PROJECT OF AN ELECTRICALLY ASSISTED BICYCLE ADAPTED TO THE URBAN MOBILITY

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ABSTRACT

The present work intends to study and create a solution to be used as a mean of transportation adapted to the metropolis environment. This solution lies in projecting and building a prototype of an electrical assisted power cycle.

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, this showed that the e-bike sales have experienced a massive growth in sales.

The components that compose bicycles and electrical bicycles were analysed and compared, this way we could do a correct and wise choice of components to be used in the project. Prior to the creation of the design, we established some main requirements for the project, these constitute the points with major importance concerning a vehicle for the specific purpose that it is meant to do.

Due to some project constraints it were developed two different models. One totally conceived from scratch and engineered taking in considerations 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, fatigue and frequency 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 made for both designs, which allowed to evaluate the different cost rates among the two designs.

Keywords: Electrically assisted power cycle, metropolis environment, prototype,

1. INTRODUCTION

The search and evolution of electrical vehicles is growing more and more as the days go by. Electrical vehicles are claiming a place in several industries, especially in the fields of transportation. The application of electrical motors in bicycles or cars opens up new possibilities and has several advantages linked to it.

The use of a foldable electrically assisted power cycle presents several advantages: it has a small ecological footprint, specially compared to cars, it's good for the health, allowing to exercise and to manage the effort with the amount of assistance given by the motor. The motor can provide assistance to the rider through tough climbs, to help rapidly achieve higher speeds or just to let the rider rest along the path, allowing him to do longer and tougher routes with less effort. In a metropolis environment it represents great mobility, it can be folded up and carried into public transportation with the rider and get near the desired destiny. Or otherwise, can be ridden to the destiny, with the electrical motor assisting through the route.

This thesis has the objective to consider the best alternatives to be used as a daily mean of transportation to commute to work. The solution must 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 studying the best alternatives from the several hypotheses available 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, so 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 the route easier, effortless and eliminating the problems inherent in the use of a common bicycle.

2. ELECTRICAL BICYCLES

Bicycles have been around for more than two hundred years now and since then they have been one of the most widely used mean of transportation.

An electric bicycle is a bike with an electric motor integrated and used to assist the rider propelling the bike. There are two main types of electrically assisted power cycles: pedelecs and E-bikes, the main difference is the way which the motor is actuated.

The first known patent for an e-bike was published in 1895 by Ogden Bolton Jr. in the United States [1]. It was a simple design and it used a direct current brushed hub motor mounted in the rear wheel. However, 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 compete against common bicycles, mopeds, motorcycles or even cars. The highest grown was in the last ten years or even recently in some countries. Due to being a relatively new mean of transportation, the legislation referring to this recent category of vehicle is 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 around this concept all over Europe, which in the nowadays it's almost achieved.

The creation and improvement of components like torque sensors, batteries or the motor itself allowed the industry to progress even more and to get the recognition that it didn't had before. Electrical bicycles became more reliable, cheaper and with bigger ranges which opened up doors to a new range of 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 comparison to the common alternatives. Electric bicycles are also starting to be used industrially, in company's like post-mails, police patrolling and several urban transportation services.

3. LEGISLATION

Electrically assisted power cycles are a relatively new concept, therefore the legislation regarding this concept is still a little premature and continuously adapting to the frequent changes and innovations. It's hard to establish legislation for EAPC as there are a wide variety of different bicycles, with different powers rates, different work modes and different applications.

3.1. 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 differently, being applied the same rules that to mopeds or motorcycles. It states that: "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 pedalling," [2]. If a bicycle is within this parameters, the laws applied are the same as with a common bicycle. 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.

To provide a standard for this vehicle category it has been developed the European standard EN15194 [3]. It concerns mostly with the electric part of the vehicle and it is valid across the whole EU.

EN15194 distinguishes EAPC in two distinctive groups. Both classifications are inserted in the category previously referred. This distinction is due to the comparatively different modes of actuating the motor:

- Pedelec (pedal electric cycle): the motorized assistance only engages when the rider is pedalling. When the driver stops pedalling, the motor switches off.
- E-bike: the motor can propel the vehicle by it self, this is, without the need for the driver to pedal. The legislation is quite different for these in some countries, due to its similarities with mopeds or low-powered motorcycles.

3.2. Portugal

Portuguese legislation is in conformity with the European Directive for bicycles with motors under 0,25kW. The last modifications in the Portuguese legislation were made in 2012, updating Artigo 112 do Código da Estrada [4] and placing agreement with the European standards. Even so, for motors with higher capacities, above 0,25kW, the Portuguese regulation is not clearly defined.

3.3. China

Electric bicycles come under the same classification as bicycles and don't require driver's license as long as the vehicle is lighter than 20 kg and slower than 30 km/h. Yet, due to a rise in electric bicycle related accidents, some cities and regions have banned electric bicycles due to concerns over environment, safety and city image issues.

3.4. 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.

4. MARKET

Since the beginning China has been dominating the global market for electric bicycles, with an estimated 85% of all 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. 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[5].

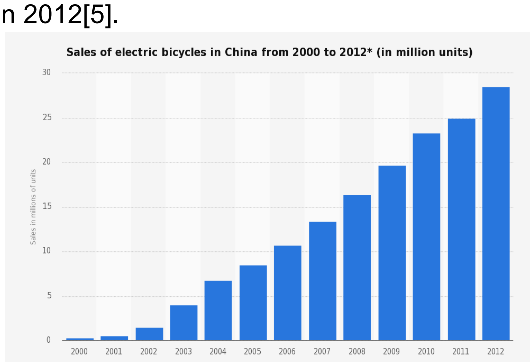

Figure 1 - Evolution of the Chinese market

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.

It is estimated that in 2014, 83.2% of all the imported e-bikes in the EU were imported from China [6]. High gas prices 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.

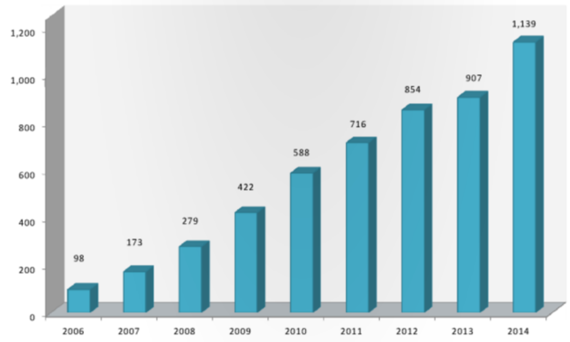

Figure 2 - Evolution of the European market

Global annual sales of electric bicycles are expected to grow from nearly 32 million in 2014 to over 40 million in 2023 under a base scenario [7]. Innovative trends have contributed to the market growth and will continue to, making the electric bike market even more attractive. EPAC's are becoming very useful and with lots of practical applications, not only in private transportation but as well as for several industries.

5. ELECTRICALLY ASSISTED CYCLE COMPONENTS

5.1. Motor

There are several ways to electrically propel a bicycle, the ones considered in this work and more commonly used are mid-drive motors, hub motors and friction drive motors.

Friction drive motors are mainly characterized by its simplicity, both of the motor itself as the mounting process required to assemble the motor. It is the type of motor that is less used from the three considered. 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 can easily decrease and won't be enough to propel the bicycle. They are usually mounted in the seat-post, making very easy to mount or dismount the motor on the bicycle.

Mid-drive motors are mounted in the crank shaft. They are known for their high performance and torque rates, one of the 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 and allowing the motor to work at more suitable speeds. Another advantage of this type of motor is his location in the bike and his effect on the mass centre. Since it is mounted in a relatively low and central position in the bike, it lowers the mass centre and keeps it centred between both wheels, which leads to a better control, stability and manoeuvrability. Despite being more expensive, these are able to provide considerable higher torques comparing to hub motors with the same power.

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 common bicycles. The other category are the motors that require a specific frame, with proper mountings and a place to accommodate the specific model of the motor in the frame. In this case, the bottom bracket becomes the motor itself.

Figure 3 - Example of a mid-drive motor

Hub motors were the first type of drive system for bicycles and its design has evolved and enhanced since then. They can be assembled on either the front, rear, or both hubs of a bike. 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. Hub motors usually tend to be low powered, specially when mounted in the front wheel, as overpowering would mean a loss of traction and make the front wheel spin.

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. With these motors, it's easy to convert almost any bicycle into an E-bike, specially using a hub motor for the front wheel, as they do not interfere with the pedals or the transmission of the bicycle.

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 and possibly create traction problems. Another draw-back, is that they will absorb all the shocks and vibration generated by the ground track.

There are two types of hub motors, geared and gearless motors.

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. 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.

Figure 5 - Geared hub motor

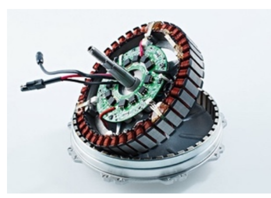

Figure 4 - Gearless hub motor

Gearless or direct-drive hub motors, 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 few moving parts. 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.

5.2. Frame

The frame is the main component of a bicycle. 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 it is the frame that makes the bicycle foldable. The most important features in a bicycle frame are the weight, strength, stiffness and here specifically, the ability to fold into a compact shape. Bicycle frames can be made out of several materials as steel, aluminium, titanium or carbon fibber.

Steel is the most common and it has been used for a long time and it is the cheapest from the referred above. It is a strong and long lasting material. In comparison with the other materials, it is heavier but also known to be easy to work with. Aluminium has a lower density and lower strength compared to steel alloys yet, it has a higher strength-to-weight ratio. Titanium is lighter than steel but just as strong. The major qualities are its durability, damping capacity and low weight. The major downside is the cost. It’s both an expensive material and it requires special machinery and skills to work with. Carbon fibber has become by far the most popular material for performance road bikes. It is incredibly light and strong. Its biggest flaw is that it is very brittle material, contrarily to metals.

For folding bicycles, the main characteristic of the frame is the way that it allows the bicycle to fold. There are uncountable designs and ways to fold the bicycle. The most common are the ones in which the bicycle folds horizontally, vertically or both. The horizontal fold is the most common, usually the frame folds in a single hinge approximately in the centre of the frame, bringing the wheels close together.

The vertical fold usually has one or two hinges along the main tube and seat stays, these allow the bike to fold and leave the wheels are also set side by side. This is often more compact but also more hard and time consuming to fold.

5.3. Gear system

The gears in a bicycle are what determines and allows 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 within the circumstances. There are four main types of gearing mechanisms for bicycles: fixed gear, single-speed, multi-speed and internal gear.

Fixed and single-speed are pretty similar, both just allow one fixed gear ratio. Fixed gear is characterized by having the pedals directly connected to the chainring. If the wheel is spinning so do the pedals. Single-speed gears have a free wheel system, allowing the wheel to spin freely. These two gear systems are characterized by its mechanical simplicity and low weight.

Multi-speed systems are the most seen gear system in bicycles. The system is composed by several components, multiple sprockets and to move the chain from sprocket to another. The system is controlled by two levers in the handlebar, one controls the front derailleur, which provides large jumps in gears and the other controls the rear derailleur.

Internal gear have all its system hidden within the wheel hub. They use an internal planetary gearing system. It uses just a single chainring and a single rear sprocket. This is a system that goes easily unnoticed once most of 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.

5.4. Batteries

The battery is the heart of any electrical bicycle. It is one of the hardest components to come by and often the most expensive. The three most common battery types and most used in electrical bicycles are lithium, nickel and lead acid batteries. It is a technology that is in constant innovation and upgrade, however, electrical bicycles are mainly limited by the battery capacity.

Lithium batteries 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, shapes and different chemistries. Some of the most common and most used li-ion batteries are lithium iron phosphate, lithium manganese oxide, lithium nickel manganese cobalt oxide or lithium polymer. Each chemistry has is main features and different power rates. Usually lithium cells need a protection circuit, 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, without this, they can become dangerous and its life expectancy abruptly reduced.

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, etc. They have a low lifespan and have to be treated carefully, both on assembling and charging. These usually present two different chemistries: nickel cadmium and nickel metal hydride, however nickel cadmium are almost out of use due to cadmium being a very hazardous substance.

Another option are Lead Acid batteries, the oldest between the three battery technologies described. 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 can be found in most fuel cars, which makes them widely available and cheaper than either lithium or nickel batteries.

5.5. Throttle/PAS

There are two main ways to control the assistance that the motor gives to the rider, throttle or a pedal assist system. Both let you manage the amount of assistance given by the motor.

Throttles are applied mostly on e-bikes and use the same concept as in a common motorcycle. These allow to control the amount of power that the motor is producing in real-time.

PAS are used in pedelecs. It is a mode that provides power only when you are pedalling. The amount of assistance is managed in an electronic circuit and takes into account information given by sensors (torque, cadence and speed). Compared to throttle, this is a much more intuitive control mode as the rider doesn't have to activate anything, just ride the bicycle as a common bicycle. It is also much healthier for the batteries, as power demand is much more constant and without big power peaks.

6. COMPARATIVE ANALYSIS OF EXISTING MODELS

Model	Characteristics	Picture	Advantages and disadvantages
Blix vika+	• 350W rear hub motor • Frame folds horizontally • Folds head tube and pedals • Weights 21,8Kg • Range of 55Km • Costs 1474€		• Easy to fold • Simplistic design • Not very compact • Hard to transport 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 style • Few 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 style • Few 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 6.3Kg • 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 pedals • Weights 12.5Kg • Costs 1500€		• Very compact • Several moving parts • Hard to transport when folded

7. 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:

- 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. 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 using a battery with higher capacity, yet higher capacities lead to bigger and heavier batteries.
- Weight - It is an important requirement and one that it's commonly used to characterize bicycles. The bicycle has 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. 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, having a proper and easy way of transporting the bicycle when folded would be very usefull.
- Practical to fold - The folding system is a crucial component on 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.
- 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.

8. CONCEIVED DESIGN

8.1. Component and material selection

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 purpose that the bicycle is supposed to be applied in.

As explained earlier, there are three types of motors available: 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 possibilities, the friction-drive motors are the first to be excluded. They present considerable disadvantages comparing with the others alternatives. The choice of the motor type relies then between mid-drive and hub motors. 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. For this study, we've considered 9 different criteria, each one rated from 1 to 5, according to the importance that it presents on choosing the best alternative for the motor.

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

After this 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 also a good solution. Even though, for this specific application and taking in care the criteria selected in the decision method, mid-drive motors are the right choice.

Since we opted to use a mid drive motor, the choice grounds on which of the various motors available in the market we would use and what type. As referred before, they can be divides in two groups, the motors that require a proper mounting and frame fitting or the motors that are aimed to transform a common bike into an electrical assisted. 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 their products seem to be between the best among the market offers. All the three systems considered are very similar and are very efficient. They use three types of sensors: cadence, speed and torque. These help to create an easy and intuitive interface between rider and bicycle, generating a very user-friendly product.

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, creating the possibility to insert it in the inside of the frame, making it go unnoticed. The first choice relies between which battery type: 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, given this, it was the first to be excluded. 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 as compared to a lithium-ion battery. Lithium batteries present several advantages when compared to nickel batteries: longer life expectancy's, more efficient and with faster recharging times. In addiction, nickel batteries require being totally discharged before charged, otherwise they experience the memory effect. Due to the pointed reasons we opted to use lithium batteries.

Taking in consideration the attributes and formats available of each of the lithium batteries chemistry's, we have chosen the Lithium Manganese Oxide ($LiMn_2O_4$). These are widely available in the market and present good characteristics in general, as size, weight and costs. Regarding the battery format, we opted for the 18650. It is a battery design that is well known for the low cost and multiple applications that it suits. 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 × 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 as it depends not only on the motor voltage and the battery capacity but in a whole range of factors as bicycle and rider weight, level of the assistance given by the motor, inclinations of the terrain and several others. We will calculate and 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 × 2.9Ah = 8.7Ah. 37 × 8.7Ah = 321.9Wh that is to say that a 10s3p disposition generates a 321.9Wh battery pack. Taking in account that a 250W motor will burn 250Wh in one hour, a 321Wh battery pack will last for 1.288 hours (321.9W h ÷ 250w = 1.288h). Considering a medium velocity of 20km/h, it results in a range of approximately 26Km (20Km/h × 1.288 = 25.76Km). It is important to emphasize once again that this is just a prediction and can and will fluctuate quite markedly.

Wheels, also have 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. In order to keep the bicycle compact we must choose a small wheel size, yet, small wheels reduce the bicycle manoeuvrability and make it hard and dangerous to overcome obstacles. Given this, we opted to use 20" wheels, they are relatively small, keeping the bike compact but still big enough to overcome most of the obstacles that a metropolis environment presents.

Regarding the gear system to be used, both fixed and single-speed gear systems were discarded. Despite its simplicity and low weight, they are not the best choices for this type of application, as they only allow one fixed gear ratio. The choice lies thus on multi-speed or internal gearing. Taking in consideration that the bicycle is designed to be used in a metropolis environment, the smart choice must be an internal gear system. Being its main advantage its simplicity and the fact that it allows to

Figure 6 - Folded bic

change gears even with the bicycle 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 and keeping the bicycle aesthetics and compact.

8.2. Model description

In this model, despite all its components are represented in the 3D model, only the frame was modelled in the CAD program and intended to be built.

Figure 7 - Conceived design

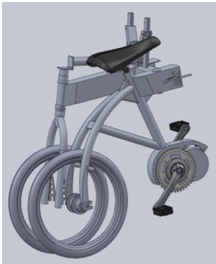

Figure 9 - Folding position

The frame is all made out of an aluminium 2018 alloy was engineered taking in account the standard measures in bicycles. Thereby making easy to find and adapt the remaining components to the frame. 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 shape. It folds horizontally along two hinges alongside the top tube, this folding position brings the front wheel to an aligned position with the rear wheel, creating a structure similar to a trolley. This position creates an easy and practical to transport the bicycle.

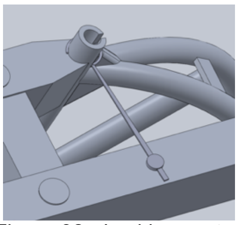

Figure 82 - Locking system

We've also designed a system capable of fixating the bicycle in the folding position, keeping the bicycle compact and easing the transport process when the bicycle is in the folding position. The system is quite simple, it was thought that way to keep it light, 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 since in the virtual model this system can not be truly tested. In the design we've sketched it to a shape similar to a wire hook, it rotates and clamps the seat tube above. 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 frame and handlebar weight 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.

To achieve the fully folded position are required three steps, folding the handlebar column down to near the top tube of the frame, retracting the seat and folding the handlebar which leaves the assembly with the following dimensions: 75cm/40cm/77cm. 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.

Regarding the steering system, an alternative would be to use a system with just one fold. This alternative brings the handlebar assembly together and obliquely to the frame, placing it alongside the front wheel (such as the one used in the prototype).

The top tube, was dimensioned taking in account the battery pack size, that way it can be easily fitted into the inside of the frame, making it go unnoticed and protected from external threats.

8.3. Cost estimation

In this section we will predicting the costs of production that this bicycle would have. However, it can not be precisely predicted as some costs, such as building processes and manpower can not be estimated with precision.

The production costs of this model are divided in three groups: raw materials, cost of manpower and costs of the components. Regarding the raw material to build the frame, the projected frame uses mainly standard size materials and have an expected cost of 290€. The manpower costs are difficult to predict with precision as the time for the frame to be built can't be anticipated with precision. Predicting that it can be built in 7 working days, 56 hours of work and a medium manpower cost of 40 €/per hour, the total manpower costs would be around 2240€. Regarding the components: electric motor (1500 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€). This leads to a total of 2400€ for the components and a total of 4930€.

9. PROTOTYPE DESIGN

9.1. Component and material selection

Due to our project limitations, as referred before, we will not be able to build a fully working prototype as the one we've modelled and presented early. Therefore, in this section it will be presented an alternative design, considering more viable and realistic choices. 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 old bicycle components and adapt them to fulfil our needs and meet the project requirements. Since we will have to use other bicycle components we've opted to use old bicycle components, lowering the costs and creating a product with an antiquate and classical aspect but modernized and improved by the actual technology.

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 shape. 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.

Regarding the motor, the choice remains to be a mid-drive motor. But here we will opt to use a mid-drive motor to mountd in the bottom bracket. This way it can be easily fitted in the frame, requiring little alterations to it. 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 up to 80N and efficiencies higher than 80%. The motor has a built-in controller and PAS and it comes along with crank-arms, chain wheel, speed sensor, brake levers that cut the power as the levers are actuated and a thumb throttle. It 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 from three different levels. It also shows the instantaneous vehicle speed, the battery charge and the distance travelled. This motor has an extra assistance mode, to be used when the rider is dismounted of the bicycle and walking by foot. In this mode, the motor gives a lithe assistance and allows the bicycle to be more easily transported and with less effort.

Figure 113 - Selected motor

With respect to the battery pack, we've opted to buy a battery pack already built. The dimensions of the chosen pack are 24.5/7/10cm and weights 2.8kg. It is assembled in holder, which is fixed to a tubular support in the bicycle frame with a holder from which it can be easily removed by sliding it from it. Regarding its capacity, 36V and 9Ah generating 324 Wh (36V×9Ah=324Wh). Considering the same method used to predict the range of the conceived model, this will have an expected range around 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.


Figure 124 - Battery pack

The handlebar in the original model wasn't foldable, it had the capacity to retrieve into inside of the head tube but this wasn't much effective to achieve a compact design. Therefore we will use a handlebar with an hinge that brings the handlebar to the side of the front wheel. This leads to a foldable position much more compact and practical to store. The folding system of the handlebar 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 handlebar with a similar classical look as the original.

9.2. Model description

The frame alone weights roughly 10Kg and considering the components missing, the weight of the bicycle assembly should be around 20Kg.

The folding process is quite easy and is made by two steps: first the frame is folded, bringing the wheels close together and the second step is to fold the handlebar, bringing it down and alongside the front wheel as it can be seen in the figure. The folded dimensions of the bicycle are 77/86/29cm.

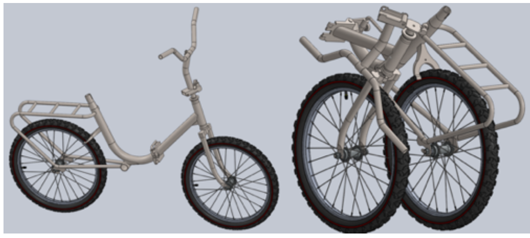
Figure 10 - Prototype

9.3. Costs

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 this work. Motor (600€), battery (350€), bicycle (100€), folding pedals (15€), braking system (35€), wheels (15€), seat (20€), chain (10€), handlebar (40€) and the ink (75€). This leads to a total cost of 1260€.

10. COMPARISION BETWEEN THE TWO DESIGNS

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.

Regarding the autonomy of the models, the capacity of both the batteries is quite similar, 321,9Wh for the conceived model and 324Wh for the prototype model. Thus their range should be around the same values but being that the aluminium frame 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 conceived model, being that it allows it to be transported similarly to a trolley.

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. The dimensions of the folded assembly for the conceived and for the prototype model are 75/40/77cm and 77/29/86cm, respectively. Thus, there are no very significant differences among the two.

11. STRUCTURAL ANALYSIS

11.1. Load cases

We will take in account three different loading cases, these are based on the study made by Maestrelli and Falsini [8] which was based on experimental loads measured by Soden and Adefeye [9]. 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.

11.2. Prototype validation

To validate the model was made a static, fatigue and frequency analysis using the three load cases.

Load case 1

The results of the static analysis showed a maximum tension of 463,6MPa and a maximum displacement of approximately 6mm. This represents a safety factor of approximately 1,3. The more problematic situation is the rear part of frame but mainly the welded connection between the bottom bracket and the chainstay.

In the fatigue analysis was considered the same force and applied through 1000 cycles. The results were: a damage percentage of 10,8%, a minimum life-cycle of 9238 cycles and a load factor of 1,8. Analysing the results, the frame as a whole performed well, the main critical situation is, as in the static analysis, the connection between the welded connection between the bottom bracket and the chainstay.

Load case 2

The results were a maximum tension of 233,8 MPa and a maximum displacement of 4,8 mm. This represents a safety factor of approximately 2,65. The more problematic situation is in the handlebar and stem and again in the rear part of frame, mainly in the welded connection between the bottom bracket and the chainstay.

In the fatigue analysis were used the same forces as in the static analysis and through 1000 cycles. The results are expressed in terms of percentage of damage (0,53%), the minimum number of cycles to fatigue failure was 1, 86 × 105 and a load factor which of 3,27.

Load case 3

The results were a maximum tension of 398,1 MPa and a maximum displacement of 11,1 mm. 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.

In the fatigue analysis the results are expressed in terms of percentage of damage (8,3%), the minimum number of cycles to fatigue failure was 12030 and a load factor of 1,93. Such as in the static analysis, the component with higher stress concentrations is the handlebar and handlebar stem, mostly around the hinge and its connections.

Regarding the frequency analysis, we've calculated the maximum rotation that the motor achieves which is about 556rpm or 9,27Hz. Comparing this value with the results obtained from the frequency analysis made for the three load cases we can conclude that these will not be an issue to the frame, as its values are far apart.

Reviewing the results from the analysis 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, 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.

11.3. Conceived design validation

Load case 1

The results were a maximum tension of 179,4 MPa and a maximum displacement of approximately 2,5mm. This represents a safety factor of approximately 1,8. The more problematic situation is in the area under the seat, which connects the seatstays, the seat tube and the top tube. Because of this stress concentration, we inserted three reinforcements, to strengthen the connections between these parts.

The results are expressed in terms of percentage of damage (22,6%), the minimum number of cycles to fatigue failure was 4423 and a load factor which of approximately 1,5. Such as in the static analysis, the area under the seat is the one that presents higher stresses. Even though, the maximum damage observed in the analysis was in the front dropout.

Load case 2

The results were a maximum tension of 175,1 MPa and a maximum displacement of 1,4mm. This represents a safety factor of approximately 1,8. The more concerning 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.

In the fatigue analysis were applied the same forces as in the static analysis and through 1000 cycles. The results are expressed in terms of percentage of damage (18,1%), the minimum number of cycles to fatigue failure was 5510 and a load factor of approximately 1,6. In this analysis the critical component is the connection between seat tube and the motor support.

Load case 3

The results were a maximum tension of 240 MPa and a maximum displacement of 3,6mm. This represents a safety factor of approximately 11,3. In this analysis the more problematic component is in the handlebar assembly, mostly in the head tube. Nevertheless, we still have some considerable stress concentrations in the motor support.

The results are expressed in terms of percentage of damage (57%), the minimum number of cycles to fatigue failure was 1754 and a load factor of 1,2. Such as in the static analysis, the components with higher stress concentrations are the handlebar, stem and mostly the support for the motor.

Considering the same maximum rotations for the motor (9,27Hz) 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.

Reviewing the results from all the analysis made, we can conclude that the most critical load case is the third one. The main component that can reveal to be problematic and should be reinforced is the support for 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 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 presented higher stress concentrations.

12. PROTOTYPE CONSTRUCTION

Along the building and mounting process we came along with some difficulties. The 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.

The handlebar stem and wedge nut didn't fit the inside of the headset, even so it was by a small margin. We used a lathe to remove a small share of material from the bottom part of the stem and wedge nut. 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. 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 centred 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 and that in the prototype would have any function.

To remove the old paint and rust from the frame we used a chemical process. We used pickle liquor several times until we've accomplished to remove all the rust and ink. 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 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 it a glossy finish.

To shape the special washers that locked the rear axle hub from spinning we started from solid piece of steel and used a lathe and a manual milling machine. 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 the washer, it was painted the same way as the bicycle frame.

13. CONCLUSION AND FUTURE WORK

This work was developed with the intend to project and build an electrically assisted bicycle adapted to the metropolis environment. It is a concept designed to create a better and more versatile alternative to be used as mean of transportation in urban scenarios. It should present advantages and better features than the usual alternatives.

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 began. 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.

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, these major drawbacks are expected to be overcomed.

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