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Morphological Design of a Bicycle Propulsion Component Using the Hierarchical Analysis Process (AHP)

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Abstract: There are many mechanical and/or electrical energy storage devices nowadays which can be mounted on standard bicycles. The current trend regarding bicycle energy storage devices is to develop and improve electrical and electronic systems that can ease transportation. However, this paper shows the design process of a purely mechanical energy storage device, with no electrical components, which instead aims to entertain the user, producing a stimulus related to speed and physical exertion. The mechanical device has been designed according to an aspect or fashion known as steampunk, so that the mechanical elements forming the device (springs and spur gears) are visible to the user. The storage and discharge of energy are only produced by the user. In order to charge the device, after reaching an appropriate speed, the user uses the pedals in reverse motion. Alternatively, the mechanism can also be charged with a controlled braking system by actuating on a crank. The design process was based on the total design of Pugh and the AHP and QFD techniques.

Keywords: propellant for bicycle; mechanical power storage; steampunk; total Pugh design; technique AHP

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1. Introduction

Energy storage mechanisms by means of elastic deformation have been widely used since ancient times, especially as clockwork mechanisms. One of the first mechanical designs capable of storing energy in the form of elastic deformation, and later releasing it voluntarily to move a vehicle, was the car designed by Leonardo da Vinci in 1495 [1]. This three-wheeled self-propelled vehicle stored the deformation energy in leaf springs and then released it voluntarily to move the vehicle. Other systems based on elastic deformation in springs have been applied more recently to bicycles. For example, in 1898 [2] an energy storage spring system was patented for mounting on bicycles and velocipedes. This new system stored energy in a controlled manner and was released voluntarily by the rider. More recently, another energy storage system based on clock springs was mounted on a bicycle in 1921 [3]. More sophisticated, but based on the same system as above, was the system patented and mounted on a bicycle in 1959 [4]. Currently, a system very similar to the above was patented in 2012 and applied on bicycles [5]. The mechanical energy storage system proposed in this article is based on a commercially available flat spring strip. The importance of this research lies in its ability to take advantage of the abundance of mechanical and electrical energy storage capabilities that exist today, which can be harnessed and integrated into standard bicycles. Devices that harness surplus energy mean that users can enhance their cycling experience and, at the same time, meet a multitude of needs. The primary research questions addressed in this study are: How can mechanical energy storage be effectively integrated into bicycles? Previous studies have explored energy storage solutions for bicycles mainly in the electrical sector in order to ease transportation; however, this approach distinguishes itself by focusing solely on mechanical elements and incorporating the steampunk aesthetic. By making the mechanical components, such as springs and spur gears, visible to the user, the aim is not only to entertain but also to provide a direct sensory stimulus correlated to speed in order to enhance physical exertion. The design process used in this paper is based on the total design of Pugh [6], which is a methodology for product design, and the Analytic Hierarchy Process (AHP) and Quality Function Deployment (QFD) techniques.

The total design of Pugh [7] is a structured approach to product design that involves identifying and evaluating different design alternatives and selecting the best one based on a set of criteria. This methodology helps to ensure that the final product meets the needs and requirements of the user. Regarding the selection of techniques for multicriteria decision making, ELECTRE, PROMETHEE, MAUT, TOPSIS, and VIKOR were not chosen for various reasons. ELECTRE offers advantages such as avoiding the transitivity of achievements [8], handling quantitative and qualitative criteria, and providing a complete ranking of alternatives. However, it has disadvantages such as subjective choice of concordance and discordance thresholds and theoretical weaknesses. PROMETHEE is easily understandable by decision-makers [9], allows for expressing preference levels, and enables obtaining a total or partial ordering of non-dominated alternatives. However, it also involves subjectivity in defining pseudo-criteria parameters and has some theoretical limitations. MAUT (Multiattribute Utility Theory) allows for decision-makers to consider preferences through a utility function [10], reflecting the value or utility each alternative has for the decision-maker. It provides a strong axiomatic foundation for rational decision-making under multiple objectives. However, its practical application requires accepting assumptions of utility functions associated with each attribute and independence of preferences between attributes, resulting in complex calculations and high interaction with decision-makers for utility function construction and aggregation. TOPSIS introduces two reference points: positive ideal and negative ideal, enabling quick identification of the best alternative [11]. However, it does not consider the relative importance of distances and depends on the evaluation unit of the criterion function for normalized values. VIKOR is a useful tool in a multi-objective environment [11], providing scientifically and reasonably sound results for decision-makers. It is particularly powerful when decision-makers are unable to express their preferences at the beginning of the problem design. VIKOR allows for conflicting criteria with different units and involves analysing stability intervals to determine weights. However, VIKOR's results depend on the ideal solution, and including or excluding an alternative can impact the ranking of a new set of alternatives. The derivation of preference rankings in VIKOR has also been subject to improvement proposals. Considering the specific objectives and requirements of the research paper, the AHP and QFD techniques were found to align effectively with the design process for the mechanical energy storage device applicable to bicycles. These techniques provide the necessary structure and methodology for evaluating and prioritizing criteria and alternatives in a manner that complements the design approach and goals.

The Analytic Hierarchy Process (AHP) is a decision-making tool [12] that allows for analysing and comparing different options based on a set of criteria. This technique is often used in product design to help identify the most important criteria and to evaluate how well different design alternatives meet those criteria [13]. Due to its ability to structure complex problems into hierarchies and facilitate systematic comparison and evaluation of criteria and alternatives, by breaking down a problem into levels and sublevels, AHP enables decision-makers to carefully analyse and weigh different factors and considerations. This is especially useful in situations where criteria and alternatives are numerous, and a clear understanding of their relationships is needed. The hierarchical structure of AHP provides a coherent framework for addressing complex problems and helps decision-makers better grasp the impact of their choices across different levels and aspects. However, it is important to note that AHP has some limitations in addressing complex problems. While it can handle both subjective and objective criteria, its focus on pair-wise comparisons and assigning numerical values to subjective preferences may fall short in certain cases. Additionally, the hierarchical structure of AHP may not fully reflect the relationships and opinions in complex projects involving multiple levels, horizontal links, correlations, and feedback. While AHP has been successfully applied in various contexts such as project management, corporate decision-making, and personnel selection, there are criticisms suggesting it may not be suitable for complex problems. These criticisms argue that AHP oversimplifies the decision-making process and fails to address the broader implications that decisions may have on the lives of many people.

In summary, AHP is a valuable tool in decision-making by providing a hierarchical structure and systematic methodology to address complex problems. However, it is important to recognize its limitations [14] in handling subjective criteria, interrelationships, and accurately representing the complexity of certain problems. When evaluating the suitability of AHP for a particular problem, careful consideration of the specific characteristics and demands of the problem, and if necessary, complementing the AHP approach with other more suitable decision-making tools or methods, is crucial.

QFD is a process that helps to ensure that the final product design meets customer needs and expectations [15]. This technique involves identifying the customer's needs and translating them into design requirements. These requirements are then used to guide the design process and to ensure that the final product meets the customer's expectations.

Overall, it seems that the design process for this device was based on a structured approach that involved identifying the customer's needs, evaluating different design alternatives, and selecting the best option based on a set of criteria. The use of AHP and QFD helped to ensure that the final product met the needs and expectations of the customer [16].

The study provides two main contributions. Firstly, a detailed design process for the mechanical energy storage device is presented, incorporating principles from Pugh's total design and utilizing analytical techniques such as Analytic Hierarchy Process (AHP) and Quality Function Deployment (QFD). Secondly, an innovative approach is introduced by incorporating a steampunk-inspired aesthetic into the design of bicycle energy storage. This aesthetic element enhances user engagement and experience. The research focuses on addressing the integration of visible mechanical elements within a steampunk-inspired design, thus addressing the research questions related to mechanical energy storage in bicycles. By highlighting the significance of the topic, presenting the contributions, and explaining the rationale behind the chosen methodology, the study aims to demonstrate the originality and motivation behind this research endeavour.

In addition, the authors of this paper have improved the previously proposed systems, and based on previous studies of back-pedal braking systems, they propose an energy recharging system for this brake by using the pedals in the opposite direction of the travel motion. The propulsion system shown in this paper is based on the storage of the deformation energy in flat coil springs or flat coil springs, in order to later, and voluntarily, release this energy and be able to move a vehicle.

The design of this new propulsion system has been carried out through a design process called morphological design. The main function of this new mechanism is to provide an impulse in a short period of time generated from stored mechanical energy. The storage of this mechanical energy is carried out by the human action of the cyclist, and this can be done in two different ways: The first consists of pedalling in reverse, and the second by the manual actuation of a crank. The two forms of operation must charge a winding mechanism (similar to the winding mechanism of an old watch) with elastic energy at the cyclist's will and release this energy when the cyclist deems it necessary.

2. Design Methodologies

To ensure a systematic approach in the development of our bicycle energy recovery system, we have expanded upon Pugh's total design methodology, which served as our guiding framework throughout the design cycle. This methodology encompasses several key stages, including problem definition, concept generation, and concept selection. By following this structured approach, we were able to effectively address the challenges and requirements of our design project.

Within our design process, we carefully considered three alternative designs for the energy recovery system. To objectively evaluate and identify the most suitable design, we employed the Analytic Hierarchy Process (AHP). AHP provided us with a systematic framework to organize our criteria hierarchy and determine their relative importance. The criteria we considered spanned various aspects, such as weight, volume, durability, comfort and pleasure, aesthetics following a steampunk-inspired fashion, sound quality, simplicity of emergency stop, affordability, resistance to falls, innovation, and minimizing mechanical losses. By assigning weights to these criteria, we were able to prioritize their significance during the design evaluation phase. Through pairwise comparisons facilitated by AHP, we quantified the relative importance of each criterion, enabling us to make informed decisions and select the optimal design alternative.

In addition to AHP, we also employed Quality Function Deployment (QFD) to assess the quality of our proposed design and align it with customer requirements. QFD allowed for us to systematically capture and prioritize the needs and expectations of our target customers. By effectively translating these customer requirements into design features and characteristics, we ensured that our final design would satisfy their expectations and enhance their overall experience.

These methodological enhancements significantly contribute to the rigor and systematic nature of our design process. By incorporating Pugh's total design methodology, AHP, and QFD, we established a solid foundation for the selection and evaluation of design alternatives.

Usually, previously established methodologies are used in the design process of a new product. In this case, the design methodology used was known as Pugh's total design. This design methodology is framed within what are known as integrative theories and is usually applied in the following 5 points:

1. Detection of the Need. Whether latent or created, the need is defined for which a solution must be determined for a future customer.
2. Market research. It is necessary to acquire knowledge about the sector that has the need for our product by carrying out qualitative and quantitative studies. The motivation of the buyer is determined, competitor products are studied, market segmentation is carried out, distribution is considered, etc. We must take into account all kinds of factors that may affect later phases of the project. This set of information regarding the market is called Marketing Specifications.
3. Technical Specifications of the Design, Functional Specifications. The need is expressed in a functional way. It establishes, in technical clauses, all the necessary indications for the development, industrialisation, production and quality assurance stages. The results are set out in the Functional Specifications.
4. Conceptual Design. Concrete solutions are sought, based on the specifications of the previous phases, making use of creativity. The ideas are expressed in the form of sketches and methods for the selection of alternatives are used. In this way, the design that best fits the specifications described is chosen. The choice of the best proposed conceptual design (sketches) is made by using established techniques such as the following. One of these selection techniques can be the AHP. In addition to this selection technique, another technique called QFD is often used to assess the quality of the product to be designed. The steps of the AHP method in this work are:

Step 1. Define the decision problem: Clearly state the objective of selecting the best conceptual design based on the specifications and requirements from previous phases.
Step 2. Establish the hierarchy: Create a hierarchical structure that represents the criteria and alternatives. The top level could be the objective of selecting the best conceptual design, followed by intermediate levels representing criteria such as functionality, aesthetics, feasibility, and other relevant factors. The bottom level would include the alternative conceptual designs.
Step 3. Pairwise comparisons: Compare each criterion with every other criterion and assign numerical values to represent their relative importance or preference. For example, compare functionality with aesthetics and assign a value based on their relative importance.
Step 4. Create a comparison matrix: Construct a square matrix for each level of the hierarchy, where the elements of the matrix represent the pairwise comparisons made in the previous step.
Step 5. Calculate priorities: Calculate the priority vector for each matrix by normalizing the columns of the matrix and computing the average values.
Step 6. Check for consistency: Assess the consistency of the judgments by calculating the consistency ratio (CR). If the CR exceeds a predefined threshold (e.g., 0.1), you may need to revise the pairwise comparisons to ensure consistency.
Step 7. Aggregate priorities: Multiply the priority vectors of each level to obtain the weighted priorities for the alternative conceptual designs.
Step 8. Perform sensitivity analysis: Conduct sensitivity analysis to evaluate the stability of the results and assess the impact of changes in the pairwise comparisons.
Step 9. Make the decision: Use the weighted priorities to rank the alternative conceptual designs and select the one that best fits the specifications and requirements.

5. Detailed Design. Once the solution for the need has been chosen, it is necessary to determine the components and interactions. Shapes are defined with greater rigour, taking into account geometries, interactions, etc. These factors condition the dimensions of the product and have to be taken into account when making overall drawings with general dimensions.

In this paper, the sections corresponding to the detection of the need, market study, and technical design specifications have been omitted, and it focuses on the Conceptual Design and Detailed Design of the Product. In addition, it is necessary to research all types of existing mechanical systems for their possible study and comparison. In this way, a sweep is made of all existing ones, observing and understanding different types of mechanisms similar to the one to be designed by means of audiovisual and written documentation, covering as many fields of study as possible. Once the sketches have been generated from the mechanical systems studied, they are evaluated, and the best ones are selected using AHP techniques. Likewise, in order to know the scope and quality of the selected product (sketch) to be designed in detail, quality assessment techniques are used. In this case, the quality assessment technique has been the QFD method.

3. Conceptual Design According to Pugh

Normally you can always innovate by using old ideas, combining and modifying them so that their new functions are different, and for this reason, this stage is of vital importance. In this case, the first sketches refer to a first design characterized by storing energy through a flat power spring housed in the interior space of the bicycle frame.

3.1. Sketch 1

In this first proposed sketch, the patent of Daniel Zaborsky [3] is modified by introducing the freewheel (3), a ratchet (7), and a toothed wheel is suppressed since said wheel is not necessary with this new configuration (Figure 1). Through the freewheel (3), the mechanism is loaded only by pedalling in reverse. For this reason, while a forward gear is being used with the pedals, the mechanism does not move since said pinion does not transmit movement. The freewheel (3) does not transfer the efforts produced with the pedals in forward direction. This has been achieved by reverting the design of the freewheel that is typically mounted in the rear wheel of standard bicycles.

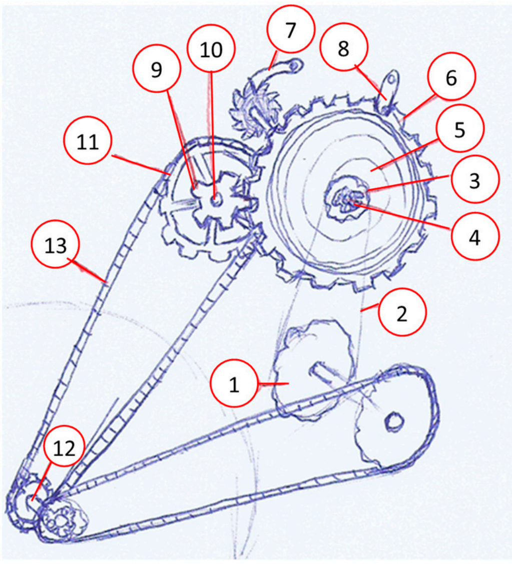


Figure 1. First proposed sketch.

As shown in Figure 1, a crank (1) is symmetrically placed on the left side of the bicycle, opposite to the right-side plate. This crank drives a gear (3) through a chain (2). The freewheel (3) is freely rotating, but its shape is opposite to the one fitted at the right-hand side in the rear wheel gear. This allows for the gear (3) to rotate freely without generating torque on its axis (4) when the plate (1) moves in the forward direction. Conversely, when a backward movement is applied to the plate, the gear forces its axis to move along. This modification allows for the axis (4) to rotate in reverse by pedalling backwards, harnessing this motion for energy generation, while remaining fixed during forward pedalling.

Axis (4) is fixed to a flat power spring (5), which stores rotational energy. One end is fixed to the axis, while the other end is connected to the inner side of a toothed wheel (6). This wheel (6) is mounted on bearings on the axis (4) to rotate independently.

During the negative load movement, the axis (4) rotates, causing the spring (5) to wind around it. To prevent the system from discharging due to intermittent loading, a ratchet (7) is placed to restrict the axis movement, allowing for rotation only in the negative direction. Furthermore, the movement of the wheel (6) is blocked by another ratchet (8). This ratchet (8) allows for the user to choose the precise moment of energy discharge. It is connected through cables to a lever accessible by the cyclist, so that when the lever is pressed, the ratchet is released, allowing for the wheel (6) to rotate in the negative direction, discharging the spring.

The wheel (6) is continuously engaged with another wheel (9), which rotates together with an axis (10). Another wheel (11) is also fixed in parallel to this axis (10). The rotation of the assembly, upon engagement with the wheel (6), is in the forward direction. The wheel (11) shares the same axis of rotation but is in a different plane than (9), so it does not engage with (6). This is another modification introduced in the mechanism compared to the original patent. By charging the system with a negative rotational direction and having the option to choose when to charge it, one gear is eliminated since the rotation of wheel (11) is in the same direction as the forward movement. Therefore, connecting this wheel to a fixed gear (12) on the rear wheel through a chain (13) allows for the entire discharge to be transmitted to the rear wheel.

3.2. Sketch 2

This second design is based on the gear-shifting mechanism of a car. It primarily consists of a spool mechanism, two gear wheels with springs inside, and a plate, chain, and sprocket mechanism, similar to a regular bicycle. It is a component located on the rear wheel of the bicycle. All the energy discharge will be transmitted to this wheel.

The mechanism is intended to operate independently of the gear-shifting mechanisms currently used in bicycles. The right side of the bicycle (mounted on the bicycle as a reference) remains unchanged, with or without gear shifting and their respective gear wheels. In this case, similar to design 1, a crank (1) is placed on the left side of the crank set, allowing for energy to be charged by pedalling in the opposite direction of forward movement, which will be referred to as the negative direction. Similarly, the sprocket (2) to which the crank is connected through a chain (3) is free during forward pedalling, known as the positive direction (see Figure 2a). This way, the sprocket (2) does not transfer the motion to the axle in this latter direction.

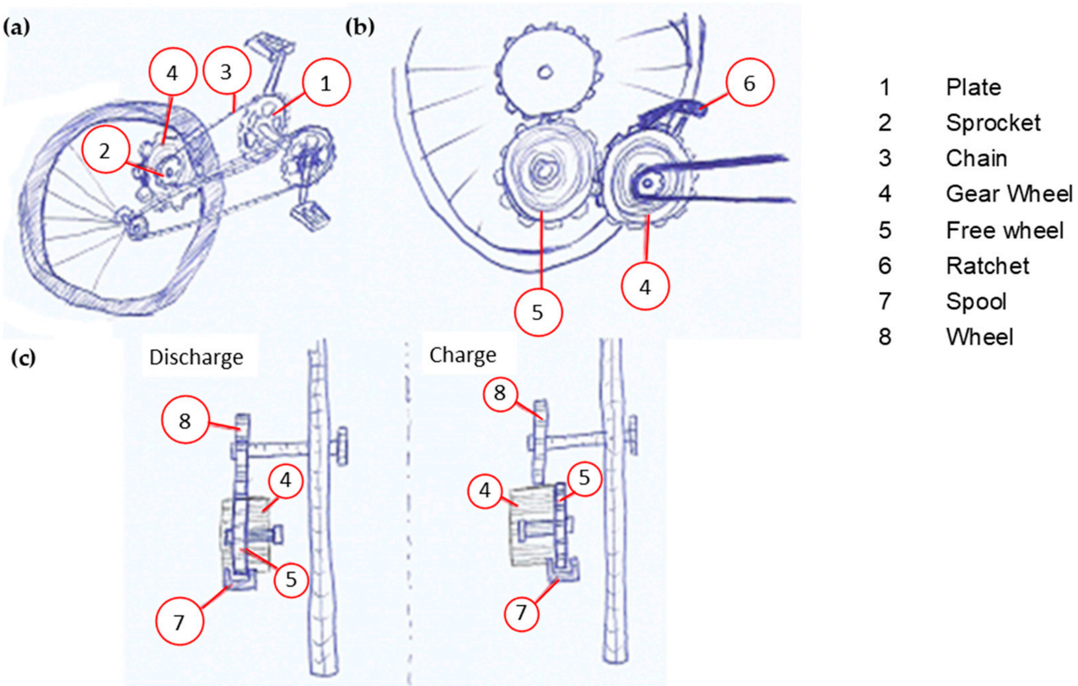


Figure 2. Second proposed sketch: (**a**) general view of the sketch, (**b**) front view of the load area assembly, and (**c**) side views of Sketch 2 in discharge and charging positions.

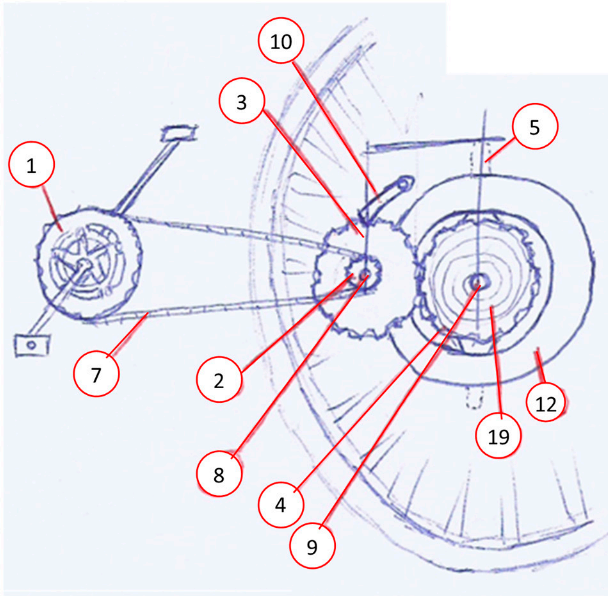
Therefore, when pedalling in the negative direction, the sprocket moves the axle to which it is attached, and along with it, a gear wheel (4) moves simultaneously. This gear wheel contains a flat power spring inside, which allows for rotational energy to be stored. The gear wheel (4) engages with free wheel (5). This wheel is similar to the previous one, containing another flat power spring inside (see Figure 2b). Since it is still a conceptual design, no calculations have been made regarding the sizes and teeth of the gears. Therefore, their size, as well as the inclusion of the springs in one or both wheels, can be freely changed.

A configuration is chosen in which both wheels (4) and (5) contain a spring. When the charging movement is performed, both gears engage, causing their respective springs to rotate. Since the charging can be intermittent, a ratchet (6) is necessary to block gear wheel (4) and prevent both springs from discharging when there is no charging movement. As mentioned at the beginning, the spool system is based on the gearbox mechanism of a car. A spool (7) is placed, allowing for the wheel (5) to be moved from the charging position to the discharge position (see Figure 2c). This spool is operated by a lever accessible to the user. To ensure that both springs discharge at the same time and to prevent wheel (5) from becoming misaligned with wheel (4), the latter should be wider, so that when (5) is moved, it continues to engage with (4).

When the discharge is activated, the ratchet (6) is released, and the wheel (5), through the spool (7), is moved to the discharge position. At that moment, wheel (5) engages with wheel (8), which moves in unison with the rear wheel's rotation axis. In this way, all the rotational movement produced by the energy accumulated in the springs of wheels (4) and (5) is directly transferred to the bicycle's rear wheel.

3.3. Sketch 3

Third, Figure 3 shows sketches developed for a design which initially was based on the differential mechanism used in the automotive sector. However, as can be seen in the drawings and later in this article, it has been necessary to modify all its forms and include new parts so that its functions are different.



1	Plate
2	Sprocket
3	Toothed Wheel
4	Toothed Wheel
5	Gear Wheel
7	Chain
8	Axis
9	Shaft
10	Ratchet
12	Disc
19	Spring

Figure 3. Third proposed sketch.

A positive direction is defined as the one produced by the pedals on the right-side crank when a forward movement of the bicycle is made, and a negative direction is defined as the opposite movement of the crank. Likewise, energy storage will be carried out solely with the strength of the legs when turning the left-side crank in the opposite direction. Taking the vision of the user mounted on the saddle as a positional reference, the right-hand side of the bicycle is left intact, when compared to a standard bicycle, and therefore no changes are applied to its sprockets and chainrings. The proposed device is mounted on the left side of the rear wheel.

As in the 2 previous cases, there is a plate (1) connected to a sprocket (2) by means of a chain (7), as can be seen in Figure 3. Said sprocket (2) is free in the positive direction and engages with its axis (8) in the negative direction, which is the loading one.

Solidary to the axis (8), there is a toothed wheel (3). This engages with the wheel (4), which has the flat power spring inside (19). Said wheel (4) can rotate freely on an axis (9). For this reason, bearings are placed between the wheel and the axis. The axis always remains fixed. One end of the spring is fixed on it, and the other end is fixed on the inside of the wheel (4). To charge the system, the wheel (4) will rotate in a positive direction. Since the shaft (9) is fixed, it will unload in the opposite direction that it was loaded, then it will rotate in the negative direction. As in previous designs, a ratchet (10) is necessary to block the wheel (3) so that the system does not unload if the load is discontinuous. This same ratchet is the one that allows for the discharge to start if it is lifted.

The key invention of this design consists of modifying the differential, used automobiles by making the wheel (4) be the drive gear and repurposing the sub-system; this way, it acts effectively as a clutch, allowing for disengaging the loading motion from the forward movement of the bicycle. Other subsystems are added and explained further below to allow for transmitting the energy stored to the rear wheel. It can be seen in Figure 4 that the wheel (4) has a conical-shaped wheel extruded on one of its faces. The wheel (4) engages with a pair of wheels (5), which in turn engage with the wheel (6). The four wheels have a straight conical profile. The wheel (6) rotates in solidarity with the axis (11).

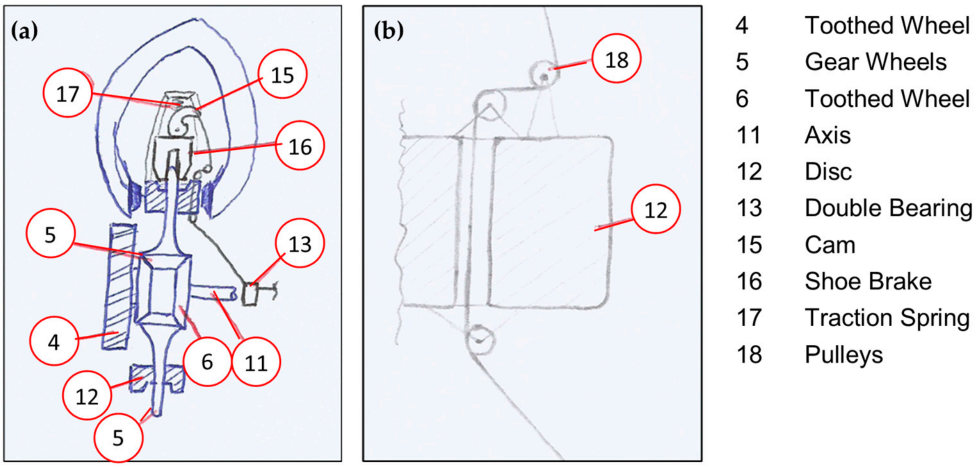


Figure 4. Detail of the energy-charging system through braking. (**a**) Front view, (**b**) detail of disc and pulleys.

The wheels (5) can rotate freely around the axis (11). In this way, while the bicycle is in normal gear and the wheel (4) remains locked without loading, the wheels (5) being in contact with the (6), are forced to move circularly in a plane perpendicular to the axis (11). If the system is loaded by pedalling backwards while driving, its result, in addition to the energy stored in the spring, is that the wheels (5) will move more slowly. Consequently, it has been possible to separate the energy-charging movement from the normal forward movement of the bicycle.

In order to have an effective discharge and transmission of the accumulated energy to the wheel (6), another innovative element is introduced. A disc (12) is placed across which supports the axles of wheels (5). These wheels can rotate freely on themselves inside the disc, and for this, bearings are placed between the axles and the disc. Finally, a brake shoe is included to block the circular movement of the wheels (5) in the plane perpendicular to the axis (11). That is to say, the disk (12) is braked by means of some shoes, which follows the same circular movement described, so that the wheels (5) can only rotate on themselves. With this configuration, the unloading movement of the driving wheel (4) will be transmitted directly to the rear wheel through the wheels (5). It will be necessary for the disc to brake and the release of the ratchet to occur at the same instant for the discharge to be effective.

In Figure 4, you can also see another brake system that is included, through which it is possible to load the system by breaking the bicycle and without action of the user's legs. When the user presses another brake lever for the sprockets (5), a double bearing system (13) moves thanks to the wire ropes that connect it to the lever. This displacement pulls on a wire rope connected to the double bearing (13) and to the cam (15). The rotation of the cam exerts pressure on the shoe (16), thus stopping the rotation of the wheel (5) with respect to the axis that joins them. The system is symmetrical with respect to the axis (11), and therefore consists of two cams, two shoes, two wire ropes, etc.

By preventing rotation on the gear wheels (5), the toothed wheel (6) and the component fixed to the rear wheel of the bicycle and the toothed wheel (4), which stores the energy, are forced to rotate jointly. Since the forward movement is positive, and the load movement is positive, the result is that when the right lever is pressed, the bicycle is braked, and the sprocket (4) is loaded. In addition, a fixed support system is placed on the disc (12) with a traction spring (17), which joins said support to the shoe brake (16). In this way, by releasing the lever that produces the rotation of the cam (15), the cam is forced to return to its initial position. This implies that the double bearing (13) will also return to its initial position.

Figure 4 shows how the wire rope connects the cam (15) with the double bearing (13) through a through hole. It is a section of the disc (12) in which the action of the pulleys (18) can be seen, without which the movement of the wire rope that joins the cam and the bearing would not be possible. It has been designed this way because the disc brake fork (12) makes any other arrangement impossible. This is fixed and the disc is not, so the rotation of the disc, and therefore the cam, would cause the wire rope to crash against the fork, thus blocking the movement.

4. Results

4.1. AHP Application

The Analytic Hierarchy Process (AHP), proposed by Thomas Saaty in 1988, is a well-known decision-making method in mathematical analysis problems. It is based on pairwise comparison matrices [17–20].

All these matrices are square matrices, and the principle of reciprocity must always be fulfilled. Given matrix A with dimensions m $\times$ m (where m represents the number of criteria defined in the structure), each element a_{ij} represents the relative score of one criterion compared to another. In other words:

$$A = \begin{pmatrix} 1 & a_{12} & \ldots & a_{1n} \\ a_{21} & 1 & \ldots & a_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ a_{n1} & a_{n2} & \ldots & 1 \end{pmatrix} \quad (1)$$

Matrix A is a pairwise comparison matrix (PCM) as long as a_{ij} defines the preference of the criterion in row (i) compared to the criterion in column (j). When comparing a criterion to itself (i = j), the value is always 1. The criteria for establishing the different scores are detailed in Table 1.

Table 1. Saaty's scoring criteria.

Scale	Description
1	Both criteria are equally important.
3	Slightly to moderately more importance of one criterion over another.
5	Essential or strong importance of one criterion over another.
7	Demonstrated importance of one criterion over another.
9	Absolute importance of one criterion over another.
2,4,6,8	Intermediate values between two adjacent judgments.
Reciprocal	Second alternative is preferable to the first.

Firstly, each attribute/criterion is compared to the rest of the attributes to quantify its importance relative to others. Then, the PCMs are created for each alternative in relation to each criterion. The number of matrices corresponds to the initially defined criteria.

All the matrices need to be normalized. Given the previous matrix [A], the normalized matrix [N] is obtained. Let w_{ij} represent each value in the matrix, and [N] is obtained by applying the equation to each value:

$$N = \begin{pmatrix} 1 & w_{12} & \dots & w_{1n} \\ w_{21} & 1 & \dots & w_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ w_{n1} & w_{n2} & \dots & 1 \end{pmatrix} \quad (2)$$

$$w_{ij} = \frac{a_{ij}}{\sum_{i=1}^{n} a_{ij}} \quad (3)$$

where $\sum_{i=1}^{n} a_{ij}$ is the sum of the columns.

For each normalized matrix, the priority vector (PV) is obtained. The PV is calculated by averaging the values of each row in the matrices [N]:

$$VP = \begin{pmatrix} \sum_{j=1}^{n} \frac{a_{1j}}{n} \\ \sum_{j=1}^{n} \frac{a_{2j}}{n} \\ \vdots \\ \sum_{j=1}^{n} \frac{a_{ij}}{n} \end{pmatrix} \quad (4)$$

On the three previous design alternatives (sketch), different selection methods are applied, such as the AHP (Discrete Multicriteria Decision), through which the value of the strongest design is quantified with respect to the others based on the requirements set above all by the client. To simplify the selection of these three previous sketches, the three alternatives are drawn in a general way, as shown in Figure 5.

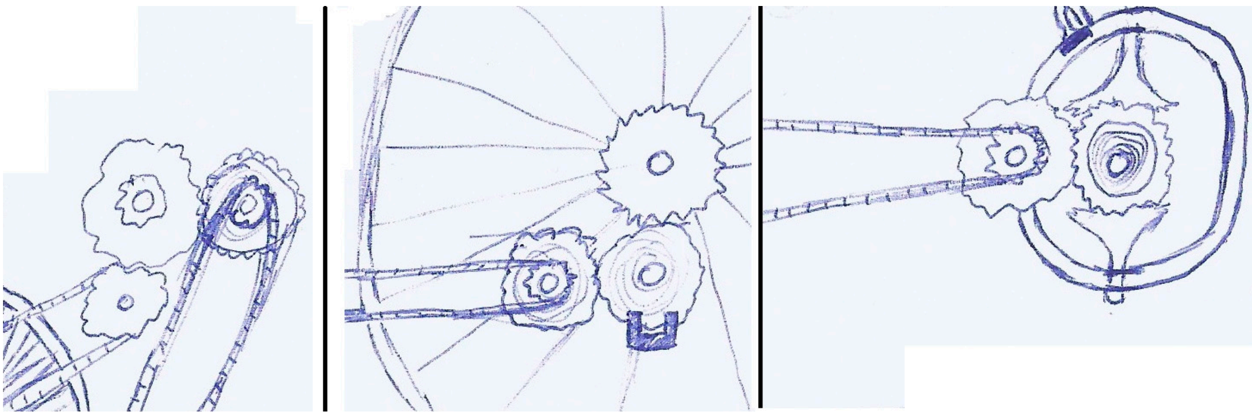


Figure 5. Three design alternatives on which AHP will be applied.

Of all the functions specified in the Functional Specifications, the most important function for the development of the AHP method is selected. Table 2 shows the requirements matrix, in which the importance of each requirement is valued one by one with respect to the rest. From these values, the weighted weights of each requirement or function will be obtained. The requirements or functions studied in this case have been: R1 weight; R2 volume; R3 durability; R4 comfort and pleasure; R5 having good looks following a steampunk-based fashion; R6 nice sound; R7 simple emergency stop; R8 not excessive price; R9 resist falls; R10 innovation; R11 minimize mechanical losses. These requirements must be selected by the designer and are based primarily on experience.

Table 2. Weighting for the different requirements studied.

		R1	R2	R3	R4	R5	R6	R7	R8	R9	R10	R11
▪	R1	1.00	3.00	3.00	0.33	0.20	0.20	0.11	5.00	0.14	3.00	3.00
▪	R2	0.33	1.00	3.00	0.33	0.33	0.20	0.11	0.20	0.14	0.20	0.20
▪	R3	0.33	0.33	1.00	0.20	0.20	0.33	0.14	3.00	0.33	0.33	0.20
▪	R4	3.00	3.00	5.00	1.00	0.33	1.00	0.20	5.00	0.20	0.33	0.33
▪	R5	5.00	3.00	5.00	3.00	1.00	0.33	0.20	7.00	0.20	1.00	3.00
▪	R6	5.00	5.00	3.00	1.00	3.00	1.00	0.20	7.00	0.33	5.00	3.00
▪	R7	9.00	9.00	7.00	5.00	5.00	5.00	1.00	5.00	3.00	7.00	7.00
▪	R8	0.20	5.00	0.33	0.20	0.14	0.14	0.20	1.00	0.14	0.20	0.33
▪	R9	7.00	7.00	3.00	5.00	5.00	3.00	0.33	7.00	1.00	5.00	5.00
▪	R10	0.33	5.00	3.00	3.00	1.00	0.20	0.14	5.00	0.20	1.00	3.00
▪	R11	0.33	5.00	5.00	3.00	0.33	0.33	0.14	3.00	0.20	0.33	1.00

The weight of each requirement is obtained by adding the sum of each row and dividing the result by the number of requirements. In this case, 11. Next, the matrices of the next level are made. Each matrix corresponds to a functional requirement of the eleven established and with it the importance of each alternative is obtained based on said criterion. Table 3 shows the matrix for the requirement to minimize mechanical losses.

Table 3. Level 3, requirement "minimize mechanical losses".

	Sketch 1	Sketch 2	Sketch 3	Weight
Sketch 1	1.00	0.20	0.33	0.11
Sketch 2	5.00	1.00	3.00	0.63
Sketch 3	3.00	0.33	1.00	0.26

To obtain the weighted weights of each design alternative based on each criterion at this level, each element of the matrix is divided by the sum of the elements of the column to which it belongs, forming a new matrix. The sum of the rows of the new matrix is performed and each sum is divided by the number of alternatives.

Finally, the weighted weights of level two are related to those of level three. The weighted weight of each criterion obtained at level 2 is multiplied with the weighted weight of the same criterion obtained at level 3. Immediately afterwards, the 11 values are added. The same procedure is carried out three times, one corresponding to each model, giving rise to three different values that correspond to the global importance of each one.

Sketch 3 has a value of 0.56702 compared to values of 0.21245, corresponding to model 2, and 0.22053, corresponding to Sketch 1. Therefore, Sketch 3 is the strongest design. From this moment, the project will be developed based on Sketch 3.

4.2. QFD Application

The QFD (Quality Function Deployment) is a quality tool used to determine the quality of a product to be designed. This tool is normally used at the beginning of the detailed design after the conceptual design has been finalized. The QFD allows for us to ensure the satisfaction of the needs established by the client so that their requirements become design objectives. In this case, the quality assessment (quality deployment) has been carried out based on the development of the relationship matrix between the client's need and the design parameters to be determined. The client's need has been extracted from the Functional Specifications, and the weighted weights of each function have been calculated using a matrix similar to that of level 2 of the AHP method. In addition, non-relevant functions have been included for the selection of alternatives, but which are extremely important in this quality section. The QFD table starts with the demand requirements, and from this, design parameters are defined so that each requirement is taken into account by at least one design parameter. The connection between each parameter created and the requirements (the numbers within the matrix) is quantitatively assessed, and the weighted weight of each requirement is also taken into account. The result of the latter gives a % to each parameter that indicates the total importance of each one with respect to the rest. Then, a new matrix is created in which the column on the left, instead of having the demand requirements, has the design parameters created from the demand and their weights (the % that has just been defined), and the component groups are placed in the first row where the parameters went before. Thus, the groups of components that respond to all parameters are designed and their quality is ensured, since the need for demand has been based on Table 4.

Table 4. Design parameters used in the QFD.

Customer Need	Weight	(9.2%) Useful Life	(17.0%) Range Pieces	(11.3%) Job Burden	(20.9%) Duration	(20.9%) Top Speed	(20.6%) Power Discharge
Weight	4.0%	-	9	3	3	3	3
Volume	1.6%	-	1	-	-	-	-
Durability	2.1%	9	3	-	-	-	-
Comfort and pleasure	4.1%	-	9	-	3	3	3
Good appearance	6.5%	-	1	-	-	-	-
Sound	7.5%	-	9	-	-	-	-
Emergency brake	17.4%	-	3	-	-	-	-
Price	1.8%	-	9	1	1	1	1
Resist falls	12.4%	9	-	-	-	-	-
Innovation	5.2%	-	-	-	1	1	-
Min. Per. Mech.	5.5%	-	3	-	9	9	9
Amuse, excite	23.7%	-	-	3	9	9	9
To exercise	8.2%	-	-	9	-	-	-

5. Detailed Design

Once the QFD has been applied, the best sketch has been selected, and the quality of the best sketch or model has been studied, the parts that make up the chosen mechanism are developed using the CATIA 3D part modelling software.

The final solution has been meticulously designed to effectively decouple the standard forward propulsion of the bicycle from the spring-charging mechanism, reintroducing the often-neglected functionality of reverse pedalling. Additionally, a significant enhancement has been implemented to augment the component's primary purpose, which revolves around leisure. This innovation enables the charging of the internal spring through a precisely controlled braking system integrated into the bicycle. While it is impractical to include an exhaustive description of the intricate part designs in the paper, Figures 6 and 7 provide a visual representation of the assembled components, showcasing their intricate 3D geometry. Figure 6 offers an overview of the entire mechanism, while Figure 7 focuses specifically on the energy recovery activation system embedded within the wheel brake (5).

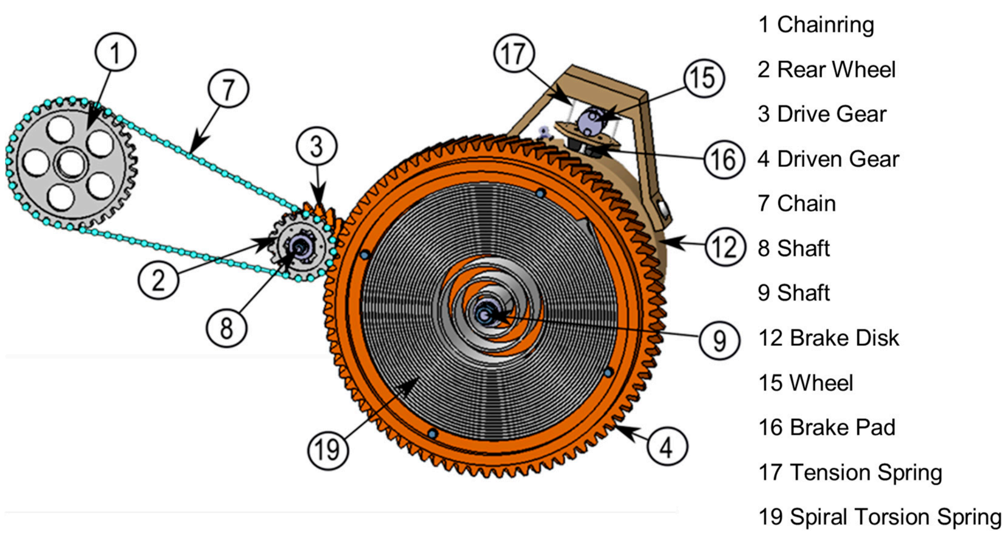


Figure 6. Detailed design of selected sketch or conceptual design.

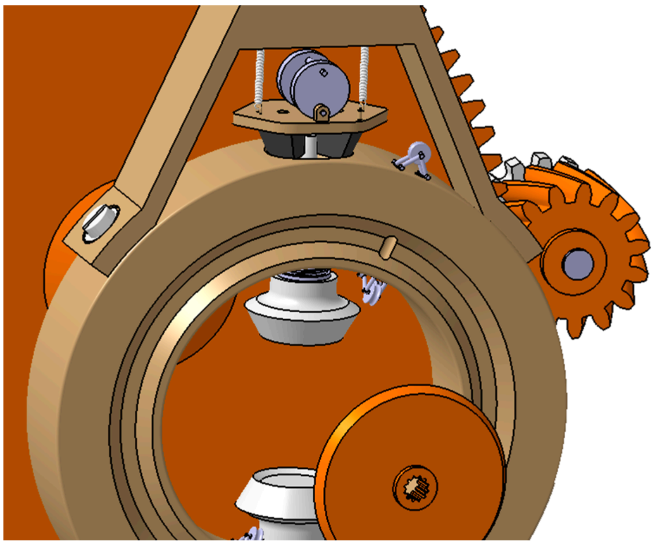


Figure 7. Detail of the braking energy recovery activation system.

6. Conclusions and Future Work

This article shows the design and development of a new energy recovery mechanical system to be mounted on bicycles. The new system is based on the elastic deformation energy of a coiled power flat spring. The design of this new mechanism has been based on Pugh's total design methodology, as well as on the application of selection techniques of multi-criteria selection methods (AHP) as well as the quality assessment method (QFD).

The design of this product has focused mainly on the conceptual and detailed design; however, Need Detection, Market Study, and Technical Design Specifications were developed in advance to generate the Functional Specifications. Finally, of the three models or sketches proposed, the one that met the best conditions in terms of design and quality with respect to customer requirements has been drawn in detail using 3D software.

In terms of design limitations, it is important to consider the inherent characteristics of mechanical elements influenced by the steampunk design style. These elements may introduce challenges such as weight, complexity, manufacturing tolerances, and clearances, which can affect maintenance requirements and overall costs. It is crucial to address these limitations and strike a balance between achieving the desired aesthetic appeal and ensuring practical functionality. By carefully managing these factors, future iterations of the design can aim to optimize performance while minimizing potential drawbacks.

Although the current study makes use of the AHP technique with satisfactory results in the framework of the bicycle design element problem, several limitations and challenges associated with the AHP method are known and its impact could be studied in more detail. These limitations include the subjectivity of pairwise comparisons, the potential discrepancy between weighted preferences and true preferences, the difficulty in modelling complex problems, the requirement for the quantification of criteria and alternatives, the lack of direct sensitivity analysis, the assumption of transitivity, the susceptibility to system rank reversal, and the potential mismatch between the hierarchical structure and the true structure of the problem [14]. In future research, the application of the Ordinal Priority Approach (OPA) [20–23] method and its extensions, such as robust OPA, DEA-OPA, fuzzy, and interval OPAs, can be explored to enhance the design process of the energy mechanical storage device for bicycles. By incorporating these advanced MCDM techniques, designers can effectively consider the diverse criteria and preferences involved in the design process. The OPA method can provide a systematic framework for incorporating ordinal preferences, allowing for designers to prioritize and select the most suitable design alternatives based on user preferences related to speed, physical exertion, and entertainment value. Additionally, the robust OPA extension can account for uncertainties in the design parameters, ensuring the selected design is resilient to variations and provides reliable performance. Furthermore, the DEA-OPA extension can be utilized to evaluate the efficiency and effectiveness of the proposed design alternatives, considering both preference information and efficiency aspects. Lastly, the fuzzy and interval extensions of the OPA method can handle imprecise or vague user preferences, enabling designers to accommodate subjective factors and optimize the design accordingly. These future research directions can significantly contribute to the development of an enhanced energy mechanical storage device design methodology that integrates state-of-the-art MCDM techniques, resulting in a more robust, user-centred, and efficient design solution.

As part of our future lines, we will focus on designing a brake system that incorporates essential brake pads to effectively immobilize the disc and enhance the power brakes. Furthermore, we aim to explore potential improvements by utilizing lighter materials that can withstand the anticipated stresses. These advancements will be accompanied by rigorous performance analysis and evaluation, enabling us to optimize the brake system design and material selection. By addressing these key aspects, our goal is to significantly enhance the overall effectiveness and efficiency of the bicycle energy recovery system.

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