watts for standard bicycles and 250 watts for tandems and tricycles, the electrical assistance must cut-off when the vehicle reaches 15 mph (25km/h) and the unladen weight must not exceed 40kg for standard bicycles and 60kg for tandems and tricycles. In the beginning of April this year (2016) it is scheduled a new legislation update in the UK where several changes are planned, these are in order to place English legislation in conformance with the European standards.

Netherlands

There is no distinction between pedelecs and conventional bicycles if the motor doesn't exceed a power of 0.25kW and if the motor assistance stops at a maximum of 25km/h. In the case of E-bikes, they are considered mopeds, requiring driver license, license plate and vehicle insurance. Both pedelecs and common bicycles have to obey to several regulations: have working brakes, have retro-reflectors in the spokes or wheels and in the pedals, illumination in the front and rear and have to use the bicycle paths when possible.

China

In China, electric bicycles come under the same classification as bicycles and don't require a driver's license to operate as long as the vehicles are lighter than 20 kg and slower than 30 km/h. But, due to a rise in electric-bicycle related accidents, caused mostly by inexperienced riders who ride on the wrong side of the road, run red lights, don't use headlights at night etc, the casualties are increasing year by year: in 2007, 2,500 people died of such accidents, and more than 3,600 died in 2009 [17]. Some cities and regions have banned electric bicycles, and handed out tickets due to the concerns over environment, safety and city image issues.

United States

In the United States the most similar category of electrical bicycles compared to the Europe is defined as "Low speed electrical bicycle". This category embraces all two or three wheeled vehicles with fully operable pedals, with a top speed when powered solely by the motor under 20 mph (32 km/h) and an electric motor that produces less than 750W. A bicycle remaining within these specifications is subject to the CPSC consumer product regulations for a bicycle and are exempt from classification as motor vehicles. The rules for electrical bicycles on public roads, sidewalks, and pathways are under state jurisdiction and vary according to the state. All commercially manufactured electrical bicycles exceeding this power and speed limits are regulated by the federal USDOT and NHTSA as motor vehicles, and must meet additional safety requirements.

2.3 Market

Since the beginning China has been dominating the global market for electric bicycles, with an estimated 85 percent of all the electric bicycles in the world being sold in China. This is due to several reasons: the government made the developing in this area an official technology goal in 1991 and more recently, a large number of cities have legally banned petrol engine mopeds and scooters. Starting in the year 2000, the Chinese market began to grew up at an exponential rate, from about 300,000 sells in 2000 to an astonishing 30 million units sold in 2012[18].

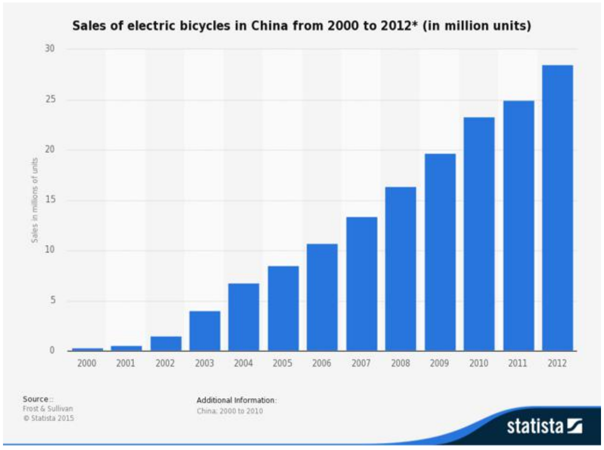


Figure 2.2: Evolution of the chinese market [18]

In Europe and North America the market only emerged afterwards, despite the delay, the market is growing very fast and is now a multi-million dollar industry, specially in the northern countries of Europe, like the Netherlands, United Kingdom, Germany or Belgium where there are long cycling traditions. It is estimated that in 2014 83.2% of all the imported e-bikes in the EU were imported from China[19]. Another important factor which made the e-bike market grow so much were the high gas prices in most of European countries. This merged with a growing aware of environment concerns made people start to look for less polluting means of transportation and cheaper alternatives than cars or motorbikes. One of the main drawbacks that slowed the market growth were the costs, which are relatively high compared to a common bicycle.

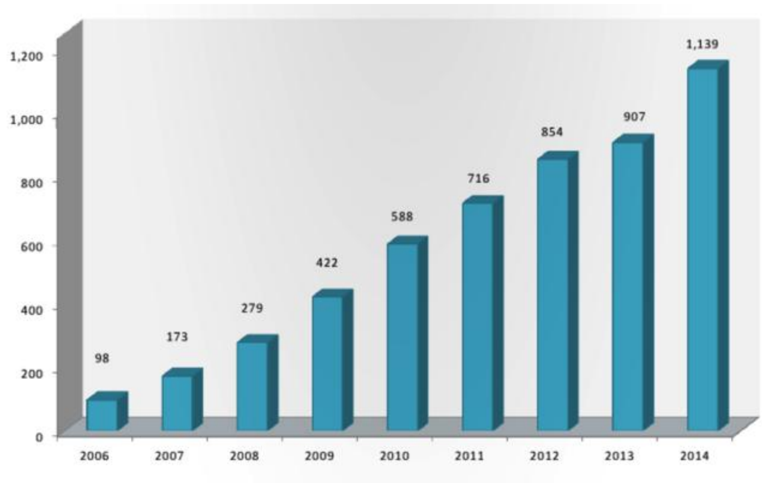


Figure 2.3: Evolution of the European market [20] (1000 units per year)

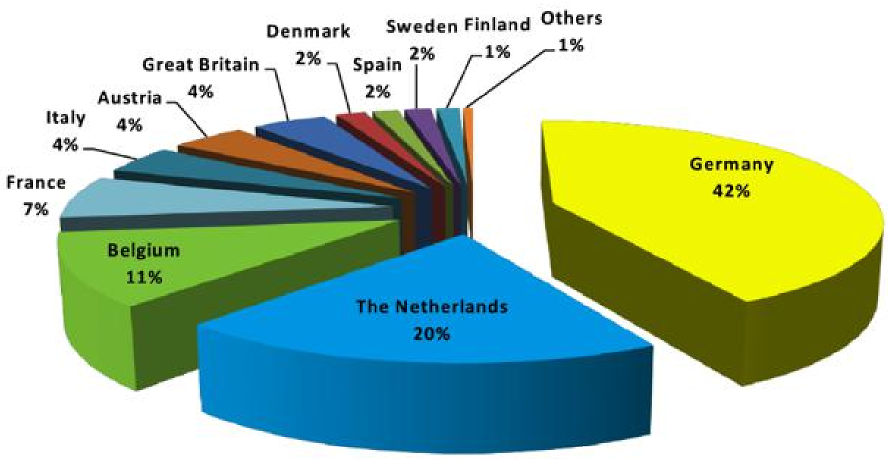


Figure 2.4: European EPAC sales in 2014 per country. [20]

According to Navigant Research, global annual sales of e-bicycles are expected to grow from nearly 32 million in 2014 to over 40 million in 2023 under a base scenario[21]. Innovative trends have contributed to the market growth and will continue to. E-cargo bicycles have started to be used as mean of transportation for several industries, post-mails, police patrolling, security companies and several others. Hybrid designs and retrofit kits are starting to appear, making the e-bike market even more attractive and as the time goes by more and more designs, with different features are surging, making EPAC's very useful and with lots of practical applications, not only in private transportation.

2.4 Bicycle components nomenclature

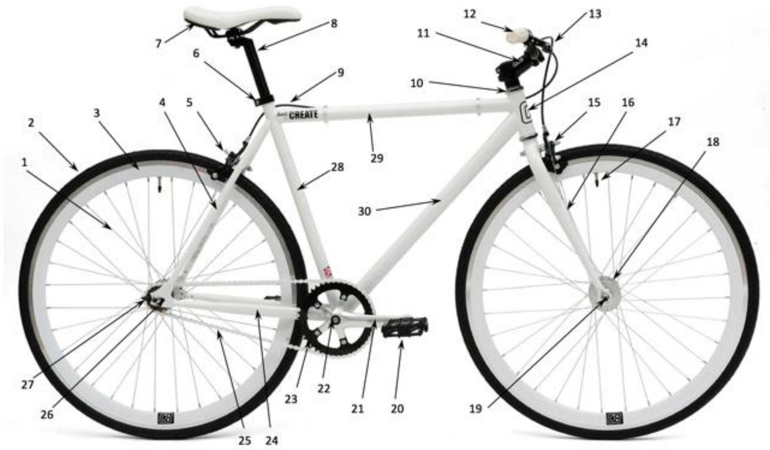


Figure 2.5: Bicycle components

1. spoke
2. tire
3. rim
4. seatstays
5. rear brake
6. seatpost clamp
7. seat
8. seatpost
9. brake cable
10. headset
11. stem
12. handlebar
13. brake levers
14. head tube
15. front brake
16. fork blade
17. valve stem
18. front hub
19. front dropout
20. pedal
21. crankarm
22. crankset
23. chainring
24. chainstays
25. chain
26. rear dropout
27. rear hub
28. seat tube
29. top tube
30. down tube

2.5 Electrically assisted bicycle components

2.5.1 Motor

There are several ways to electrically propel a bicycle, the considered ones in this work and more commonly used are mid-drive motors, hub motors and friction drive motors. In this section we will be considering both the advantages and disadvantages of these types of motors in order to be able to choose the most suitable option for the needs that the bicycle will be subjected to.

The bicycle is designed with the city of Lisbon in view, a city well-known for its steep and long hills, so well known that it is commonly referred as *"Cidade das sete colinas"* ("City of the seven hills"). The roads in the Portuguese capital have known better days and currently some of the roads have very poor pavement conditions. Potholes or disable rails are an ordinary sight in the Portuguese metropolis, even though these don't represent a big or substantial jeopardy for cars, for bicycles or motorbikes they can be very dangerous and lead to serious casualties.

Friction drive motors are mainly characterized by its simplicity, both of the motor itself as the mounting process required to assemble the motor. Despite its simplicity and compactness it is the type of motor that is less used from the three considered, as it presents considerable disadvantages among the others. The motor transmits its power to the bicycle using a roller that spins, this roller is pressed against the bicycle own tire making it spin. Despite having advantages as its small size, weight and high ratio power-weight, they are mainly characterized for the low efficiency on transmitting the power to the bicycle. The power transmission is made due to friction between the motor drive and the bicycle tire, this friction coefficient can easily decrease and won't be enough to propel the bicycle, specially with wet weather. They are usually mounted in the seat-post, making very easy to mount or dismount the motor on the bicycle without the need to use any tool.

Figure 2.6:
Friction drive motor mounted on seat-post. (source: `http://electricbikereport.com/electric-bike-motor-comparison/`)

Mid-drive motors, also referred as crank motors, are mounted in the crank shaft. Mid-drive motors are known for their high performance and torque rates, one of the key reasons and key advantages of this type of motor is that it drives the crank, and not the wheels, which lets it take advantage of the bicycle own gears, multiplying its power.

Figure 2.7: Example of a mid-drive motor.

Another advantage resulting from the use of this type of motor is his location in the bike and his effect on the mass center. It is mounted in a relatively low and central position in the bike, which lowers the mass center and keeps it centered between both wheels, this leads to better control, stability and maneuverability for the rider. Despite being more expensive, these provide considerable higher torques and speeds comparing with hub motors with the same motor power. Once the power is transmitted to the crank and chain, the amount of force that it applies is limited by the bicycle components, as the chain and crank. This also implies bigger wear and tear in the bicycle transmission components. One way to minimize this wear and tear would be to momentarily reduce the power when changing shifts, as you would do in a common bicycle. Using a bicycle with suspension, in bumpy or uneven grounds, mid-drive motors are very advantageous, as the bike suspension would alleviate the vibrations and shocks felt by the motor and leaving the wheels lighter, allowing then to rebound quickly and efficiently, leading to a more fluid and smooth ride.

Mid-drive motors can be divided in two categories, there are mid-drive motors that are made to transform a common bicycle into an electrically assisted. These are mounted in the bottom bracket and can be applied to most of the present bicycles. The other category are the motors that require a specific frame, with proper mountings and the place to accommodate the specific model of the motor in the frame. In this case, the bottom bracket becomes the motor itself, this creates the opportunity to use a torque sensor to measure the torque applied by the rider. With the use of another parameter of what the rider is doing or applying to the bicycle, the motor can control much better how to act in order to assist the rider. This creates a product more sensitive and user-friendly.

Mid-drive motors	
Advantages	**Disadvantages**
Uses the own gears of the bicycle	Wear and tear
Consistent in steep hills	Big contact forces changing gears
Light	Expensive
Efficient	More noisy
Low and centered mass center	Several moving parts - more maintenance
High torques	
Better suited for poor pavement	
User friendly	

Table 2.1: Advantages and disadvantages on the use of Mid-drive motors.

Hub motors were the first type of drive system for bicycles to be patented [9] ,his design has evolved and enhanced since then. They can be found on either front, back, or both wheels of a bike. There are two types of hub motors, geared and gearless motors, both can operate independently of the rider pedaling. It's a type of motor better suited to operate in medium/high speeds and in even grounds, as they struggle to overcome steep hills

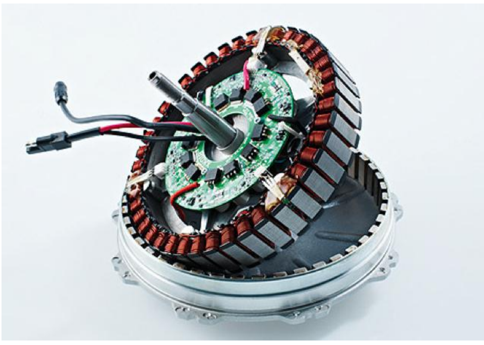
Figure 2.8: Example of a hub motor.

Hub motors usually tend to be low powered (250 to 350 W), specially the ones to use in the front wheel, overpowering would mean a loss of traction and make the front wheel spin, resulting in lost of control of the bike. Nevertheless it is possible to find much more powerful motors in the market, even up to 1000 W of power. This type of motor goes back a long way, since the first electric bicycles and nowadays are the most widely available option, they are "tried and true", making them the most affordable option. In China they are produced in massive numbers, making them pretty affordable and easy to acquire.

These motors have few moving parts, leading to less wear, both for the motor and for the chain and any other components of the transmission. They are mounted in sealed cases, not requiring any kind of maintenance, even so, the sealed case can prove to be harmful and lead to overheating issues, as there is no easy way for the heat to escape. With these motors, it is easy to convert almost any common bicycle to an E-bike, specially using a hub motor for the front wheel, as they do not interfere

with the pedals or the transmission. The bigger disadvantage would be the possible loss of traction in the front wheel. Mounting a rear wheel hub motor can be a little harder, as they interfere with the bicycle derailleur, but it can avoid the risk of having the wheel spinning and loosing traction. With respect to the weight distribution, these can disrupt the balance of a bike towards the front or back, which can make the bike harder to handle and control. Another drawback, and once they are mounted in the center of the wheel, is that they will absorb all the shock and vibration generated by the ground track, which in the long run can lead to problems or malfunctions. Hub motors make much harder to change a flat tire, essentially because of all the wiring connected to the wheels.
Geared hub motors, in contrast to gearless hubs, do not generate drag when unpowered. Usually they have their cases connected to the stator through a planetary gear reduction system, for every rotation of the case, the motor inside will actually turn many times faster, which makes them better suited for hills than gearless motors. This allows the motor to work at higher and more efficient speeds, making them smaller and lighter motors which can achieve greater output, yet this also produces more friction, noise and wear.

(a) Geared hub motor



(b) Gearless hub motor

Gearless or direct-drive hub motors, as the name states, have no gear system, thus one revolution of the motor is equal to one revolution of the wheel. Are known to be very reliable due to their simplicity and almost no moving parts compared with geared motors. Direct-drive motors tend to be larger and heavier as they have to be large in diameter in order to provide a sufficient amount of torque. They rely purely on electromagnets and may not include a freewheel mechanism, generating drag when unpowered. Some present the possibility to recharge the batteries using regenerative braking.

Hub motors	
Advantages	**Disadvantages**
Cheaper	Drag
Easy to mount	Inconsistent in steep hills
Few moving parts - low maintenance	Less efficient
Possibility for both driving wheels	Struggle to start in high inclinations
Wide variety of models available	Unbalance the weight distribution
Regenerative braking	Absorbs all vibrations and shocks
Can power the bicycle without the need for pedaling	More alike to puncture and harder to change the tire

Table 2.2: Advantages and disadvantages on the use of Hub motors.

2.5.2 Frame

As said before in chapter 1, the frame is the main component of a bicycle, it's the component that connects all the other bicycle parts and where these are fitted in. It has extreme influence in the bicycle performance, safety and nearly all aspects of the bicycle. Particularly in a foldable bicycle, it has a massive effect on the bicycle as a whole, once it is the frame that makes the bicycle foldable. The most important features in a bicycle frame are the weight, strength, stiffness and in this work specifically the ability to fold into a compact shape.

Bicycle frames can be made out of several materials, the most common are: carbon steel, chromoly steel, aluminum, titanium and carbon fiber. Steel is the most common to be seen in bicycles, it has been used for a long time and is also the cheapest from the referred above. It is a strong and long lasting material. It is known to be easy to work with, in comparison with the other materials, and the tools needed to work with it are also cheaper (welding gases, welding machines, etc). One of the major disadvantages is his high density, making it the heaviest of the materials considered.

Aluminum has a lower density and lower strength compared to steel alloys, however, it has a higher strength-to-weight ratio, meaning it can build a lighter frame. Despite being more expensive than steel alloys, it is getting cheaper and very widely used on today's bicycles. It's a light, strong, durable and stiff material, making it one of the best choices for this type of application.

Titanium is lighter than steel but just as strong. The major qualities of Ti frames are its durability, damping capacity and low weight. Titanium frames usually aren't painted, this is because they don't need any protection as the material naturally resists the corrosion. His damping capacity allows him to flex while maintaining its shape, resulting in shock absorbing and a more smooth ride. The major downside is the cost. It's both an expensive material and it requires special machinery and skills to work with.

Carbon fiber has become by far the most popular material for performance road bikes. It is incredibly light, some carbon fiber frames weight less than 700g and are strong enough to be ridden to their limits in some of the toughest races in the world. The biggest flaw is that it is very brittle, contrarily to metals, it easily cracks. This is because the carbon fiber frames are made to sustain loads in a specific direction and can't out stand them in different directions.

The material from which the frame is made is very important but so does the geometry. Essentially the length and angles of the tubes, these dimensions will determine how comfortable, stable and maneuverable the bicycle will be, among other practical aspects. For common bicycles (unfoldable), there are hundreds of different designs with different features, some of the more basic and most seen shapes are the diamond shape, the step-through and the cantilever frame.

(a) Diamond frame (b) Step-through frame (c) Cantilever frame

Figure 2.9: Frame shapes

For folding bicycles, the main characteristic is the way that it allows the bicycle to fold. There are also uncountable designs and ways to fold and compact the bicycle. The most common are the ones in which the bicycle folds horizontally, vertically or both. Another common variation in the use of telescopic tubes, allowing the frame to retract. The horizontal fold is the most common, usually the frame folds in a single hinge approximately in the center of the frame, leaving the wheels close together and almost concentrically aligned. Having the wheels aligned creates the opportunity to transport the folded bicycle as a kind of trolley, facilitating its transport when folded. Although for this to work properly the frame cannot just fold in half, this way the wheels would be near but in a different alignment. So it has be to created a fold in a dimension parallel to the wheel alignment, allowing the wheels to be perfectly aligned.

Figure 2.10: Example of hozintontal folding bicycle with unaligned wheels.

The vertical fold has one or two hinges along the main tube and seat stays, these allow the bike to fold both horizontally and vertically. When folded, the wheels are also set side by side, this is often more compact but also more complicated than the horizontal folding design. It also has some complications, the bicycle cannot just fold vertically, since the wheels would collide. It has to have some kind of system that allows the frame to move to the side, creating space for the wheels to be set side by side. Usually this system has more folding stages compared with the horizontal fold, once it normally has more hinges, making it more complicated and time consuming to fold.

Figure 2.11: Example of vertical folding bicycle.

2.5.3 Wheels

Wheel is a very important component in a bicycle and it's size must be selected wisely. For a foldable bicycle, one of the main goals is to minimize the volume that it occupies and the weight, so at the first sight the smart choice would be to use small wheels but, these show several disadvantages in comparison with wheels with bigger diameters. Small wheels limit the mobility of the bicycle, and mobility itself is one of the major advantages of using a bicycle as a mean of transportation, specially in an urban environment as this is intended to serve. Small wheels can represent a problem to overcome simple obstacles as sidewalks or small steps. Even a small hole or stone in the pavement can be enough to unbalance the rider and create a dangerous situation, either for the rider or for the surrounding people.

Figure 2.12: Wheel size [22]

Using wheels with big diameters makes the ride more stable, safer and easier to overcome obstacles, but as said before, one of the main goals in this work is to minimize the volume occupied by the bicycle. Therefore, we must choose a wheel size that is as small as possible, keeping the bicycle compact but still big enough so that the bicycle keeps on being easily maneuverable and provide a comfortable and smooth ride.

To define a bicycle wheel are required two measures, one that states the diameter of the wheel and another to define the width. The diameter is the dimension that stands out more and that has more influence in the bicycle. The standard sizes are stated in inches and there are several different sizes available: 8,10,12,16,20,24,26,28,29,32 and some intermediate sizes, usually from old or very specific bicycle designs. The smaller sizes have little applications, mostly being used only in child bicycles or wheel chairs. The 16" and 20" sizes are usually used in foldable bicycles, BMX or juvenile and light weight riders. The sizes 24" up to 29" are the are the ones with more applications in the market, being used in most of mountain and road bicycles. 32" or even 36" sizes are rather unusual and can be seen in unicycles or some novelty bicycles.

Figure 2.13: Different wheel sizes

2.5.4 Gears

The gears in a bicycle are what determines and allows you to change the relation between the cadence on which the rider pedals and the cadence of the driving wheel. This allows the rider to properly choose the gear ratio for efficiency and comfort in accordance with the circumstances. Gear systems have different gear ratio ranges and features, they must be chosen taking into account the main purpose for the bicycle. There are four main types of gearing mechanisms for bicycles: fixed gear, single-speed, multi-speed and internal gears.

Fixed and single-speed are pretty similar, both just allow one fixed gear ratio. Fixed gear was the first gear system to be used in bicycles and is characterized by having the pedals directly connected to the chainring. If the wheel is spinning so do the pedals, which allow you to brake counteracting the pedals movement. The difference between fixed and single-speed gears is that single speed has a free wheel system, which allows to cruise, without the need to pedal. These two gear systems are still in use in modern days, essentially because of the mechanical simplicity and low weight.

Figure 2.14: Fixed gear system

Multi-speed systems are the most seen gear system in bicycles, it is composed by several components, multiple sprockets of different sizes (up to four chainrings in the front and five to eleven attached to the rear wheel), a mechanism called derailleur used to move the chain from one sprocket to another. The system is controlled by two levers in the handlebar, the left one controls the front derailleur, which provides large jumps in gears and the right one controls the rear derailleur, allowing to fine-tune the gear ratio. For example, when cycling uphill it would be easier using a high gear, a small chainring in the crankset (front) and a larger in the rear.

Figure 2.15: Multi-speed gear system

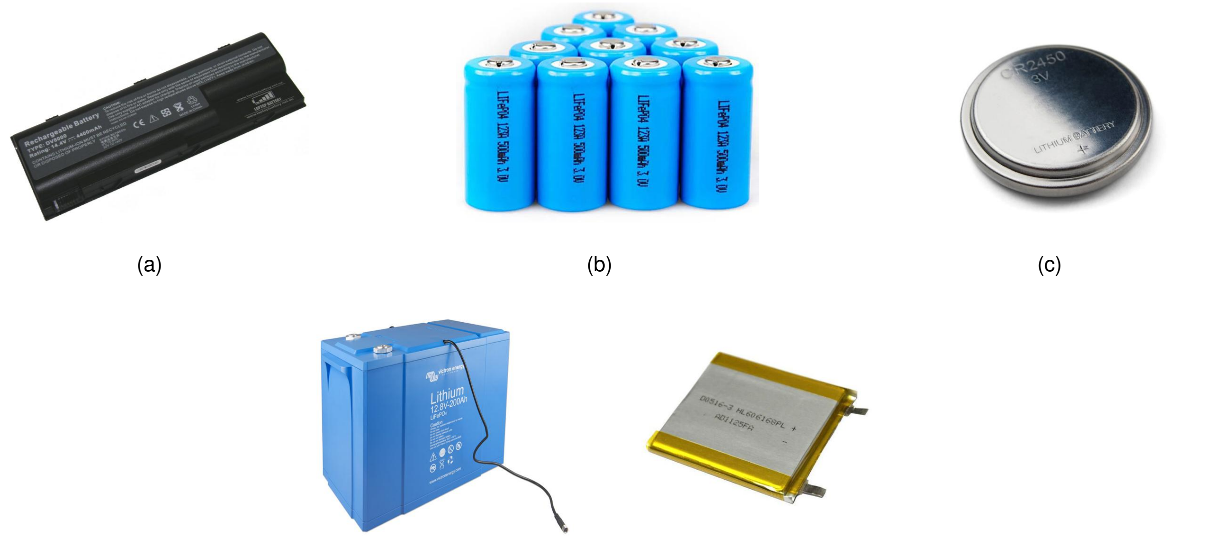
Internal gearing have all its system hidden within the wheel hub. Internal gears work using an internal planetary gearing system which alters the speed of the hub casing and wheel relative to the speed of the drive sprocket. They have just a single chainring and a single rear sprocket. Internal gear systems are available with between 2 and 14 speeds. This is a system that goes easily unnoticed once all its components are hidden inside the wheel hub. It is very advantageous for a metropolis environment as it enables the gear change even when the bicycle is stopped, no other gear system has this feature.

Figure 2.16: Internal gear system

2.5.5 Batteries

The battery is the heart of any electrical bicycle. The motor is useless without all the energy that is stored in the battery. It is one of the hardest components to come by and often the most expensive. Being a crucial component in any electrical bicycle, its choice must be made taking into account the purpose that the bicycle is designed for, as well as the range we're aiming for. Of course, it also has to be in compliance with the other components of the bicycle, as the controller, the motor and all the electrical components that make up the bicycle. The three most common types, and most used in electrical bicycles are lithium, nickel and lead acid batteries, each one with several advantages and disadvantages.

Like the others referred, li-ion batteries are rechargeable, the lithium ions move from the negative electrode to the positive electrode during discharge and back when charging. They are used in most of the laptop batteries, cellphones, electrical vehicles like Tesla's Model S and several other applications. They can be found in different sizes and shapes, all commonly referred as li-ion batteries, a nomenclature that represents a whole class of batteries.



(a) (b) (c)

(d) (e)

Figure 2.17: Examples of different lithium based batteries

There are several combinations of material and different chemistry's of lithium batteries available in the market and as days go by more and more appear, with different and somehow better characteristics. Here we will be describing what can be considered a small share of the market alternatives, even though, these are some of the most used and well known alternatives, specially in the e-bike industry:

- Lithium Iron Phosphate ($LiFePO_4$) - Were one of the first widely used in the e-bike industry and are still one of the most used in this kind of applications. This type is the one that provides the longest lifespan among the other li-ion batteries, rated at 2000 charge cycles or even more. In comparison with the other li-ion batteries these are the safest, their chemistry makes them inherently safe and almost fireproof. They are also some of the largest and heaviest in the li-ion class. One drawback is that most of them have discharge rates relatively low, so they would not be suitable for high powered electrical bicycles, non the less they are very suited for a standard every day bike. These cells also need a protection circuit, usually called Battery Management System (BMS). This is used to keep the cells from becoming unbalanced or over charged or discharged during the successive charge and discharge cycles. Most lithium type batteries need this protective circuit otherwise they can became dangerous and its life expectancy abruptly reduced.

- Lithium Manganese Oxide ($LiMn_2O_4$) - This type is a good middle ground in nearly all regards among the other li-ion batteries, in terms of size, weight, safety and cost. The main downside is its lifespan, which is relatively low considering the other lithium type batteries, generally allowing only 600-800 charge cycles. Despite handling a more balanced charging and discharging, most of the battery packs come along with a BMS.

- Lithium Nickel Manganese Cobalt Oxide ($LiNiMnCoO_2$) - This type is relatively new in these kind of applications. It became popular around 2013-2014 but is rapidly taking over the electric bicycle industry. They have a safe chemistry that can deliver high power in a lighter and smaller package than the two types referred before. These batteries are also commonly preferred for electric vehicles due to its very low self-heating rate.

- Lithium Polymer batteries ($LiPo$) - These are the smallest, cheapest, lightest and most powerful of the lithium batteries described. But they have several disadvantages, including short lifespan (a couple hundred charges) and propensity to combust into giant fireballs. This is due to its unstable chemistry and if they're not carefully and correctly handled, when over-charged or over-discharged, punctured or dropped they will ignite and burst into flames. Basically, they have to be treated with much care, otherwise can became very dangerous and in this specific application, where they are meant to be used near the rider, or even between its legs, they are not a safe choice. These are widely used in the remote control industry, in cars, airplanes and more.

Nickel batteries are another type of rechargeable batteries available in the market. These predate the lithium batteries and are mostly used in portable equipment's as power tools, flash lights, electric vehicles, remote-controlled devices, among others. They have gain its popularity as a replacement for the lead acid batteries, presenting much better qualities than these. Even though, lithium batteries had replaced them in most of its uses and applications. They have a low lifespan and have to be treated carefully, both on assembling and charging.

(a) (b) (c)

Figure 2.18: Examples of different nickel based batteries

There are two main chemistry's of nickel batteries:

- Nickel Cadmium ($NiCd$) - This is the oldest type, they were invented in 1899 but only started to be widely used around the 1960's. Nowadays, they have less uses as they were replaced by $NiMH$ and lithium batteries, also, and one big drawback, is that cadmium is a very hazardous substance and can be dangerous to people and the environment. This led the governments to introduce very restrictive laws and normatives surrounding this battery type, nowadays most landfills won't take them or require paying an extra fee. It is not a battery type very suitable for low powered electrical bicycles as they have a high rate discharge capacity. Also, these can experience what's called the "memory effect", in which it is required for the battery to be totally discharged before charged, otherwise after some life-cycles, the batteries will gradually lose their maximum energy storage capacity.

- Nickel Metal Hydride ($NiMH$) - This is a battery type that was developed after nickel cadmium batteries, it was first patented in 1986. They are very similar to $NiCd$, the main difference is that instead of cadmium, hydrogen is used as the active element and thereby, it is environmentally friendly. Comparing to the rechargeable $NiCd$ batteries, these have a higher energy density per volume and weight (40% more). Their lifespan is about 3000 cycles, being that it can vary according to the manufacturers or the battery type. This batteries also suffer from the "memory effect", even so not as pronounced as in the $NiCd$ batteries. Regarding the costs, they are considerable cheap, usually about half the cost of lithium batteries.

Another option would be the Lead Acid batteries, the oldest between the three battery technologies described before, dating from around 1860. Despite being an old technology, they are still experiencing constant innovations and still being widely used worldwide. It is the same type of battery that you would find in most fuel cars, which makes them widely available and of easy access. Are much cheaper than Li-ion or nickel batteries and this is mainly due to the weight and capacity, they weigh twice as much as nickel batteries, and three times as much as lithium batteries (low energy-to-weight and low energy-to-volume ratios). One important feature that has to be guaranteed, specially for this kind purpose, is that the battery has to be what's called a Sealed Lead Acid (SLA), otherwise, the acid might start leaking from the battery and create a dangerous situation.

(a)

(b)

Figure 2.19: Examples of different lead acid batteries

2.5.6 Throttle/PAS

In this section we will be describing the alternatives to control the amount of motor assistance. It is a very important feature and with the right control you can either use the full potential of the motor or use little help from the motor, majoring the possible range. There are two main ways to control the assistance that the motor gives to the rider, both allow to manage the amount of assistance that is desired with some differences.

- **Throttle** - The concept is pretty much the same as in a common motorcycle. These allow to directly control the amount of power that the motor is producing in real-time. There are several types, as thumb throttles (the throttle is engaged by pushing the lever forward with your thumb), full twist throttles (the throttle is engaged by twisting the throttle grip, seen in most motorcycles) or half twist throttles (the throttle is engaged by twisting the throttle grip,which is this case is just half of the grip. These are the most common throttles used in e-bikes).

(a) Thumb throttle (b) Full twist throttle (c) Half twist throttle

Figure 2.20: Types of throttles

- **Pedal Assist System (PAS)** - Also referred to as pedelecs (pedal electric cycle), is a mode that provides power only when the rider is pedaling, the motor will stop if he stops pedaling or if he actuates the brakes. The amount of assistance is managed in a electronic circuit and takes into account information given by a torque sensor, a cadence sensor and a speed sensor (not all models have the three types of sensors combined). The faster the pedal cadence, the faster the controller will make the motor spin, the same with the torque sensor or a speed sensor. The cadence sensor measures the pedal revolutions per time, you could be pedaling very lightly or very hard and it will provide the same level of assist. It is mounted in the bicycle frame and one or several magnets are mounted in the crank, measuring the revolutions made by the crank. The torque sensor is usually mounted on either the pedal crank or near the rear dropout and it measures the amount of torque being applied by the rider on the pedals. The speed sensor is usually mounted in the bike spokes, it works with the same principle that the cadence sensor but measures the bicycle actual speed.

(a) Torque sensor (b) Cadence sensor (c) Speed sensor

Figure 2.21: Types of sensors

The control of the inputs from the sensors is made so that the output is the most desired for the rider, of course that with information from three types of sensors in stead of just two makes it easier. It's a much more intuitive control mode compared to throttle, as it doesn't requires to activate anything, just to ride the bicycle as a common bicycle, the only difference is that it will feel like cycling with constant tail wind. Most pedal assisted bikes allow to choose between different levels of assistance, low medium or high for example.

Hand throttles were the first that started to be used in EPAC's, mainly due to its similarity to the usual motorcycle throttles. However, because of EU regulations, as referred before in the section "Legislation", the requirement that the motor only assists the rider when the rider is pedaling led to the creation of the pedal assist system.
PAS presents several advantages against throttle mode, it is much more healthier for the batteries, as power demand is much more constant and without big power peaks. Once the rider always has to pedal, the pedal assist mode will generally give more range, allowing to achieve bigger distances with the motor assistance. It's also a much more simple and intuitive driving mode, just like a common bicycle, since the rider doesn't has to activate nothing for the motor to assist, he can focus purely on pedaling and follow his path. Some E-bike models combine the two types of controller. This is very advantageous as the driver is always being assisted by the PAS and still able to have an additional boost from the hand throttle.

2.6 Comparative analysis of existing models

In this section we will be paying attention to the varied offer of electrical foldable bicycle designs that exist in the market. It will allow us to have a more extensive comprehension of the alternatives that the market offers, highlighting its main features, vantages and disadvantages. The models selected are some of the most common and most seen designs but also some of the newest and cutting edge-designs. Of course, and due to the large variety and possible designs in the market, this selection is quite brief, therefore the model selection was made trying to address some diversified alternatives in today's market.

Figure 2.22: Blix Vika+ [23]

The first model in consideration is the "Blix Vika+" [23]. It has a simple and one of the most common folding designs in the market. In the frame it has one single hinge which folds the frame horizontally and roughly in half, this hinge brings the wheels together to a non coaxial position. It also folds the steering tube, bringing the handlebar to a more compact position near the bicycle fork. Its motor is inserted in the rear hub and has a power of 350W that combined with a battery of 36V and 11Ah leads to a range of approximately 55Km. The battery is settled in the back part of the seat tube. The folded bicycle can be quite difficult to transport, so it comes along with a carrying bag designed to transport the folded bicycle.

Figure 2.23: GiFlyBike [24]

The ”GiFlyBike” bike [24] is one of the most forward-looking designs and still in a preliminary state but is already possible to pre-order it. The bicycle folds vertically and by a single hinge in the midle of the frame, which brings the wheels side-by-side. It doesn’t fold into a very compact shape but it is a very practical design and can be folded astonishingly fast. Folded, it can be easily transported in the both wheels, similarly to a trolley. The frame is made out of recycled aircraft aluminum alloy and weights around 17kg. It uses a 250W rear hub motor and the battery is accommodated inside the frame. It has an estimated range of 60km. The cost for a pre-order is 2047€. The transmission is made through a belt drive, helping reducing the weight and reducing maintenance. It has a smartphone application which allows you to connect and charge the smartphone and also to activate an integrated locking system or to activate it automatically when the phone is far away from the bicycle.

Figure 2.24: Mando footlose [25]

”Mando footlose” [25] can be put in a different conceptual category as it is considered a hybrid bicycle. It has no mechanical link between the pedals and the wheels, the pedaling motion is used to re-charge the battery which feeds a 250W rear hub motor. It has a very unusual and futuristic design, the frame is made out of an aluminum alloy and some components as the fork out of carbon fiber. It weights 21.7kg and has a range between 30 to 45km, depending on the pedaling action. The folding mode is pretty similar to the ”GiFlyBike”, folds vertically and brings the wheels side-by-side into a coaxial position, allowing its folded transportation as a trolley. It also folds the steering tube, achieving a very compact shape. It costs 3580€. The concept has won several awards, being the last the ”Red Dot Design Award 2015”.

Figure 2.25: Go cycle [26]

"Go Cycle" [26] has a 250W motor mounted in the front hub. It cannot be completely accounted as a foldable bicycle because to achieve a fully folded setup it's necessary to remove both wheels and the seat-post. For this reason the brand has created and patented a very practical and fast locking system to attach and detach the wheels. The frame has a hinge in the cranckset axle, which allows the chainstay to fold vertically into a compact shape. The steering tube also folds down, as it is usual in foldable bicycles. Despite not folding completely, it can became a little more compact without removing the wheels. It has a basis for fixing the folded bicycle, it's called portable docking station and it was created with the objective of facilitating the transport and accommodation of the bicycle when completely folded. It weights 16.3kg and has a range of approximately 80km which of course depends a lot on the pedaling action. It costs 4500 €, which is quite expensive comparing to the other models in the same category.

Figure 2.26: Jivr Bike [27]

"Jivr Bike" [27] is one the most compact alternatives in the market. To achieve its folded setup the frame folds twice, one hinge which rotates the chainstay, bringing it vertically to the front and the other rotates horizontally the front part of the frame, setting the wheels side by side . The wheels are accomodated aproximately at the center of the frame and in a coaxial position. The frame is made out of aluminum and the complete setup weights 16kg. It uses a 250W motor positioned in the front wheel hub with an estimated autonomy of 30km, again depending on the pedaling action. It has no chain as it uses a mechanical drivetrain with a single gear ratio (3:1). The cost is about 2100 €. It also has an application for smartphones which allows to plan the route and check the bicycle and rider performance.

Figure 2.27: Weelin [28]

”Weelin” [28] is another of the most compact alternatives, it’s in a preliminary state and and still being developed but it is already possible to pre-order it from the website. The frame is made out of injected Magnesium and has several hinges to allow it to achieve its compact shape. It folds in both the wheels holders, fork and chain-stay, folds the steering tube and the seat-post. It is one of the lightest models in the market, weighting a meres 12.5kg, this makes it very easy and practical to transport when folded. It has a mid-drive motor but once it is still under development some of the main features, as motor power, range and several others are still unavailable. The estimated cost will be around 1500 €.

The table bellow summarizes the description of each of the models studied above, and enumerates the main features of each design, presenting their main vantages and disadvantages.

Table 2.3: Comparison and analysis of the existing models

Model	Main characteristics	Mounted	Folded	Advantages and disadvantages
Blix vika+	350W rear hub motor Frame folds horizontally Folds the head tube and pedals Weights 21.8kg Range of 55km Costs 1475 €			Easy to fold Simplistic design Not very compact Hard to transport when folded
GiFly	250W rear hub motor Frame folds vertically Wheels in parallel when folded Range of 60km Costs 2050 €			Fast and easy to fold Trolley Low moving parts Not very compact Practical
Mando Footlose	250W rear hub motor Hybrid Frame folds vertically Folds head tube Weights 21.7kg Range of 30 to 45km Costs 3580 €			Fast and easy to fold Trolley Low moving parts Not very compact Practical
Go cycle	250W front hub motor Folds the chainstay vertically Folds the head tube and seat To fold completely it's necessary to remove the wheels Weights 16.3kg Range of 80km Costs 4500 €			Practical Few moving parts Hard to transport when folded
Jivr Bike	350W front hub motor Folds the chainstay vertically Front frame folds horizontally Chainless Weights 16kg Range of 30km Costs 2099 €			Very compact Several moving parts Hard to transport when folded
Weelin	250W central motor Folds the chainstay vertically Folds the head tube, seat and pedalls Weights 12.5kg Costs 1500 €			Very compact Several moving parts Hard to transport when folded

Chapter 3

Electrical bicycle project

To build a state of the art electrical bicycle, a concept design and with features that would be able to directly compete with the concurrence and the current innovations that the market is presenting nowadays is not an easy task. It requires a big monetary investment and a considerable amount of time, more than the available for this type of project. Also, it would require the access to state of the art materials, building methods and machinery, as well as specialized and skilled manpower. Thus, and once that we will not be able to overcome this obstacles or at least some of them, we will be conceiving two different designs.

The first design, from a concept projected from scratch and with the objective of creating an unique electrically assisted power cycle. This one was projected without paying close attention to the obstacles referred before, this is, considering a larger delivery limit, as well as enough financial investments and access to building methods, machinery and specialized manpower. Even so, we've tried to use relatively common and of easy access materials and building methods. With this, our intention was to design a electrically assisted bicycle that would be able to compete with the current market but more importantly that would be able to fulfill all the needs and requirements that we've assumed necessary for a bicycle designed for this specific application. It is important to note that this design presents just a base case, it still needs to be tested and refined in order to achieve a good and reliable final product.

Once that we wouldn't be able to build a prototype suchlike, we will have to consider an alternative design within our range of possibilities. For this design, we will try to maintain the main features and the best characteristics of the first one. It should be as close as possible to the one we've conceived from scratch but within our chances, in order to build a fully working prototype. This prototype is intended to be built using other bicycle parts and adapt them to obtain a testable and usable prototype.

In this section, after defining the main requirements for the project, we will be presenting both the designs, defining their main features and choices that we had to make for each of the components, as well as the reasons that made us took such decisions. Also, we will be evaluating the main differences between both designs and what practical consequences these changes would have in the use of the bicycle.

3.1 Project requirements

Projecting a vehicle has several factors inherent to it, even more, if the vehicle is designed for a specific purpose and application as it is in this work. Therefore, it's important to define some base requirements, despite some do have more importance than others. We will be defining its main requirements and objectives that the vehicle has to be able to show or to achieve during its normal use:

- Autonomy - It is a very important factor in any kind of vehicle, but especially in an electrical one, as it limits the range and reduces the possibilities for the rider. Also, recharging the battery is not an instantaneous process, and it is necessary to use the battery charger and a power outlet, in other words, if the battery fully discharges during the path, it can not be charged without specific conditions and instruments. We've considered that the bicycle has a specific purpose of concept, two daily routes and a constant route, house-work-house or house-public transport-work and returning home again. A census analysis made in 2011 and covering the regions of England and Wales concluded that residents living and working in London had an average daily distance to cover of 11 km, traveling to work and returning back home[29]. With this in mind, we defined a minimal autonomy of 25 km, considering that it would be enough for the daily routine or to be able to cover more distance in case of need. This autonomy can be easily enlarged by having two sets of batteries, one substitute to replace the other as it discharges, or by using a bigger battery with higher capacity, but bigger capacities lead to bigger and heavier batteries which collides to the weight requirement.

- Weight - It is an important requirement and one that it's commonly used to characterize and evaluate bicycles. The bicycle has of course to be as light as possible, but we have to keep a realistic mind, once we are limited by the building processes available and building materials we won't be able to build a really light bicycle compared to the today's market. Nevertheless, the weight will be an ongoing concern during all the project and will play an important role in every choice that we will have to make.

- Ease of transportation - The bicycle, with all its components will be quite heavy, possibly too heavy to be easily transported in weight for long paths. Thus should find a solution so that it can be easily transported when folded, compensating its weight. The desired way of doing it is by folding the bicycle in a way so that it can be transported folded, in a compact shape, with both wheels on the ground and in a balanced and friendly user way.

- Practical to fold - The folding system is a crucial component of a folding bicycle. It has to be safe and strong, to keep the bicycle rigid and stiff, but also has to be practical and easy to lock and unlock. It must allow a practical and fast way of folding and unfolding the bicycle, but also it must guarantee that when it is locked it will not unlock by accident or without the intention of doing it, as it can lead to dangerous situations for the rider.

- Safe - As in every vehicle, the safety is an important and crucial requirement, all the project must be designed and conceived taking into account the rider safety and the safety of any bystanders, as the bicycle is designed to be used in public environments.

3.2 Conceived design

3.2.1 Component and material selection

Motor

The motor is a crucial component in an electrical bicycle, therefore its choice must be made carefully and thoughtfully. To choose the most suitable motor we must take into account the bicycle components as the frame, wheel size and gear system. Equally or even more important for the motor selection is the purpose that the bicycle is supposed to be applied in. For instance, a bicycle designed to be used in a metropolis environment as a mean of transportation has very different set of characteristics and features compared to a bicycle designed to be used for weekend rides or to ride in off-road terrains.

As explained in section 2.5.1, there are three types of motors available to apply in bicycles: mid-drive, hub and friction-drive motors. Each one of the three presents their own advantages and disadvantages and are better suited for different purposes and environments.

From the three given possibilities, the friction-drive motors are the first to be excluded, as they present considerable disadvantages comparing to the others. Despite its simplicity, whether the motor or the ease on transforming a common bicycle in an electrical one, they are more likely to fail than the other types of motors considered. As explained in the previous chapter, the power transmission is made through friction between the rear tire and motor drive. The friction coefficient between these components has a major impact on the motor performance and output obtained. This friction coefficient may vary widely and can easily be reduced or even became nonexistent, making the motor drive slip on the tire, making the motor fail its purpose. Such situations may reveal to be problematic to the bicycle use and may occur commonly and due to several different reasons: with wet weather, due to the tire tracks, with the vibration caused by uneven terrain or even when trying to departure in a steep hill, a situation that requires high torque rates, such forces can easily overcome the friction needed to propel the bicycle.

The choice of the motor type remains now between mid-drive and hub motors. Their are both considered good options and to be the best alternatives for the purpose in question. Each one present its own advantages and disadvantages and in order to be able to contemplate all the criteria that affects this choice we will be appealing to the Pugh Method. With this, it is expected that we will be able to do a thoughtful and justified choice between both alternatives.

First it's important to define the criteria that is meant to influence the motor choice, as well as the weight and importance that each of the criteria presents according to the bicycle's purpose and range of applications. For this study, we've considered 9 different criteria, each one rated from 1 to 5 (1 being less important and 5 the most important), according to the importance that it presents on choosing the best alternative for the motor.

- Weight - Weight, is an important factor in any case when the subject is a bicycle. The weight of the

Table 3.1: Decision analysis for the motor choice.

Criteria	Weight (5)	Mass center (4)	Performance (4)	Driving control (4)	Cost (4)	Wear and tear (3)	Climbing capacity (3)	Exposure (3)	Ease on transformation (1)	TOTAL
Hub motor	5	1	2	2	5	4	2	4	5	100
Mid-drive motor	4	5	4	4	3	2	5	3	3	117

motor in an electrical bicycle has a big influence on the total weight of the bicycle, in general they represent 25% or even more of the total weight of the bicycle. Thereby this factor was determined to the one with major importance within the others for the motor choice. For the purpose that this bicycle is meant to do in particular, it can reveal to have even a bigger importance, as it will most likely have to be carried in weight at some part of the path. Regarding the classification attributed, it was 5 to hub motors and 4 to mid-drive motors. Despite both motor types present similar weight variations in general, hub motors usually tend to be lighter. Even though it depends heavily on the motor itself and which of the manufacturers produced it. Therefore, the weight variation doesn't depend much in the motor type but mostly in the motor itself.

- Mass center - This criterion focuses in the influence that the mounting position of the motor has in the bicycle mass center. As referred before, the motor usually represents 25% of all the bicycle weight, therefore it has a strong influence on the bicycle mass distribution. The localization of the mass center of the bicycle or the rider and the bicycle, considering it as a whole, plays an important role on how the bicycle handles and behaves when riding it. Thus is also one very important factor for the motor choice. Hub motors are mounted in the wheel hubs, this takes the mass distribution closer either to the front or the rear wheel, depending on which wheel it is mounted. Considering that our objective, concerning the mass distribution, is to have the mass center as low and centered in the bicycle as possible, this is not the best option, specially taking in account the mid-drive alternative. This type of motor, as it was explained earlier, it is mounted near or in the crankset, which is considered to be the best position to be placed, once it lowers and centers the mass center. Given this, we've attributed 1 to the hub motor and 5 for the mid-drive alternative.

- Performance - Regarding the performance, mid drive motors are able to achieve better results and with higher toques. This is mainly because they can transmit more power, as it is directly transmitted to the crank and chain, allowing them to work with the bicycle own gear system. By contrast, hub motors are mounted in the wheel center, compelling the motor to do more effort to obtain the same output. Hub motors aren't able to achieve the same torques that mid-drive systems do, also because if they did, and considering a front hub motor option, a motor with big torque rates would make the front wheel spin and lose traction. Given this, we've attributed 2 to hub motors and 4 to the mid-drive alternative.

- Driving control - This criteria focuses on the influence that the different motors have on the handling characteristics of the bicycle. With a mid-drive motor, the bicycle will be operated virtually the same way that a common bicycle would be, keeping it simple and near unchanged. This would make the bicycle more user-friendly and not requiring any extra skill than knowing how to ride a common bicycle. Using a hub motor can change the bicycle a bit, using a motor in the front wheel would make both the wheels driven, this could lead to big changes in the way that the bicycle feels, moves and rides, therefore it would require more attention and skill by the rider. This option would thus be less user-friendly and require more from the rider, therefore, we've attributed 3 to hub motors and 4 to the mid-drive alternative.

- Cost - Regarding the costs, hub motors are relatively more cheap than mid-drive motors. The different cost rates are mainly because hub motors are simpler and it is a type of motors that nowadays is widely available on the market. This motors, as explained in the previous chapter appeared with the first electrical bicycles, around 1900, this makes them much easier to access nowadays and with more affordable prices, comparing to mid-drive motors. Hub motors were classified with a 5 and mid-drive motors with a 3.

- Wear and tear - This is a criterion that despite showing no influence at first in the bicycle, after some use it can reveal to be problematic and generate some extra costs. Of course there are measures to prevent or reduce as much as possible the wear and tear, a constant lubrication and inspection on the components that suffer major wear and tear can prevent or predict accidents. Hub motors have all they components confined inside the hub and few moving parts, this results in virtually no tear either on the motor or the bicycle components. Mid drive motors have more moving parts and as known, they transmit their power through the bicycle components, as the crank, chain and chainrings, therefore this system requires more maintenance and leads to higher wears on some of the bicycle components. Being so, we attributed 4 to the hub motor and 2 to the mid-drive motor alternative.

- Climbing capacity - Climbing capacity defines the capability for the motor to overcome steep terrain. It can be an important feature in this type on bicycle, depending on the city that it will be used in. Hub motors are known by struggling or even failing in steep hills, revealing low capacity to overcame such obstacles. This is mainly because this type of motors are made to operate at a fixed ratio, making them more trustworthy to operate in flat terrains and with some speed. On the contrary, mid-drive motors can easily overcame steeps hills, being able to produce higher torques. This added up to the fact that these work and take advantage of the bicycle own gear system, makes them the best choice in what matters to performance in uneven terrains. Given this, we've attributed 2 to hub motors and a 5 to the mid-drive alternative.

- Exposure - This criterion takes into account the impact that the motor has on the bicycle aesthetics. Hub motors, can easily go unnoticed, as they are disguised in the center of the wheel. As for the mid-drive alternative, it doesn't go unnoticed so easily, never the less, and depending from model to model they can as well go unnoticed. Being so, we've attributed 4 to hub motors and 3 to the mid-drive alternative.

- Ease of transformation - This factor measures the easiness that each of the motors types presents to be mounted in the bicycle. Hub motors are usually easier to mount, as you simply need to change the wheel and little more. Regarding mid-drive motors this can require more work and depending on the model, some even require a proper frame design, adapted to the motor shape and mountings. Even so, there are mid-drive motors in the market that are relatively simple to mount and that allow transforming almost any common bicycle into an electrical one. Given this, we've attributed 5 to hub motors and 3 to mid-drive motors.

After this extensive analysis and taking into account the results of the decision method, 100 for hub motors and 117 for mid-drive motors, we can conclude that the best alternative for the motor would be a mid-drive system. This doesn't mean that hub-motors are bad systems and don't make a good solution to electrically propel a bicycle, on the contrary, they are a good solution and it is a system that is ”tried and true”. Even so, for this specific range of applications and taking in care the criteria selected in the decision method, mid-drive motors should be a better choice to fulfill our requirements.

Now, knowing that we are going to use a mid drive motor, the choice grounds on which of the various motors available in the market we would use. They can mainly be divided in two groups, one that requires a proper frame, matching the motor fixation points and contour and another that suits most of the bicycle models, mounted in the bottom bracket and that allows to transform almost any common bicycle into an electrically assisted bicycle. Being that the better and more innovative motors available in the market are inserted in the first group and that creating the right fits and mountings would not be a problem since we would build the frame, we've opted for this alternative. Some of the manufacturers considered for the motor were the ”Bosch ebike system”, ”Shimano Steps” or ”Yamaha ebike system”. These are renowned brands and theirs products seem to be between the best among the market offers. All the three systems considered have very efficient systems and use three types of sensors in the motor: cadence, speed and torque. These help to create an easier and more intuitive interface between rider and bicycle, generating a very user-friendly product.

(a) Bosch (b) Yamaha (c) Shimano

Figure 3.1: Drive units

Battery

Regarding the battery and once the frame would be made out from scratch, our intention would also be to build the battery pack. This would allow us to customize the battery pack shape and adapt it to better suit the frame and, as explained earlier in the chapter, the battery pack is supposed to be inserted in the inside of the frame, this would make it go unnoticed in the assembly. All the battery wiring and connections to the motor would also be placed inside the frame, disguising it and making it non visible from the outside. One thing that is common to all batteries is that more power and more storage capacity results in more weight and volume. Therefore, we have to find the best suited solution, in order to keep the bicycle with enough range and light enough to serve the purpose that it is meant to do.

First, the choice relies between the three major types presented: Li-ion, Nickel or Lead acid batteries.

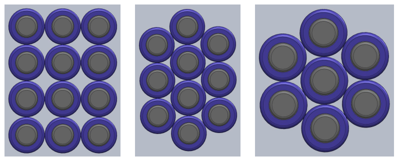
Lead acid batteries, being the oldest type among the others, is also the type that presents less advantages and more drawbacks. They are considerable more heavy and large than whether lithium or nickel batteries, and as said before, weight and volume are major factors in this project requirements. They also present life expectancy's much more reduced, as they usually only allow up to 500 charge cycles. With respect to the power transmission, lead acid batteries have less efficiency, they present energy losses whether when charging or discharging, contrarily to lithium batteries with efficiencies close to 100%. Another major drawback in the use of lead-acid batteries is that their voltage throughout the discharge cycle drops consistently, this not only effects the riding conditions, as the bicycle loses power as the battery is discharging but can also lead to problems with the other electrical components, as the motor.

With respect to the choice between nickel and lithium batteries, the primary difference between them lies in terms of energy storage: nickel has a lower energy density than lithium, resulting in a larger and heavier nickel battery compared to a lithium-ion battery with the same power and energy storage capacities. Lithium batteries present several advantages when compared to nickel batteries. Lithium batteries have longer life expectancy's, are more efficient, have higher voltages outputs, recharging times are considerable smaller (requiring around up to 70% less time to fully recharge, depending on the batteries). In addiction, nickel batteries require being totally discharged before charged, otherwise they can experience the memory effect: after being repeatedly recharged when only partially discharged, batteries gradually lose their maximum energy capacity. Still, lithium batteries also have disadvantages, they are more expensive than the nickel chemistry's, require an extra component, a protective circuit, also known as BMS (battery management system) as explained in the previous chapter. In regard to the environmental impact, where as lithium batteries are safe and have non hazardous materials, the same can not be said about the nickel chemistry's, in particular the ($NiCd$), these batteries contain between 6 to 18% of cadmium, a toxic heavy metal. These require thus special care during battery disposal and is some countries, as the United States, part of the battery price is a fee for its proper disposal at the end of its service lifetime.

After this analysis, and taking in account both the advantages and disadvantages of the three battery types considered, the choice is quite obvious: lithium batteries are better suited for the kind purpose that these are meant to do. Yet, lithium batteries have several variations and material combinations, thus we have to choose the most appropriated chemistry and format for the battery pack. Taking in consideration the attributes and formats available of each of the lithium batteries chemistry's, we have chosen the Lithium Manganese Oxide ($LiMn_2O_4$). This is the most commonly used lithium battery chemistry in the electric bicycle industry. It is a battery type that is widely available in the market and presents good characteristics in general, as its size, weight and cost. This chemistry is also one of the safest from among the other lithium battery alternatives. Regarding the battery format, we opted for the 18650. It is a battery design that is well known for the benefits that it presents, as the low cost, the multiple applications that it suits, the chance from buying from established manufacturers and its longevity. Manufacturers have developed this design in order to create a multi-purpose and reliable battery. 18650 batteries attributes can vary depending on both the manufacturer specifications or model type, even so, their main features can be generalized. They became to be a durable and safe option, this led to some well known and trustworthy manufacturers such as Sony and Panasonic to develop and produce the lithium-charged battery. This led to higher production rates and lower prices. As researchers find additional ways to use the 18650, the production rates of the battery continue to increase and the prices to get lower, making it very popular among consumers of electronics. The cylindrical shape and battery design prevents harmful electrode liquid leaks. 18650 got its denomination from its size, which is 18mm of diameter and 65mm height.

Figure 3.2: 18650 battery

Batteries or battery packs are often described by two factors, voltage (V) and capacity (Ah) or by the multiplication of both (Wh), which is a way to measure the energy capacity of a battery pack. Typically, 18650 batteries have a power of 3.7 volts and a capacity of 2.6 Ah. The motor in subject was designed to operate at 36V, so to reach the intended voltage of the motor, we have to connect ten 18650 cells in series (10s): $10 \times 3.7V = 37V$. With respect to the battery pack capacity, this will be the feature that will mainly define the range of the bicycle, even though, it can not be calculated accurately. It depends not only on the motor voltage and the battery capacity but in whole range of factors as the bicycle and rider weight, the level of the assistance given by the motor, the inclinations of the terrain, the velocity, the efficiency of the motor or even if the route is made at a steady pace or in the typical stop-and-go in the metropolis environment. We will calculate and try to predict the range that a given battery pack presents, even though it will not be very precise. Let's consider a battery pack with the batteries in series of 10 and 3 connected in parallel (10s3p): $3 \times 2.9Ah = 8.7Ah$. $37 \times 8.7Ah = 321.9Wh$ that is to say that a 10s3p disposal generates a 321.9Wh battery pack. Taking in acount that a 250W motor will burn 250Wh in one hour, a 321Wh battery pack will last for 1.288 hours ($321.9Wh \div 250w = 1.288h$). Considering a medium velocity of 20km/h, it results in a range of approximately 26km ($20km/h \times 1.288 = 25.76km$). It is important to emphasize once again that this is just a prediction and can and will fluctuate quite markedly according to the several factors mentioned before. Comparing the range values that we've obtained with the values that are often expressed by manufacturers with similar bicycle designs and battery capacities, ours are much lower, revealing that they were made conservatively and should represent one of the worst case scenarios possible. Once that we have already established the amount of 18650 batteries needed to build the battery pack to fulfill the requirements of the project, we now have to choose the best way to accommodate them inside the frame. It were considered three different options for the battery pack shape and batteries alignment:



(a) Rectangular alignment (b) Alternative rectangular alignment (c) Circular alignment

Figure 3.3: Battery pack

Our choice was the option presented on the second figure, essentially because it is the most compact alternative from the three and by creating three equal groups of batteries, as presented in the figure, we would obtain a very compact pack and as small as possible battery pack. The frame was therefore designed in a rectangular profile and with the dimensions needed to fit the pack in the inside.

Nowadays there are already several alternatives and companies that make and sell battery packs similar to the one described and that we intend to build, but by buying a already made pack we wouldn't be able to shape it at our desire, and therefore put inside the frame and make it unnoticed.

Wheels

As referred before, wheels, and the wheel size has a big influence in the bicycle. They have a big impact on how the bicycle handles, rides and how comfortable and smooth the bicycle feels. Once one of the main objectives is to reduce the volume occupied by the bicycle as much as possible, we should opt to chose a small wheel size. Even though, small wheels reduce the bicycle maneuverability and make it hard or dangerous to overcome obstacles as kerbs or potholes in the roads. Thereby we've chosen 20" to be the best suited size for a bicycle with this type of applications. Its small size is enough to keep the bicycle compact, but are still big enough to be safe and easily overcome most of the obstacles that a metropolis environment presents.

Gear system

Regarding the gear system to be used in the bicycle, we first must choose which of the systems are better suited for this kind application. There are four alternatives, as it was presented in section 2.5.4, fixed-gear, single-speed, multi-speed and internal gearing. Both fixed and single-speed gear systems are the first to be discarded. Despite their best asset being its simplicity and low weight, they are not the best choices for this type of application, as they only allow one fixed gear ratio. Given that we've chosen a mid-drive motor, and that one of the main advantages of choosing a mid-drive motor is that the motor propels the crank, allowing it to work with the bicycle own gears, it wouldn't make sense to use a gear system with a fixed gear ratio.

The choice lies then between multi-speed and internal gearing system. With mind that the bicycle is designed to be used in a metropolis environment, the smart choice must be an internal gear system.

Being that its main advantage is the fact that it allows the gear ratio change even with the bicycle stopped. Imagine the following scenario for instance, you arrive at a stop light or you have to stop suddenly because of traffic or some kind of obstacle, which should happen frequently in urban areas: if you were using a multi-speed gear system you would have to start shifting gears before you actually stopped, otherwise you would have a hard time starting to ride the bicycle in a high gear. On the contrary, using a internal gear system you wouldn't have to care with any of these problems, as you could just reduce the gear after you had stopped. Another feature that makes internal gear systems a better choice that multi-speed is that its mechanism is all inserted inside the wheel hub, requiring virtually no maintenance. Regarding the aesthetics, internal gears system are also ahead, their mechanism is all inserted inside the wheel hub, making it easily unnoticed, even more comparing with a multi-speed system. Once the multi-speed system has all its components in the exterior it also makes it occupy more volume than internal gears, being a foldable bicycle, the volume that it occupies is one of the requirements that we want to reduce as much as possible.

Concluding, the alternative that is better suited for application in an internal gear system. Internal gear systems are available with between 2 to 14 speeds. For the purpose that this bicycle in meant to do, we've considered that a 3-speed system should be enough. The 3 different gear ratio alternatives should be enough to fulfill all our needs. Off course that more gear ratios would allow more control and possibilities, however a system with more speeds is also heavier, one feature that should be as reduced as possible.

3.2.2 Model description

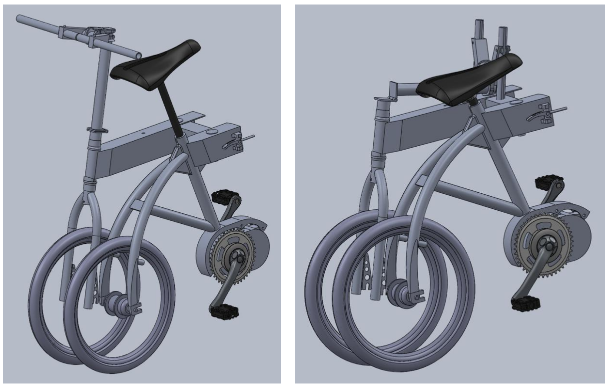
In this model, despite all its components are represented in the 3D model, only the frame was modeled in the CAD program and intended to be built. This frame was thought and projected with the intention of fulfilling our project requirements and as said before, to create a viable and better solution as a mean of transportation in metropolis environments, mostly directed to the "last mile" concept.

(a) (b)

Figure 3.4: Conceived design

Since the frame was the only part designed to be built and conceived from scratch, it was engineered taking in account the standard measures and usual components in bicycles. Thereby making easy to find and adapt the remaining components to the frame, components as the wheels, seat and seat post, headset, fork, stem and braking system.

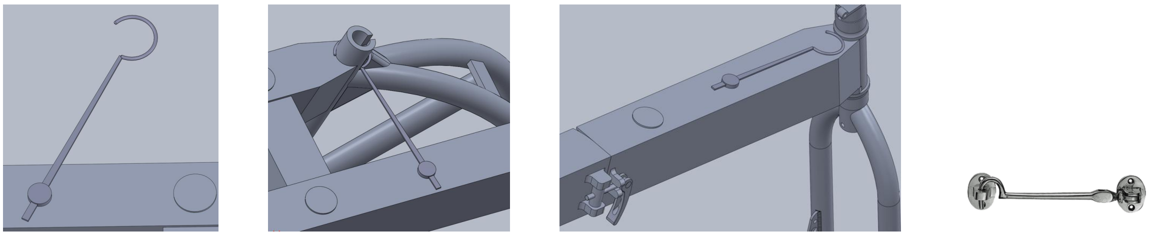
It has two folding positions, one allowing an easy and practical way of transporting the bicycle and the other, to achieve a smaller and more compact assembly, allowing it to be storage in a small place.



(a) (b)

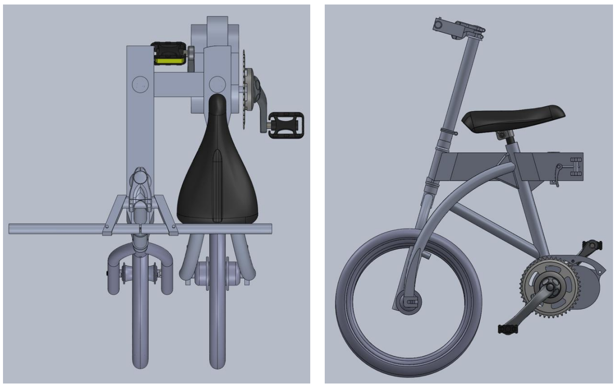
Figure 3.5: Folding positions

The frame is all made out of an aluminum alloy and folds horizontally along two hinges along side the top tube, this folding position compacts the bicycle to a considerable smaller size and brings the front wheel to an aligned position with the rear wheel, creating a structure similar to a trolley. This folded position creates an easy and practical way of transporting the folded bicycle, by pulling the handlebar and transporting it similarly to a trolley. We've also designed a system capable of fixating the bicycle in the folding position, Keeping the bicycle as compact as it allows and easing the transport process when the bicycle is in the folding position. The system is quite simple, it was thought that so way to keep it light weigh, small and with low production costs. Even though, this is a component that should be revised and tested in the first prototype of the model. Using the virtual model this system can not be truly tested. To know how it will behave and if it will play its role, it has to be tested and tried. In the design we've sketched this system to a shape similar to a wire hook, it rotates and clamps the seat tube above the frame. In the prototype this alternative should be tested in different materials (steel, plastic, composites) as well as possible other alternatives that may create a better and more suitable options. The system envisaged is very similar to components used to hold doors, called ”door catches” or to components with similar uses. In the market we weren't able to find any bicycle with a similar folding method as this one, that has a system with this function, of keeping the bicycle stable in the folding position.



(a) (b) (c) (d) Example of a door catches

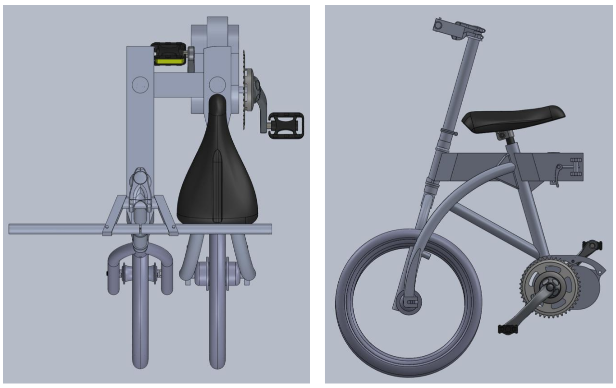
Figure 3.6: Locking system for the folded position



(a) (b)

Figure 3.7: Folding position for transport

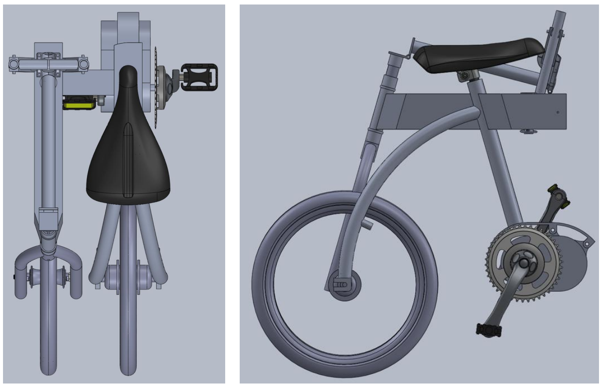
The dimensions of this first folding position is: 1m high, 60cm of widh and a length of 77cm. Regarding the material, we've considered an aluminium 2018 alloy with an yield strength of 317,1 MPa, a tensile strength of 420,5 MPa and a density of 2800 kg/m^3. The frame and handlebar set weights about 6 kg. If we consider the weight of the total assembly, including motor, battery and all the other components, the expected weight should be around the 15 kg.



(a) (b)

Figure 3.8: Folding position for transport

To achieve the fully folded position are required three more steps, folding the handlebar column down to near the top tube of the frame, retracting the seat and folding the handlebar bar. This leaves the assembly with the following dimensions: 75cm high, 40cm of widh and a length of 77cm.



(a) (b)

Figure 3.9: Storage folding position

Regarding the steering system, we've considered the use of two folds, one lowering the steering column and bringing it to near the frame and the use of a foldable handlebar. An alternative would be to use a system with just one fold. This alternative would bring the handlebar assembly together and obliquely to the frame, placing it alongside the front wheel (such as the one used in the prototype). Both options are widely available in the market and their components are common and easy to acquire.

The top tube, was dimensioned taking in account the battery pack size that we've presented, that way it can be easily fitted into the inside of the frame, making it go unnoticed and protected from external threats. The pins of the hinge are easily removed, creating access to the battery or to disassemble the bicycle.

Concerning the electrical connections, they would be accommodated inside the frame, connecting battery, motor and controls in the handle bar. This way the wires would only be visible between the front part of the frame and the handlebar.

The system responsible for locking the folded frame in the riding position uses a quick release skewer, this allows the frame to be easily secured and to do it in a very practical, fast and safe way. It is a very simple and vulgar system, in other words, a light and compact system and that in case of need, easy to replace.

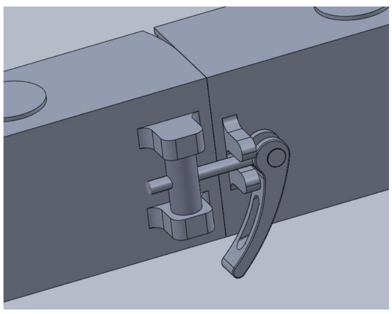


Figure 3.10: Locking system

3.2.3 Cost estimation

In this section we will predict the cost of production that this specific bicycle would have. However it can not be precisely predicted as some costs, such as building processes, manpower, among others can not be estimated with precision. Even so we will try to be as precise as possible and conservative with the unpredictable costs.

The production costs of this model can be divided in three groups: raw material, cost of manpower and costs of the components. Regarding the raw material to build the frame, and since the projected frame used mainly standard size materials, we can make an estimation on the costs for the raw-material. For the pipes used for the seat tube, seatstays and chainstays 150 €, the rectangular tube for the top tube 100 € and the plate for the motor support and the reinforcements in the frame 40 €. The manpower costs are difficult to predict with precision, the time for the frame to be built can't be anticipated as it may vary widely, depending on possible and probable building problems that may occur during the process. Predicting that it can be built in 7 working days, 56 hours of work and a medium manpower cost of 20 €/per hour, the total manpower costs would be around 1120 €. In terms of the components these include:

Table 3.2: Component costs

Component	**Price**
Motor	1500 up to 2000 €
Battery pack	160 €
Gear system	60 €
Folding pedals	15 €
Braking system	50 €
Wheels and rims	40 €
Seat	10 €
Chain	10 €
Headset	20 €
Foldable handlebar	25 €
Stem	10 €
TOTAL	1900 €

Thereby, the total cost for building and assembling the bicycle, considering generic prices for the components, will be around 3310 €.

3.3 Prototype design

In this section we will be describing the model that we've designed to be built and to create a fully working prototype. Describing and justifying what choices we had to made regarding the model components and describing its main features and characteristics. Since we had to depart from a frame already built, we opted to use a frame and components from an old bicycle. We've tried to maintain its basic aesthetics and classic appearance. This way we intend to build a cheap prototype that keeps its classical and old appearance but restored and improved. This way the final result will create a bridge between new and old technologies in order to achieve a better outcome.

3.3.1 Component and material selection

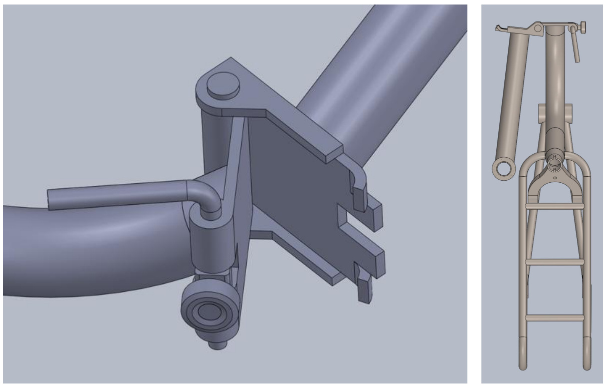
Frame

Due to our project limitations, as referred before, we will not be able to build a fully working prototype as the one we've modeled and presented early. Therefore, in this section it will be presented an alternative design, considering more viable and realistic alternative choices taking in account our limitations. Nevertheless, this prototype will be engineered in order to try to maintain the conceived design main features and advantages. It is intended to be built from other bicycle components and adapt them to fulfill our needs and meet the project requirements.

Since we will have to stem from other bicycle components we've opted to use old bicycle components, lowering the costs and creating a product with an antiquate aspect but even so modernized and improved with the actual technology.

Figure 3.11: Original bicycle

The frame chosen is from an old foldable bicycle, from the Portuguese manufacturer Órbita. It is made out of a steel alloy and has one hinge roughly in the middle of the frame which allows the bicycle to fold to a more compact assembly. The locking mechanism of the hinge works similarly to a quick release skewer, allowing an easy, practical and safe lock. The frame alone weights around 10 kg and for the structural analysis we've considered the material to be a steel alloy with an yield strength of 620 MPa, a tensile strength of 723,8 MPa and a density of 7700 kg/m^3.



(a) Hinge (b) Folded frame

Figure 3.12: Folding system

Motor

Regarding the motor, the choice remains to be a mid-drive motor. But here, instead of using a motor that requires an adapted frame with special mountings, and since we are building the bicycle from an already built frame, we will opt to use a mid-drive motor to be mounted in the bottom bracket. This way it can be easily fitted in the frame, requiring little alterations to it.

Figure 3.13: Selected motor

The motor chosen was from the Bafang manufacturer, a relatively reputable manufacturer among the e-bike market. It is the ”Bafang BBS01B”, it weights 3,7 kg, has two types of sensors: speed and cadence. It uses 36V and 250W to power the bicycle. It can produce torques higher than 80 N and efficiency higher than 80%. The motor has a built-in controller and PAS and it comes along with crank-arms, chain wheel, speed sensor to be mounted in the rear wheel, brake levers that are connected to the motor and cut the power as the levers are actuated, a thumb throttle that creates the option to manage the motor output and in case of need to be used for an ”extra push”. Also comes along with a LCD display to be mounted on the handlebar and that allows to manage the level of assistance given by the motor, having three assistance levels available. The LCD display also shows various informations as the instantaneous vehicle speed, the battery charge and the distance traveled. This motor has an extra assistance mode, this one is to be used when the rider is dismounted of the bicycle and walking by foot, carrying and pushing the bicycle through the handlebar. In this mode, the motor gives a lithe assistance and allows the bicycle to be more easily transported and with less effort.

Figure 3.14: Handlebar assembly

Battery

With respect to the battery pack, we've opted to buy a battery pack already built. This decision was made due to several reasons: the limitations regarding building processes and machinery, building a battery pack as we described in the conceived design requires a spot welder machine to connect the batteries, a battery management system as well as skills and knowledge to build a viable product. Also, another main advantage of building a battery pack was that that way we could manage its dimensions and fit it inside the frame. Since we are not building the frame and the chosen frame doesn't has capacity to store it internally, we wouldn't take much advantage on building a battery pack. The battery pack was thus chosen taking in account our project requirements, mostly the range and weight.

(a) Battery pack

(b) Battery pack characteristics

Figure 3.15: Selected battery pack

The dimensions are 24.5 x 7 x 10 cm and weights 2.8 kg. The battery pack chosen comes along with holder which is used to fix the battery to a tubular support in the bicycle frame. The holder encloses the frame tube and is bolted around it. The battery can be easily removed from the holder by sliding it from it. The holder also has a key lock that secures that the battery is firmly fixed and reduces the chances of being stolen.

Regard its capacity, 36V and 9Ah generate 324 Wh ($36V \times 9Ah = 324Wh$) . Considering the same calculation method used to predict the battery pack range: $324Wh \div 250W \simeq 1.3h$, this is, the motor will be able to run for 1,3 hours in one charge. Considering a medium velocity of 20km/h, the expected range will be around 26 km ($20km/h \times 1.3 = 26km$). As said before, this method to calculate the range is conservative and represents an approximation, as the range is affected by several other factors than the battery pack capacity.

(a) Holder that secures the battery (b) Battery

Figure 3.16: Battery pack localization

Considering the allocation of the electrical components in the bicycle, some components have the freedom to be mounted in almost any part of the bicycle as it is the case of the battery. Even though, components as the motor, the LCD display or the throttle have specific places to be mounted and can only perform its function in these places. To choose the place to fix the battery pack we took in attention a few factors: its influence on the mass center, the ease on removing and mounting the battery, the proximity to the motor and the ease to make the electrical connections. The factor that we've considered to be of major importance is the influence of the battery on the mass center, as the battery is a component considerable heavy, its localization along the frame will have a strong influence in the bicycle mass center and therefore in the bicycle handling characteristics. The alternatives to allocate the battery were: the grid behind the seat or above the rear wheel, the seat tube and in the top tube, ahead of the hinge that folds the frame. Taking in account the factors mentioned before, the best alternative was considered to be the seat tube. It can be mounted in a lower position, compared to the other alternatives, which leads to a lower mass center of the assembly. It requires less wire length, as it is close to the motor, leading to a safer connection and reducing the complexity of the assembly. Removing the battery from the holder would be an easy task in any of the positions considered as the holder allows the battery to be removed simply just by sliding it to the side.

Handlebar

The handlebar in the original model wasn't foldable, it had the capacity to retrieve into inside of the head tube. This wasn't much effective to achieve a compact design when folded, therefore we will use a handlebar with an hinge that brings the handlebar to the side of the front wheel. This led to a foldable position much more compact and practical to store. The folding system is locked with a quick release skewer, allowing a practical and fast fold of the handlebar. Trying to keep the bicycle original and classic look, we looked for to acquire a handle bar with similar appearance to the original, but better and that could improve the bicycle folding ability.

(a) Handlebar assembly

(b) Folded handlebar

Figure 3.17: Handlebar

The stem (bottom part of the handlebar set) is fixed to the headset through an conical wedge bolt, similar to the one in the figure. It is thigh up from inside the hinge in the folding position, pushing the wedge up and against the inside of the headset, creating a tight fix.

Figure 3.18: Example of a similar stem fixation system

3.3.2 Model description

Most of the bicycle components are from a steel alloy and the handlebar set is from prated steel. The frame alone, like it is represented in the figure below but excluding the wheels and counting with the seat and seat-post, weights roughly 10 kg. Considering the components missing, mainly the battery pack and the motor, the weight of all the bicycle assembly should be around the 20 kg, 2.8 kg just for the battery and 3.8 kg for the motor. Its dimensions in the mounted position are about 1,40 m of length, 1.06 m high and 56 cm of width, being the handlebar the component that drives this dimension.

(a)

(b)

Figure 3.19: Assembly of the model

The folding process is quite easy and is composed by three steps: first the frame is folded, bringing the wheels close together. Then the seat must be lowered as much as it allows and the final step is to fold the handlebar, bringing it down and alongside the front wheel as it can be seen in the figure below. It can be folded in a practical way and it takes little much than thirty seconds to achieve the completely folded position. The folded dimensions of the bicycle are 77 cm high, 86 cm length and 29 cm of width. This creates a compact set for the bicycle, allowing easy and practical storage.

(a) (b)

Figure 3.20: Assembly of the model in folding position

3.3.3 Costs

In this section we will be presenting the costs of production of the prototype. In contrast to the estimated costs for the conceived model, the production costs of the prototype can be resumed to the components price, as the building processes and manpower were made by the author of the thesis.

Table 3.3: Component costs

Component	**Price**
Motor	600 €
Battery	350 €
Bicycle	100 €
Gear system	45 €
Folding pedals	15 €
Braking system	35 €
Wheels	15 €
Seat	20 €
Chain	10 €
Foldable handlebar	40 €
Paint job	75 €
TOTAL	1305 €

Thereby, the total cost for building and assembling the prototype was 1305 €.

3.4 Comparison between the two designs

In this section we will be comparing the two models, evaluating how they meet our project requirements and analyzing its main features and differences between the models.

First we will be analyzing and comparing both models on how they meet the project requirements: weight, autonomy, ease on transportation, practicability on folding and safety. The expected weight of the conceived model is 15 kg while the prototype model is 20 kg which is a substantial difference among the two. This difference is mainly due to the different mass density of the raw materials of the frames, steel and aluminum. Even so, the weight is quite high on both the aluminum and the steel frame, but using this type of common and relatively easy to work materials it can not be significantly lowered. Regarding the autonomy of the models, the capacity of both the batteries is quite similar, 321.9 Wh for the conceived model and 324 Wh for the prototype model. Thus their range should be around the same values but being that the aluminum frame is 5 kg lighter, this should lead to a bigger range to this model. Transporting the bicycle in the folded position is expected to be easier in the first model, being that it allows it to be transported similarly to a trolley. In relation to the prototype, it can also be transported in the same way but more challenging and less practical for the rider. Concerning the folding capacity, both models present practical and fast folding methods to achieve a compact shape. With some practice both models can be folded and unfolded with ease and rapidly. The dimensions of the folded assembly for the conceived and for the prototype model are 75x40x77 cm and 77x29x86 cm, respectively. Thus, there are no very significant differences among the two. Regarding the safety of the models, both frames were structurally analyzed using the finite element method as will be shown further on, and thus their structures are considered to be safe to use. The wheel base in the conceived model is 1 m and in the prototype model 90 cm. This makes the prototype model, a little smaller when it is in the mounted position, this allows it to be more easily transported in this position. It extends the possibility of being easily transported, being that it can not be easily transported in the folding position and that it is to heavy to be transported in weight.

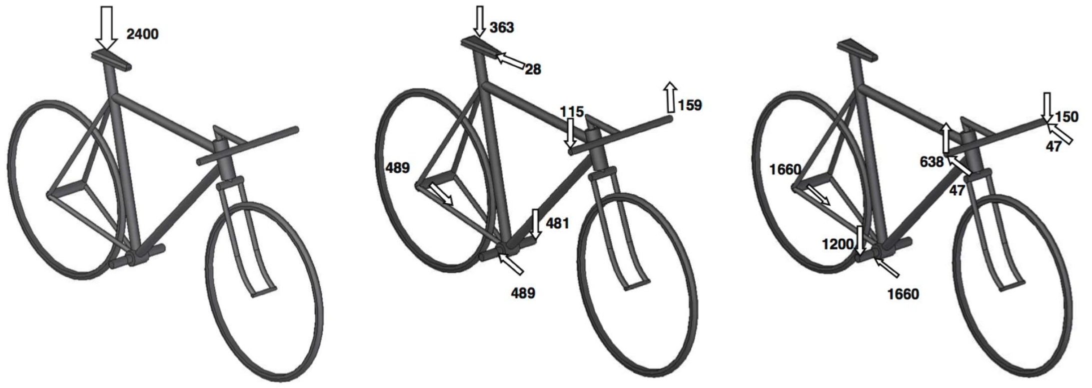
Chapter 4

Structural analysis

4.1 Load cases

Bicycle frames are exposed to very different and varied loading conditions. These conditions vary according to the different driving circumstances, even through a short route, a bicycle frame can experience several different loading conditions. In this section we will be specifying the loads that we will be using to make the structural analysis of the frame, defining them in terms of magnitude, direction and points of application on the frame. A correct loading information has extreme importance on obtaining reliable and credible results. Since there isn't a standard set of loads from the bicycle industry, we will try to use the most realistic and take in consideration previous study in the field. Using them, we hope to correctly define the load cases and implement them in the finite element method and thus obtain reliable results.

We will take in account three different loading cases, these are based on the study made by Maestrelli and Falsini [30] which was based on experimental loads measured by Soden and Adefeye [31]. The first loading case considers a single vertical load on the seat post of 2400N, it represents a situation with the rider in a sitting position, considering road irregularity's. The second load case represents a situation where the rider is seated and pedaling, applying forces both in the seat, the bottom bracket and in the handlebar. Finnally, the third load case simulates a situation where the rider is standing and pushing on the right pedal, this scenario has a great importance in the study of the lateral displacement and stiffness and it should represent the most critical situation in the analysis.



(a) Resting sitting rider (b) Sitting rider pushing left pedal (c) Standing rider pushing right pedal

Figure 4.1: Load cases [30]

4.2 Prototype validation

4.2.1 Mesh and Fixtures

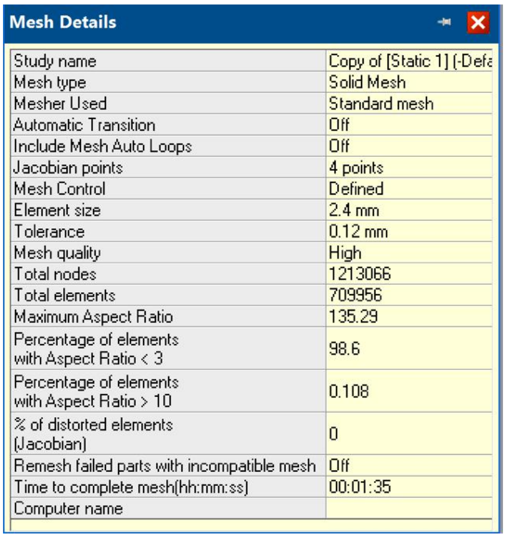
As stated before, the finite element method divides the model into a finite number of elements, this way it expresses the response of each of these elements to the applied forces and constraints. All the elements together form what is called mesh. The parameters and quality of the mesh is very important as it has extreme influence in the results of the method. Thus, to do a proper evaluation of the mesh quality we used several factors: element size, number of nodes, maximum aspect ratio, percentage of elements with aspect ratio lesser than 3, percentage of elements with aspect ratio higher than 10, time to complete mesh and maximum jacobian. Our objective for the mesh to be used is to minimize as much as possible the element size, the maximum aspect ratio, the percentage of elements with aspect ratio higher than 10 and the maximum jacobian. The aspect ratio represents the ratio between the dimensions of the element and should be as close to 1 as possible. The jacobian represents the difference between the element in the mesh and the reference element, thus it should be as small as possible, resulting in a mesh as similar to the real model as possible.

The CAD software (Solidworks) has three options for the mesh type, standard, curvature-based and blended curvature-based mesh. Standard is the more basic and usual mesh type, good for meshing prismatic and flat surfaces. The curvature-base mesh which is better suited for geometry containing round features like holes and fillets and usually does a good job transitioning between rounded detail features and larger prismatic features than the original standard mesh. The blended curvature-based mesh uses a new algorithm that does a better job transitioning between the high quality surface mesh and the less refined sub-surface elements in situations where there is fine detail on the surface. This type of mesh allows you to choose the maximum and the minimum element size, providing a more efficient global mesh and a high-quality surface mesh. Furthermore, edges in areas not of interest do not have excessive mesh detail, simplifying the mesh where it is possible.

Table 4.1: Mesh characteristics

Mesh	1	2	3	4	5
Element size	7	5	3.5	2.4	1,62
Number of nodes	125031	221612	489404	1213066	3517361
Max. aspect ratio	408.35	156.136	411.56	135.29	109.1
aspect ratio $<$ 3(%)	60.9	91.6	97.1	98.6	99.4
aspect ratio $>$ 10(%)	0,523	0,21	0,176	0.108	0.0475
Maximum jacobian	29.63	29.87	20.51	27.04	15.1
Time to mesh (seg)	30	34	50	95	341

Using the standard type, we've started from an element size of 7 mm and then proceeded to its refinement until we've achieved values for the mesh quality that satisfied us, so that we could proceed to the analysis. We've also tried to use the curvature-based and blended-curvature based to compare the results and try to find a mesh with as higher quality as possible within our possibilities. The mesh chosen to do the analysis was the number 4. Despite the fifth mesh presents characteristics relatively better than the fourth, the time that it takes to make the mesh and even more, the time to do the analysis using such mesh, with such small elements, doesn't compensate as the results were very similar to the ones obtained using the fourth mesh.

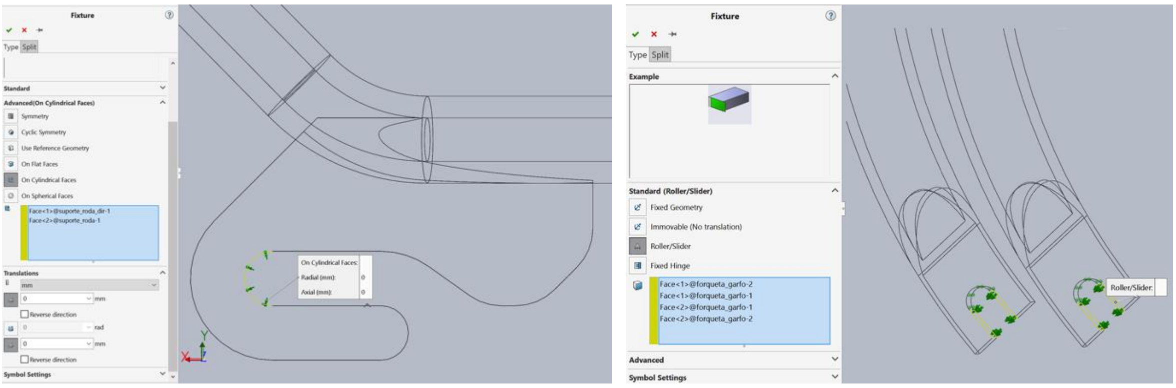


Mesh Details

Study name	Copy of [Static 1] (-Defa
Mesh type	Solid Mesh
Mesher Used	Standard mesh
Automatic Transition	Off
Include Mesh Auto Loops	Off
Jacobian points	4 points
Mesh Control	Defined
Element size	2.4 mm
Tolerance	0.12 mm
Mesh quality	High
Total nodes	1213066
Total elements	709956
Maximum Aspect Ratio	135.29
Percentage of elements with Aspect Ratio < 3	98.6
Percentage of elements with Aspect Ratio > 10	0.108
% of distorted elements (Jacobian)	0
Remesh failed parts with incompatible mesh	Off
Time to complete mesh(hh:mm:ss)	00:01:35
Computer name	

Figure 4.2: Characteristics of the mesh used in the analysis.

Regarding the fixtures, as stated before they are to be applied in the rear and front dropouts. In the rear dropout, we've applied the "advanced fixture" "on cylindrical faces", by fixing it axially and radially the rear dropout was left with one degree of freedom. This way it simulates the reaction that a wheel would have. Concerning the front dropout, we've used the same function "on cylindrical faces" to lock the axle axially. Using the function "roller/slider", we've locked the front dropout, allowing it with freedom to move only in the wheel direction. This set of fixtures was assumed to be the best configuration to simulate the reactions that the wheels would have during the use of the bicycle.



(a) Fixtures applied to the rear dropout (b) Fixtures applied to the front dropout

Figure 4.3: Fixtures applied

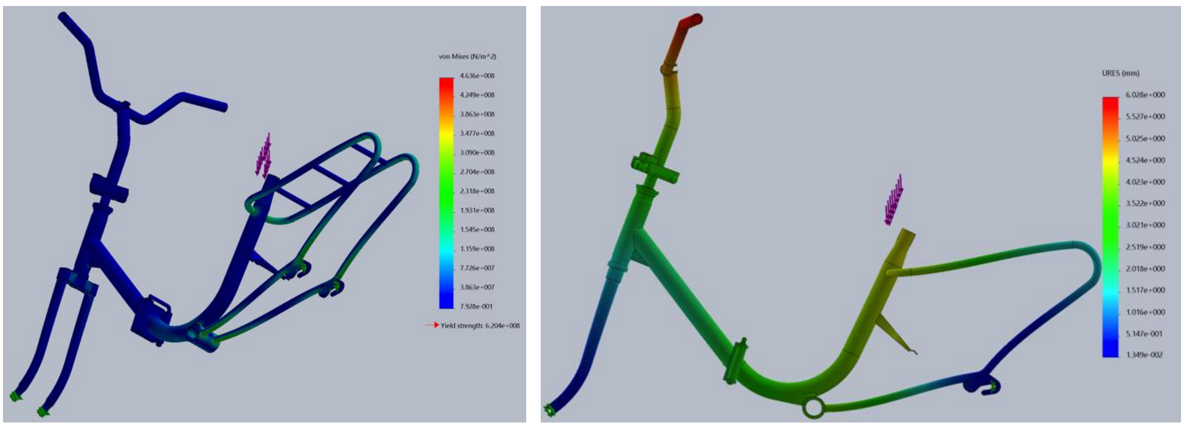
4.2.2 Load case 1

Static analysis

In the first load case, a force of 2400N was applied in the seat, simulating a seated rider through road irregularity's. The results were a maximum tension of 463.6MPa and a maximum displacement of approximately 6 mm as can be seen in the figures. This represents a safety factor of approximately 1.3.

$$SafetyFactor = yieldstress \div workingstress$$

The more problematic situation in the bicycle is the rear part of frame but mainly in the welded connection between the bottom bracket and the chainstay.



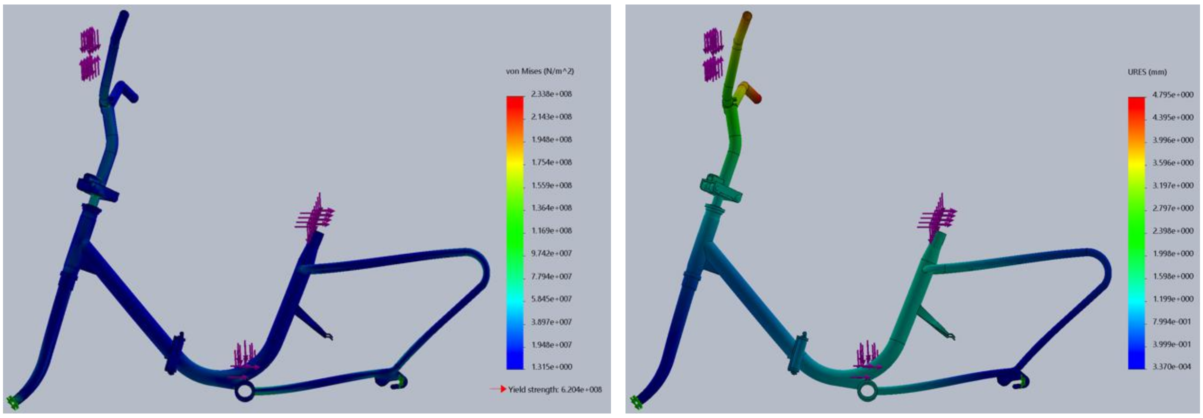
(a) Plot of the static nodal stress (b) Plot of the static displacement

Figure 4.4: Static results - Load case 1

4.2.3 Load case 2

Static analysis

In the second load case, forces are applied in order to simulate the situation where the rider is in the seated position and pedaling. Loads are applied to the bottom bracket, seat and handlebar. The results were a maximum tension of 233.8 MPa and a maximum displacement of 4.8 mm, as can be seen in the figures. This represents a safety factor of approximately 2.65. The more problematic situation is in the handlebar and stem and again in the bicycle is the rear part of frame, mainly in the welded connection between the bottom bracket and the chainstay.



(a) Plot of the static nodal stress

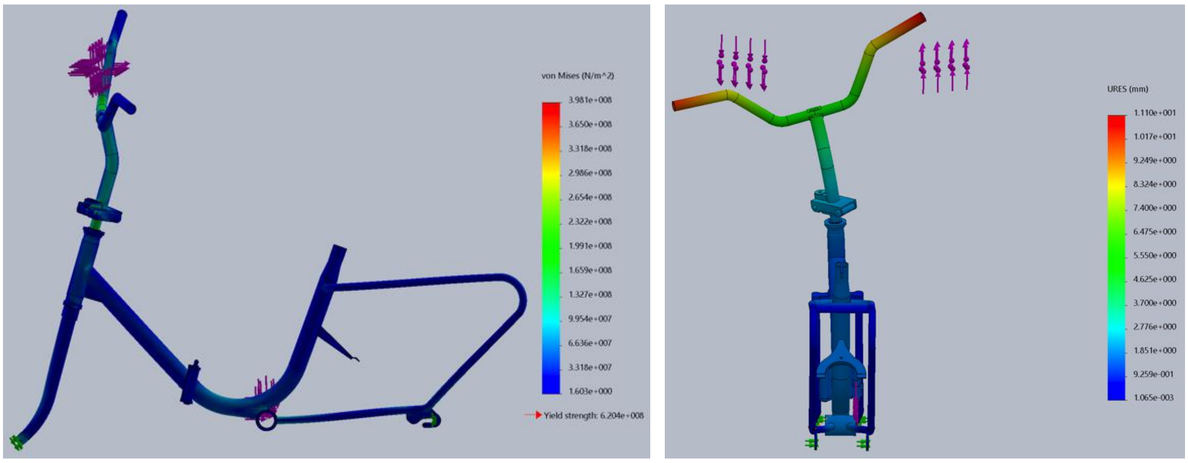
(b) Plot of the static displacement

Figure 4.5: Static results - Load case 2

4.2.4 Load case 3

Static analysis

In the third load case, forces are applied in order to simulate the situation where the rider is standing and pedaling. Loads are applied to the bottom bracket and handlebar. The results were a maximum tension of 398.1 MPa and a maximum displacement of 11.1 mm, as can be seen in the figures. This represents a safety factor of approximately 1.56. In this analysis the more problematic situation is in the handlebar assembly, mostly in the stem and the hinge that folds the handle bar. Nevertheless we still have some stress concentrations near the bottom bracket.



(a) Plot of the static nodal stress (b) Plot of the static displacement

Figure 4.6: Static results - Load case 3

4.2.5 Frequency analysis

The motor has a gear train composed by two gears, one smaller directly connected to the motor and other connected to the chainring. The drive gear, this is, the smaller one and that is connected to the motor has 11 teeth and the bigger one 68. The bigger gear is directly connected to the chainring, this is, it rotates at the same speed that the rider pedals. Considering that the maximum cadence achieved by a common rider is between 70 to 90 rpm, we can easily calculate the gear ratio of the gear train and therefore the frequency that the motor spins, using the relation between gears (teeth and velocity).

$$N_A \times \omega_A = N_B \times \omega_B$$

$$68 \times 90 = 11 \times \omega_B$$

Being N the number of teeth and ω the angular velocity. Solving the equation we obtain the result of 556.4 rpm for the maximum rotation that the motor achieves. Converting to Hertz, this is, number of cycles per second, we obtain 9.27Hz.

The frequency analysis, also called modal analysis, finds the natural or resonant frequencies of a structure and the shape of the structure at each frequency or vibration mode. In this case, since the body is constrained, the 6 first frequencies represent rigid body modes and don't have importance in this analysis. The next vibration modes, starting on 7 represent the elastic modes and these are the vibration modes to take in attention for the analysis.

Comparing the maximum frequency that the motor operates, around 9 Hz, to the results from the frequency analysis, we can conclude that these will not be an issue to the frame, as its value are far apart.

List Modes

Study name:Frequency 1

Mode No.	Frequency(Rad/sec)	Frequency(Hertz)	Period(Seconds)
1	198.92	31.66	0.031586
2	245.87	39.131	0.025555
3	284.26	45.241	0.022104
4	409.29	65.14	0.015352
5	518.64	82.545	0.012115
6	531.27	84.554	0.011827
7	581.15	92.493	0.010812
8	661.29	105.25	0.0095014
9	850.66	135.39	0.0073863
10	1266.1	201.51	0.0049625
11	1410.5	224.48	0.0044547
12	1572.2	250.22	0.0039964
13	1689.4	268.87	0.0037192
14	1843.1	293.35	0.0034089
15	1900.9	302.53	0.0033055

Close Save Help

(a) List of the resonant frequencies in load case 1

List Modes

Study name:Frequency 2

Mode No.	Frequency(Rad/sec)	Frequency(Hertz)	Period(Seconds)
1	200.33	31.883	0.031364
2	246.04	39.158	0.025538
3	288.09	45.852	0.021809
4	408.97	65.089	0.015364
5	518.52	82.525	0.012117
6	532.67	84.776	0.011796
7	582.28	92.673	0.010791
8	661.18	105.23	0.0095031
9	858.87	136.69	0.0073156
10	1266.3	201.54	0.0049619
11	1411.1	224.58	0.0044527
12	1572.2	250.23	0.0039964
13	1692	269.29	0.0037134
14	1846.5	293.88	0.0034027
15	1901.6	302.65	0.0033042

Close Save Help

(b) List of the resonant frequencies in load case 2

List Modes

Study name:Frequency 3

Mode No.	Frequency(Rad/sec)	Frequency(Hertz)	Period(Seconds)
1	0.001048	0.00016679	5995.5
2	0.0023149	0.00036843	2714.2
3	0.0037004	0.00058894	1698
4	0.0051849	0.0008252	1211.8
5	0.006283	0.00099997	1000
6	0.0065293	0.0010392	962.31
7	267.25	42.533	0.023511
8	372.26	59.247	0.016878
9	465.64	74.108	0.013494
10	651.49	103.69	0.0096444
11	659.31	104.93	0.0095299
12	668.36	106.37	0.0094009
13	694.06	110.46	0.0090528
14	804.98	128.12	0.0078054
15	924.62	147.16	0.0067954

Close Save Help

(c) List of the resonant frequencies in load case 3

Figure 4.7: Frequency results

4.2.6 Result analysis

Reviewing the results from the nine analyses made, we can conclude that the most critical load cases are the first and third. In the first, the component that is subjected to bigger stress and most probable to fail is the rear part of the frame and mostly the connection between the bottom bracket and the chainstay. Concerning the third load case, the component subjected to higher stresses is the handlebar assembly, presenting high stress concentrations around the hinge that folds the handlebar and its connections. Taking in consideration the obtained results it's possible to conclude that the model prototype is suitable to be used with safety.

Table 4.2: Mesh characteristics

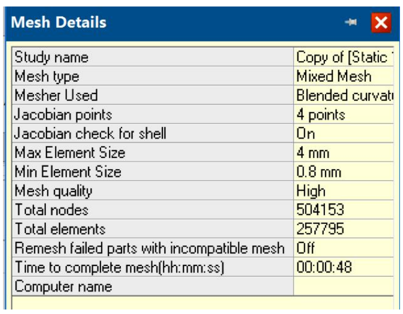
Mesh	1	2	3	4
Maximum element size	7	5	4	3
Minimum element size	1.4	1	0.8	0.6
Number of nodes	171597	318354	504153	2553753
Max. aspect ratio	44.4	39.7	35.9	49.0
Maximum jacobian	38.3	38.7	25.43	19.43
Time to mesh (seg)	26	26	48	136

4.3 Conceived model validation

4.3.1 Mesh and Fixtures

Due to the big complexity of some parts, we weren't able to use either the standard mesh or the curvature-based mesh. Thus, using the blended curvature-based mesh and defining the maximum element size we produce several meshes, with different element sizes in order to chose the one with better quality. Using this mesh the parameter that influenced our choice were: the maximum element ratio, the jacobian, the total node number and the time to mesh. In the structural analysis, the motor was considered as rigid component, as well as the handlebar and stem. Since we intend to buy already manufactured and commercialized components, that are tried and tested. This way we intend to reduce the complexity of the analysis and focus in a more precise analysis regarding the frame itself.

The mesh used to do the analysis was the number 3. Despite the fourth mesh presented better characteristics, to do the analysis using a mesh with elements so small takes a very long time and requires computers with high processing characteristics. Thus, and because the third mesh also presented a lower maximum aspect ratio, it was chosen to be applied to the analysis.

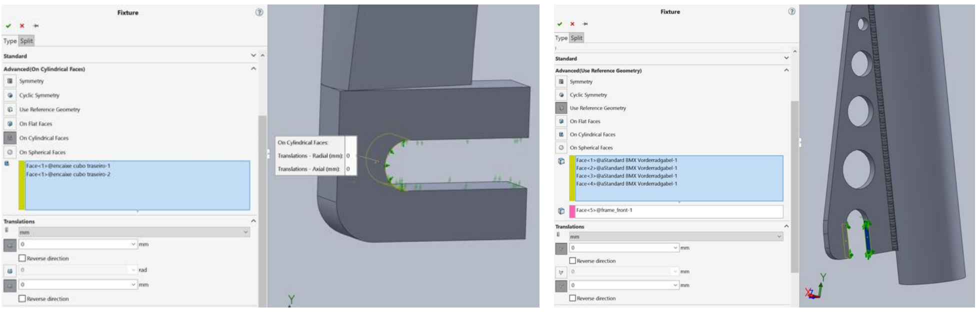


Mesh Details

Study name	Copy of [Static
Mesh type	Mixed Mesh
Mesher Used	Blended curvat
Jacobian points	4 points
Jacobian check for shell	On
Max Element Size	4 mm
Min Element Size	0.8 mm
Mesh quality	High
Total nodes	504153
Total elements	257795
Remesh failed parts with incompatible mesh	Off
Time to complete mesh(hh:mm:ss)	00:00:48
Computer name	

Figure 4.8: Characteristics of the mesh used in the analysis.

Concerning the fixtures used in the analysis, it were the same as in the first model analysis, as the situations that we were trying to simulate were the same.



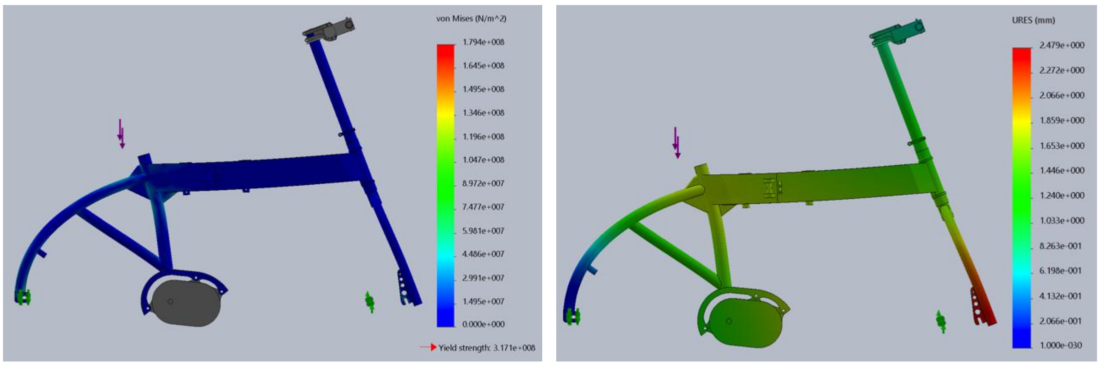
(a) Fixtures applied to the rear dropout (b) Fixtures applied to the front dropout

Figure 4.9: Fixtures applied

4.3.2 Load case 1

Static analysis

The first load case, applying a force of 2400N in the seat, which simulates a seated rider through an irregular road. The results were a maximum tension of 179.4 MPa and a maximum displacement of approximately 2.5 mm as can be seen in the figures. This represents a safety factor of approximately 1.8. The more problematic situation in the bicycle is in the area under the seat, which connects the seatstays, the seat tube and the top tube of the frame. Because of this stress concentration, we inserted three reinforcements, to strengthen the connections between these parts and spread and reduce the stress concentration. the component the presents higher displacements is the front dropout.



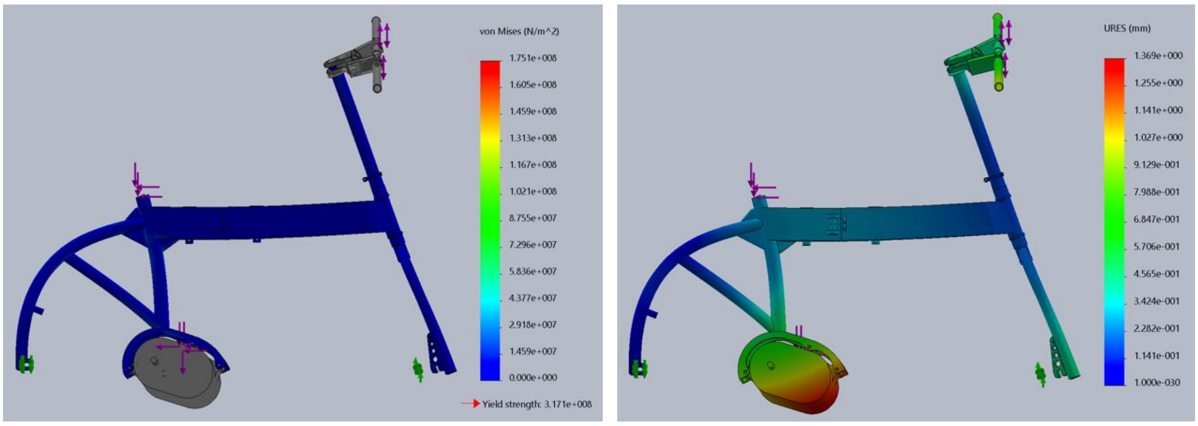
(a) Plot of the static nodal stress (b) Plot of the static displacement

Figure 4.10: Static results - Load case 1

4.3.3 Load case 2

Static analysis

In the second load case, forces are applied in order to simulate the situation where the rider is in the seated position and pedaling. Loads were applied in the bottom bracket, seat and handlebar. The results were a maximum tension of 175.1 MPa and a maximum displacement of 1,.4 mm, as can be seen in the figures. This represents a safety factor of approximately 1.8. The more problematic situation in the frame is the seat tube, as well as in its connections to the top tube and to the part where the motor is fixed to. The part where the motor is fixed also presents high stresses, yet these should dissipate by creating a support with a perfect fit and shape for the motor.



(a) Plot of the static nodal stress

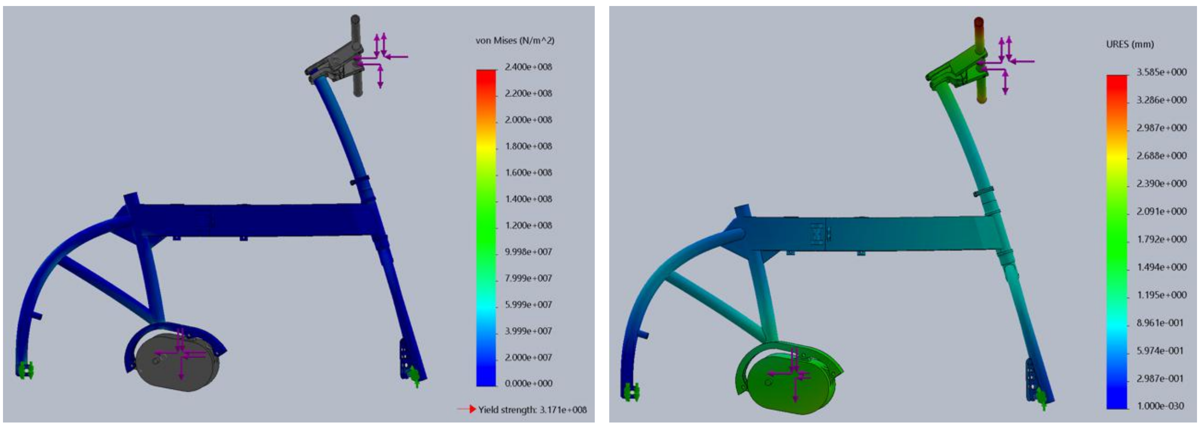
(b) Plot of the static displacement

Figure 4.11: Static results - Load case 2

4.3.4 Load case 3

Static analysis

In the third load case, forces are applied in order to simulate the situation where the rider is standing and pedaling. The loads were applied to the bottom bracket and handlebar. The results were a maximum tension of 240 MPa and a maximum displacement of 3.6 mm, as can be seen in the figures. This represents a safety factor of approximately 1.3. In this analysis the more problematic situation is in the handlebar assembly, mostly in the head tube. Nevertheless we still have some considerable stress concentrations in the part that secures the motor.



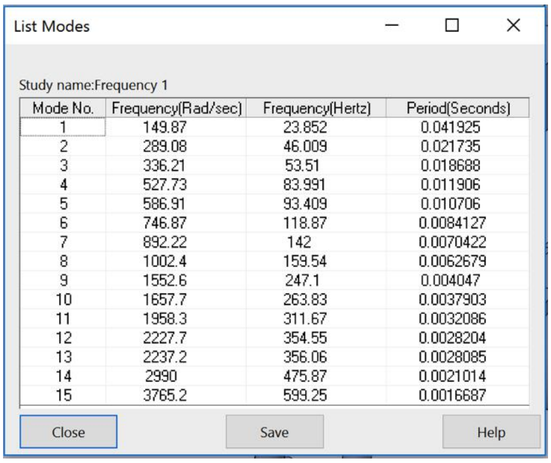
(a) Plot of the static nodal stress

(b) Plot of the static displacement

Figure 4.12: Static results - Load case 3

4.3.5 Frequency analysis

For this analysis we've considered that the motor in use will present frequencies with values similar to the ones obtained by the motor used in the prototype (9.27 Hz). Thereby, and comparing the results from the analysis with the motor maximum working frequency, it is possible to conclude that the vibrations created by the motor will not be an issue on the frame, as they present values quite distanced.

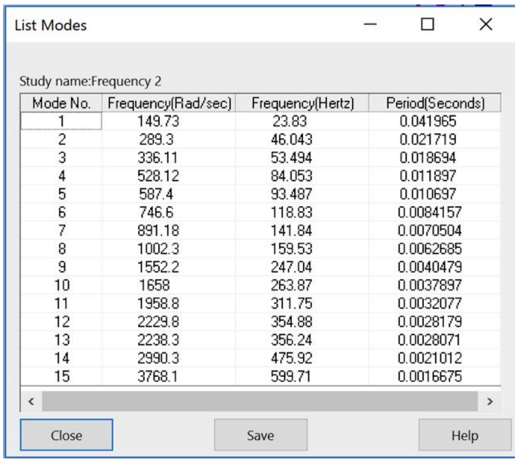

List Modes

Study name:Frequency 1

Mode No.	Frequency(Rad/sec)	Frequency(Hertz)	Period(Seconds)
1	149.87	23.852	0.041925
2	289.08	46.009	0.021735
3	336.21	53.51	0.018688
4	527.73	83.991	0.011906
5	586.91	93.409	0.010706
6	746.87	118.87	0.0084127
7	892.22	142	0.0070422
8	1002.4	159.54	0.0062679
9	1552.6	247.1	0.004047
10	1657.7	263.83	0.0037903
11	1958.3	311.67	0.0032086
12	2227.7	354.55	0.0028204
13	2237.2	356.06	0.0028085
14	2990	475.87	0.0021014
15	3765.2	599.25	0.0016687

Close Save Help

(a) List of the resonant frequencies in load case 1

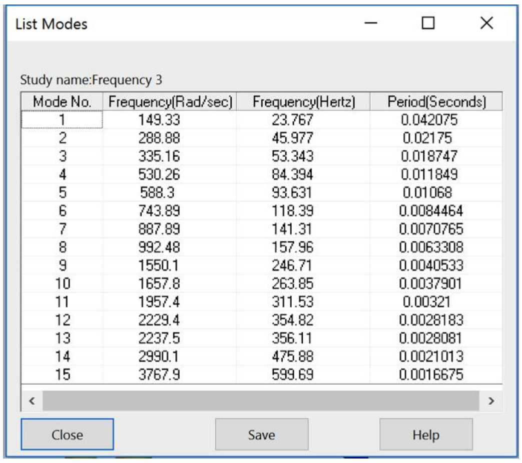

List Modes

Study name:Frequency 2

Mode No.	Frequency(Rad/sec)	Frequency(Hertz)	Period(Seconds)
1	149.73	23.83	0.041965
2	289.3	46.043	0.021719
3	336.11	53.494	0.018694
4	528.12	84.053	0.011897
5	587.4	93.487	0.010697
6	746.6	118.83	0.0084157
7	891.18	141.84	0.0070504
8	1002.3	159.53	0.0062685
9	1552.2	247.04	0.0040479
10	1658	263.87	0.0037897
11	1958.8	311.75	0.0032077
12	2229.8	354.88	0.0028179
13	2238.3	356.24	0.0028071
14	2990.3	475.92	0.0021012
15	3768.1	599.71	0.0016675

Close Save Help

(b) List of the resonant frequencies in load case 2


List Modes

Study name:Frequency 3

Mode No.	Frequency(Rad/sec)	Frequency(Hertz)	Period(Seconds)
1	149.33	23.767	0.042075
2	288.88	45.977	0.02175
3	335.16	53.343	0.018747
4	530.26	84.394	0.011849
5	588.3	93.631	0.01068
6	743.89	118.39	0.0084464
7	887.89	141.31	0.0070765
8	992.48	157.96	0.0063308
9	1550.1	246.71	0.0040533
10	1657.8	263.85	0.0037901
11	1957.4	311.53	0.00321
12	2229.4	354.82	0.0028183
13	2237.5	356.11	0.0028081
14	2990.1	475.88	0.0021013
15	3767.9	599.69	0.0016675

Close Save Help

(c) List of the resonant frequencies in load case 3

Figure 4.13: Frequency results

4.3.6 Result analysis

Reviewing the results from the nine analysis made, we can conclude that the most critical load case is the third one. The main areas that can reveal to be problematic and should be reinforced is the component that fixes the motor and its connection to the seat tube. As said before, the stress concentrations in this part should dissipate by creating a support that fits perfectly the motor case, drawing the stresses that form around the three bolts that secure the motor. Other component that presented generally high stresses compared to the whole bicycle was the seat tube and its connection between seat tube, top tube and the seat stays. After the first analysis made to the model, we already reinforced this connection, yet it continues to be one of the components of the bicycle that presents higher stress concentrations.

Chapter 5

Prototype construction

In this section we will be describing the construction processes that led to the final prototype, presenting the main difficulties that we've came across, the alterations or adaptations that we had to make to the components and the processes used to do it.

5.1 Major difficulties

Along the building and mounting process we came along with some difficulties. This biggest problems were due to the frame, as it is an old frame, some of its dimensions aren't standard, requiring adaptations to make the components compatible.

One big problem was to find components that could be fitted to the bicycle dimensions and fixation points. Components as the brake calipers were hard to find, the original bicycle and frame mountings were designed to use a braking system that nowadays had lost its use, a system in format of a horse-shoe. Still, after a vast research along several dealerships we manage to find the same caliper model that the frame was prepared and that was used by factory default. The handlebar was also hard to acquire, as there are few old bicycles with foldable and viable handlebars. Since we pretended to do some kind of restoration, keeping the bicycle classical look, we tried to use components alike, this made the components selection and acquisition slightly harder, but we've surpassed the problem.

The internal gear system used, in the rear hub, requires a special washer that locks the hub axle and prevents it from spin. This washer connects the rear hub axle to the rear dropout, the axle has two parallel faces that fit perfectly inside the washer and prevent it from spinning. The outer side of the washer also has to have two grooves, these fit in the rear dropout. These washers are crucial components as without them the gear system wouldn't work. The washers that came in the bicycle (manufacturers original) were very worn out and deformed and weren't able to perform its function, therefore had to be replace. Even with a vast search we weren't able to find these components as the manufacturing of this part has stopped long ago, since it a part that suffers a lot of wear we also weren't able to acquire it from any used bicycles. Thus we had to build two of these washers, in order to the gear system to work properly.

In the end, all the difficulties related to the building process and component adaptations were surpassed.

5.2 Component alterations/adaptations and processes used

The handlebar stem and wedge nut didn't fit the inside of the headset, even so it was by a small margin. The handlebar, being a component from a more recent model, had the standard diameter but the headset didn't. Since it didn't fit by a small margin, we decided to use a lathe and remove a small share of material from the bottom part of the stem and from the wedge nut. The amount of material removed was about or less than one millimeter. The material removal was made with care, and advancing little each time, this way we ensured a thigh and safe connection between the handlebar and the headset.

The bottom bracket was to long for the motor to fit, again due to its non standardized dimensions. Assembling the motor in the bottom bracket with its original length also created a pronounced misalignment in the chain, between the chainring of the motor and the rear sprocket. Thus we used an electric grinder to reduce the length of the bottom bracket. The material was removed from both sides, to keep the bottom bracket centered in the bicycle. This way we also reduced satisfactorily the misalignment of the chain, reducing the possibility for the chain to jump off. The grinder was also used to remove several supports that were welded to the frame. These supports were there initially to secure an air pump, a dynamo that was fixed in the fork to power the bicycle old lights and a heavy casing that was used to cover the chain so that the rider wouldn't reach it with his feet.

To remove the old paint and rust from the frame we used a chemical process. Using pickle liquor, and by several times until we've accomplished to remove all the rust and ink, leaving the frame clean and ready to be painted. The paint job was made in three phases, first we applied a primer coat with a spray, using a proper ink for this type of application. It protects the metal from corrosion and creates a rough and proper surface for the ink to adhere. Then, also by spray, were applied two coats of black ink, achieving the final result.

The bicycle also has several chrome plated components, as the handlebar, stem, hubs, spokes and some adornments in the top of the fork and headset. To treat these, first we used steel wool to sand and clean them. After, and to obtain the final result we used a product called ”Duraglit”, which is a metal polisher designed to remove tarnish and give a glossy finish.

To create the special washers that locked the rear axle hub from spinning we started from solid piece of steel. To obtain its round external shape we used the lathe, them to create the grooves to slide into the frame dropout we used a manual milling machine, as well as to bore the fitting for the axle. To the final adjustments and in order to obtain a perfect fit between the washer, axle and frame a small squared shaped file was used. After finished the building process of the washer, it was painted the same way as the bicycle frame.

5.3 Final result

Figure 5.1: Concluded prototype

Figure 5.2: Handlebar assembly

(a) (b)

Figure 5.3: Prototype in the folding position

Chapter 6

Conclusions and Future work

This work was developed with the intent to project and build an electrically assisted bicycle adapted to the metropolis environment. It is a concept designed to create a better and versatile alternative to be used as mean of transportation in urban scenarios. It should present advantages and better features than the usual choices, as public transports, private cars or common bicycles. The project was thought to simplify and ease the transport in a in big city environments in general, yet, it was mainly aimed to be applied in the ”Last mile” concept. It was made a study on the market of electrical bicycles which revealed a large and exponential growth of sales of electrical bicycles in the last years. It showed that the future will certainly include electrical bicycles, not only to be applied in urban environments but to a varied range of applications. Growing environmental concerns allied with the development of the technology were two of the main reasons that led this market to experience such a high popularity in the present.

In order to achieve a product that represents a viable solution as a mean of transportation and mainly directed to the ”last mile” concept a survey was made aiming to specify its main requirements. These requirements constitute crucial characteristics and features that the bicycle should present and they were considered to be: autonomy, weight, ease on transportation, practicability and safety. Starting from these key aspects, we could then proceed to project and engineer a suitable solution. Being a bicycle, or electrical bicycle, composed by several components, all these have to be properly chosen in order for them to be in compliance with each other and create a viable and capable solution. Since bicycles are old means of transport, they’ve experienced a wide evolution as well as their components. Hence, there are several different options for the different components that compose a bicycle. This way we made an evaluation to the different component alternatives in order to choose systems suitable for our purposes and that could create a viable set.

Due to project limitations, as referred before, we’ve designed two different designs, one to be designed from scratch and without paying much attention to the restrictions stipulated and other designed to be built and to constitute a fully working prototype for the project. Both models were structurally validated using a CAD software. After its structural validation and component choices the construction process was allowed to begin. The final result presents a fully working prototype, able to represent a viable solution to be used as a mean of transportation in a metropolis environment. The prototype was built from old bicycle parts, this way we created a product that bridges the past to the present, with a bicycle with a classical look but improved by the new technologies available in the present.

A future work and development of this project would be the improvement and reinforcement of the design as well as considering other alternatives, possible better suited, to hold the bicycle in the folding position. Regarding the raw material used, it can be analyzed different alternatives for it, with lighter and better suited materials, as carbon fiber for example.

With this work it was possible to conclude that bicycles, and even more, electrically assisted bicycles, not only have played an important role as a mean of transportation but its importance tends to keep on growing, as they are continuously improving. With the technology advances and breakthroughs, electrical bicycles are a concept that is meant to grow increasingly more and tend to extend its range of applications. With this work we were also able to conclude that despite the technology surrounding the concept had seen great developments, the concept is still severely limited by it. This refers mostly to the batteries, as they constitute a crucial component, limiting the bicycle range and extending its weight (two of the requirements considered to the project). In a close future, and with the advance of technology, this major drawbacks are expected to be overcomed, as batteries are in continuous update. New and more efficient motors are also starting to appear, as well as retroactive systems which allow to recharge the battery while the bicycle is being ridden.

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Appendix A

Technical Datasheets

Voltage		DC36V							
Limit current		15A							
Limit speed		25KM/H							
Motor weight		3.7KG							
Chain wheel tooth		46T							
no-load value		Rated value						Max value	
current (A)	speed (RPM)	Output power (W)	speed (RPM)	efficiency (%)	torque (Nm)	current (A)	MAX torque	MAX efficiency (%)
≤1.0	83±5	250	78±5	≥80%	≥30	≤9	≥80N.m	≥80%

Figure A.1: Characteristics of the motor used in the prototype.

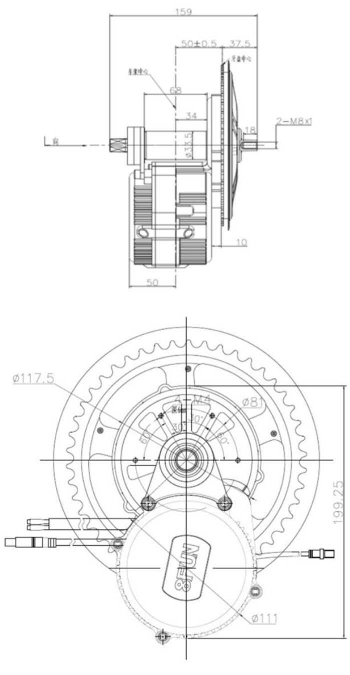


Figure A.2: Main dimensions of the motor.

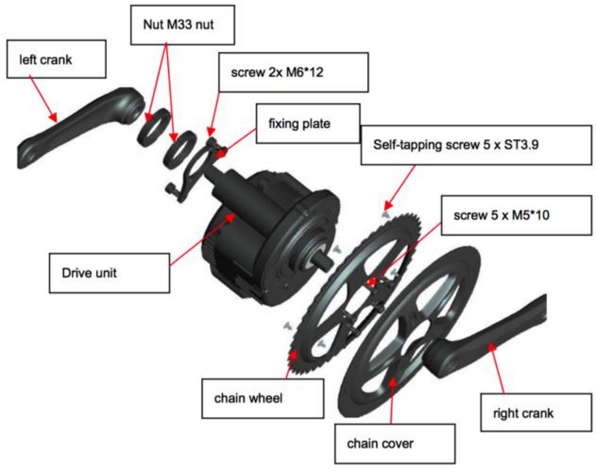


Figure A.3: Exploded view of the motor.

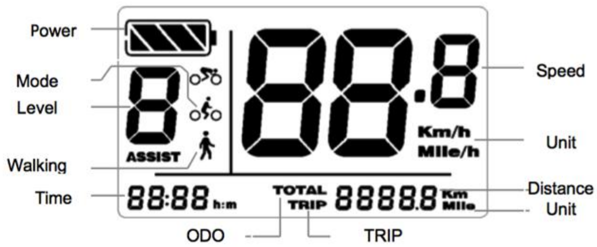
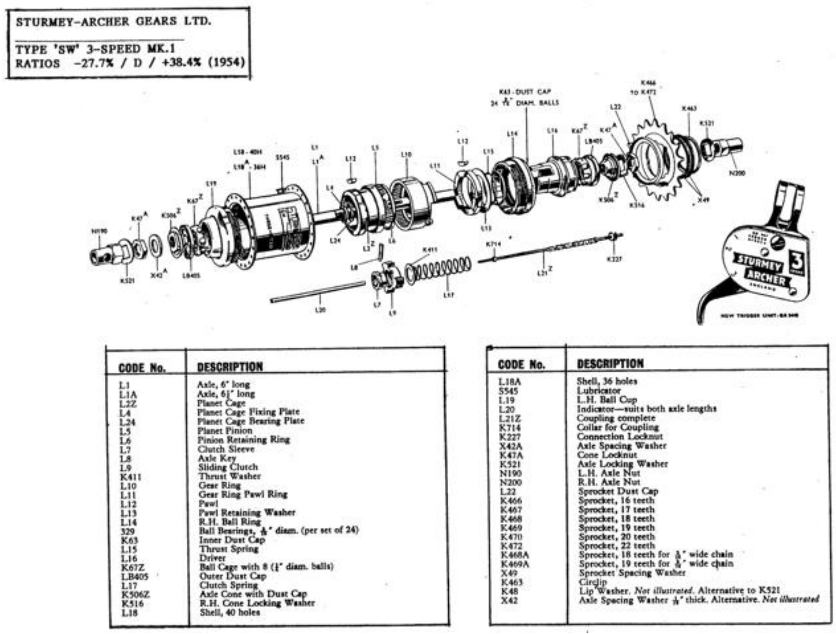


Figure A.4: Interface of the LCD display.



CODE No.	DESCRIPTION
L1	Axle, 6" long
L1A	Axle, 6½" long
L2Z	Planet Cage
L4	Planet Cage Fixing Plate
L24	Planet Cage Bearing Plate
L5	Planet Pinion
L6	Pinion Retaining Ring
L7	Clutch Sleeve
L8	Axle Key
L9	Sliding Clutch
K411	Thrust Washer
L10	Gear Ring
L11	Gear Ring Pawl Ring
L12	Pawl
L13	Pawl Retaining Washer
L14	R.H. Ball Ring
329	Ball Bearings, 3/16" diam. (per set of 24)
K63	Inner Dust Cap
L15	Thrust Spring
L16	Driver
K67Z	Ball Cage with 8 (¼" diam. balls)
LB405	Outer Dust Cap
L17	Clutch Spring
K506Z	Axle Cone with Dust Cap
K516	R.H. Cone Locking Washer
L18	Shell, 40 holes

CODE No.	DESCRIPTION
L18A	Shell, 36 holes
S545	Lubricator
L19	L.H. Ball Cup
L20	Indicator—suits both axle lengths
L21Z	Coupling complete
K714	Collar for Coupling
K227	Connection Locknut
X42A	Axle Spacing Washer
K47A	Cone Locknut
K521	Axle Locking Washer
N190	L.H. Axle Nut
N200	R.H. Axle Nut
L22	Sprocket Dust Cap
K466	Sprocket, 16 teeth
K467	Sprocket, 17 teeth
K468	Sprocket, 18 teeth
K469	Sprocket, 19 teeth
K470	Sprocket, 20 teeth
K472	Sprocket, 22 teeth
K468A	Sprocket, 18 teeth for ⅛" wide chain
K469A	Sprocket, 19 teeth for ⅛" wide chain
X49	Sprocket Spacing Washer
K463	Circlip
K48	Lip Washer. *Not illustrated.* Alternative to K521
X42	Axle Spacing Washer 1/16" thick. Alternative. *Not illustrated*

Figure A.5: Exploded view of the internal gear system used in the prototype.

Figure A.6: Original bicycle used to build the prototype.

Figure A.7: Frame cleaned and ready for the paint job.

Figure A.8: Primer coat applied to the frame.

Figure A.9: Frame painting job completed.

Figure A.10: Finished prototype and the components from the original bicycle.

Figure A.11: IST logo detail