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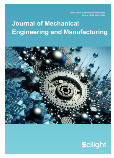

Article

Development of a Rapid Assembly Mechanism for a Child Bike Seat

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Abstract: With the evolution of cities towards a model characterised by multiple urban centres, where housing and services coexist near, the way people move and how transport is ensured shifts from long-distance commuting to the concept of micromobility. This transformation necessitates the development of new mobility solutions adapted to this context, such as the subject of this study: the development of a coupling system for a bicycle child seat. To meet the emerging needs of the population, the proposed system aimed to improve existing market solutions. In this regard, the Design Science Research (DSR) methodology, which is well-suited for such development-oriented studies, was employed to guide the process. A set of initial design proposals were generated and evaluated based on their strengths and weaknesses. Subsequently, a selection matrix was applied to identify the two most promising concepts. Through an iterative design process, these two concepts were merged, refined, and enhanced, resulting in a product that features a mechanical clamping lever system, protected by an anti-theft locking mechanism and compliant with current safety regulations. Finally, the system's structural performance was validated using Finite Element Analysis (FEA), which confirmed its resilience and mechanical integrity under the EN 14344:2004 standard's proposed loading conditions, thus ensuring user safety and supporting the product's position within the existing market.

Keywords: baby bike seat; fastening system; product development; finite element method

1. Introduction

Societies throughout human history have been driven by development and the incessant need for commodities, triggering the imperative to create more advanced and optimised infrastructure systems, in which modern and high-tech cities came along with the process. To implement such a concept, cities are being built of multiple clusters providing services and hospitality that accommodate all the needs demanded by the population in one region [1,2], contributing to a daily reduction in travel time, and therefore, giving more hours to each individual to enjoy their free time, benefiting their well-being. In this innovative city architecture, transport plays a crucial role in ensuring all the benefits and efficiency, culminating in micromobility solutions that enable a fast and autonomous mode of transport [3] which is already happening in dense urban centres of Europe and East Asia, where between 33.33% and 66.66% of all trips are made by bicycle or on foot [4]. Moreover, this transport concept makes a positive contribution to achieving the full decarbonization goal set by political institutions, which aim to reduce global emissions to limit the average temperature increase to 2 °C above pre-industrial levels [5,6], driving institutions and private companies incentivise the use of bicycles as a means of transport. Therefore, developing solutions that can be integrated into bicycles to increase the convenience of users, and their safety can beneficially support the market needs and additionally trigger the use of bicycles as transport.

To respond to this new paradigm, in recent years, there has been substantial growth in bicycle-related research [7,8], with a focus on understanding dynamic performance, comfort and in improving safety. Regarding dynamic performance, efforts are being made to understand and develop tools that can simulate and measure the impact of factors like slope and wind on the battery consumption of electric bicycles [9–11]. In terms of comfort, devices equipped with sensors are being developed to measure the vibrations in a bicycle, and a respective software capable of processing it to determine the amount transmitted to the human body [12,13]. In the same line, various trials are being made to understand the impact of vibrations related to cycling in the human body, with studies showing vibrations experienced by riders can increase the cardiopulmonary and respiratory system response [14], the capacity of vibrations in activating muscular groups causing energy waste [15,16], and that damping solutions in road-bicycles do not affect neuromuscular response, resulting in no power gains [17]. Concerning safety and user convenience, the developments focus on both passive and active solutions that enhance risk mitigation, which is intertwined with upgrades that make daily life easier for bicycle users. For active devices, some evolutions go towards the development of a brake mechanism that assists the rider during unexpected situations, where a self-detecting mechanism assists the braking operation, being particularly targeted to elderly people who possess lack of strength and have low reflexes [18]. Other approaches focus on developing an active stabilising system using a gyroscopic, that assists the rider in situations where loss of control may occur due to contact with external objects, low speeds, or abrupt turns [19]. When it comes to passive solutions, they serve as a bridge between instruments that contribute to a safer approach, with upgrades that add extra utility to bicycles. Among these options, adjustable handlebars are characterised by allowing the precise adjustment of their position depending on the rider's physiology, providing a bigger range of users and a positive contribution in preventing back fatigue that can lead to injuries [20]. Other upgrades developed throughout the year include child bicycle carriers, an accessory designed to provide a practical and versatile solution for families, enabling efficient planning of daily school drop-offs or functioning as a general means of transport, thereby enhancing user convenience. Therefore, some authors are focusing on researching and improving this device to make it safe for children and more assembly convenient, answering to market demands. In this way, several studies addressing this subject will be summarised.

Ptak et al. [21] by perceiving the lack of kinematics understanding involving children in accidents, transported by child bicycle seats, had modelled a finite element model where they coupled the physics used in vehicle cars, with a multibody bicycle with a respective 3D scanned seat. By running the model for multiple scenarios where a car at different velocities runs over a bicycle with the respective users, it was possible to conclude in most cases, the three-point seat belt is not capable of withstanding the crash, thus protecting the child, and the seat geometry has faulty features that not restrain the child's head movement during the crash, causing head and neck injuries in lateral impacts. The one fixation point in bicycle seats was also highlighted as a problem. Ptak et al. [22] conducted a study where they research the influence of multiple bicycle-mounted seats on safety. Observing for front-mounted child seats, the head injuries and height droppings are higher compared to rear-mounted seats. The Authors also underlines the importance of equipping the child carrier with a five-point seat belt, disregarding other systems. Oxley et al. [23] used data collected from a hospital over 15 years, relative to child transport by bicycle for three different age gaps: 0–3 years, 4–6 years, and 7–10 years. With its analysis, it was possible to determine that younger children suffer more head injuries and open wounds compared to other age groups, with others being more prone to suffer arm and wrist injuries. It was found that, in the case of a collision, the natural reflex of human beings is to use their hands to absorb the impact with the colliding object, and 0–3 year child's present higher cases of wrist and arm injuries in bicycle transport seats. Connecting these two facts leads to the conclusion that by a 0–3-year-old child being transported in a seat constraint the natural reflex of using the arms and hands as a protective measure to absorb the impact. This underlines the importance of developing safer design seats. Attending to the tendency of head and neck injuries, Ptak et al. [24] had researched this question deeply, making it possible to understand that in studies using only head injury criteria and acceleration to assess safety decisions regarding child seats is not enough; with torsional bending should also be part of the equation to make decisions. Moreover, the authors also concluded that a higher seat backrest would improve safety by better encapsulating the child during a crash. In terms of comfort and long-term impact in child carriers, there are also some advances. Rothhämel [25] had concluded, like van Driessche [26] and Schwanitz et al. [27] also did, that children are significantly more exposed to vibrations during their transportation in bicycles rather than a car. Due to the higher vertical stiffness of tyres and lower suspension damping. Furthermore, although the impact of vibrations on children has not yet been studied, these conclusions raise important questions that should be considered in future child carrier designs to enhance comfort during transportation. To improve the safety and comfort flaws described, Jiang and Meng [28] developed a bicycle child seat based on already existing solutions in child car carriers, regarding ergonomics and physiology. In Jiang and Meng [28] proposal for bicycle seat, elements like headrest with cushioning effect, flank foam, front guard and five-point seating belt are installed to improve safety, by absorbing energy during a crash and restraining the child's torsional movement. The seat was validated by a battery of tests using a dummy equipped with sensors. On the other hand, Park and Yoo [29] invented and validated a seat design with multiple restraint points. Not only was safety the main goal to achieve, but also a seat that is lightweight and possible to be manufactured without complex methods. Thus, the software Ansys was used to understand how stress is distributed along the seat and therefore optimize by decreasing material thickness in places where high stress is not verified, resulting in a seat made of polypropylene with a six-point fixation system, which can reduce the head and chest acceleration from 580 m/s^2 to 341 m/s, compared with the traditional three-point seat belt. All these efforts reveal the continuous importance of the product development with the eyes put over the customer needs, permanently innovating in all aspects, since the product design to the manufacturing process.

The present study objective focuses on the development of a coupling system that allows the assembly of a child bicycle seat, which allows parents to carry their children, enhancing green transport solutions. The development of the system is based on current solutions and tries to overcome the problems and limitations presented by them, using the DSR methodology. The design culminates on a system that features a mechanical clamping lever system, protected by an anti-theft locking mechanism. Its mechanical design is subjected to consecutive FEM analyses to validate the system in compliance with the EN 14344:2004 standard.

2. Methods

2.1. Methodology

Since the main goal of this study is to develop a coupling system that attaches a child seat to a bicycle, exceeding existing market solutions by offering features that positively affect the user's experience, the Design Science Research (DSR) methodology is suitable for this purpose and will be used throughout the study. As this methodology focuses on developing or improving existing products, it is particularly relevant in applied fields where intervention and innovation are essential [30,31]. The application of the DSR methodology involves a six-step process: (1) problem identification, (2) defining objectives based on the identified problems, (3) designing and developing the product, (4) demonstrating a prototype to explain the ideas and objectives, (5) evaluating the prototype's performance, and (6) drawing conclusions [32]. Considering the problems and improvements identified for current products (Section 2.2), objectives will be set to address these issues and to provide additional benefits (Section 2.3). Once objectives are established, product development will aim to meet these goals while also addressing potential operational problems. This process is illustrated in Section 3. The final stage involves concluding the product development process.

2.2. Problem Identification

Through a thorough analysis of existing products and by gathering customers' experiences and difficulties when using child carriers, it is possible to identify a list of problems and barriers to address. Additionally, the literature review offers specific considerations for future developments, which can help resolve future issues encountered with the product. Consequently, the first step of the DSR methodology, objectives and requirements, is now presented.

P1. The existing market solutions for the coupling mechanism do not allow a quick assembly process of the seat on a bicycle, discouraging users from using it.

P2. Besides the fact that it is not easy to disassemble, the coupling system design is not appealing and can interfere with other bicycle components.

P3. The system is not lightweight.

P4. In cases where the user rides are bicycle off-road, the system geometry is prone to accumulating mud and debris, making it unpleasant for the user.

2.3. Exposition of Traditional Bicycle Child Seats

This type of device is traditionally characterised by three main components: the seat, in which the child is placed and transported; a coupling system that ensures the attachment of the seat to the bicycle; and a connecting tube between the coupling system and the seat (Figure 1). Typically, the device can be mounted either on the bicycle's carrier or on the seat tube, with the latter being the more common configuration.

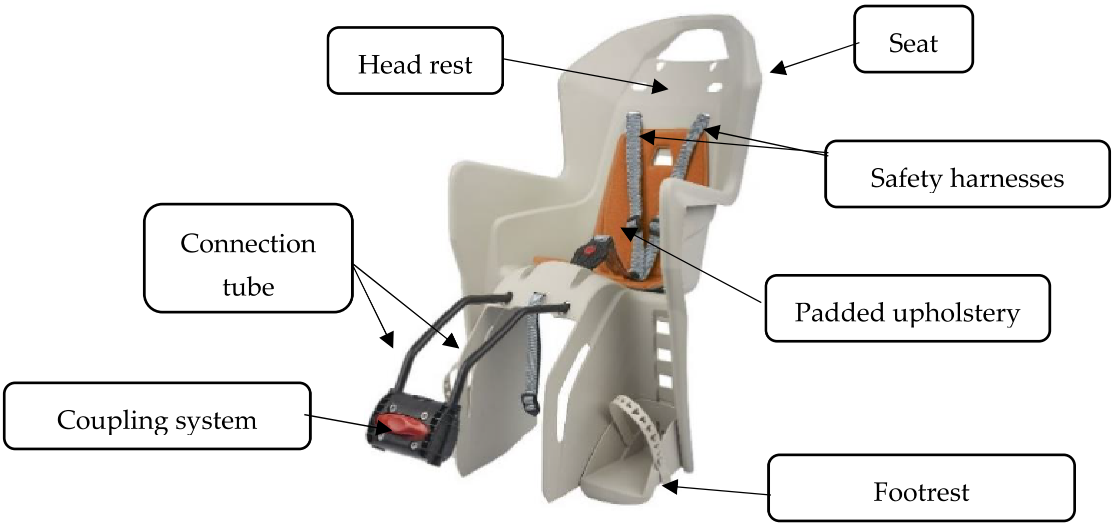
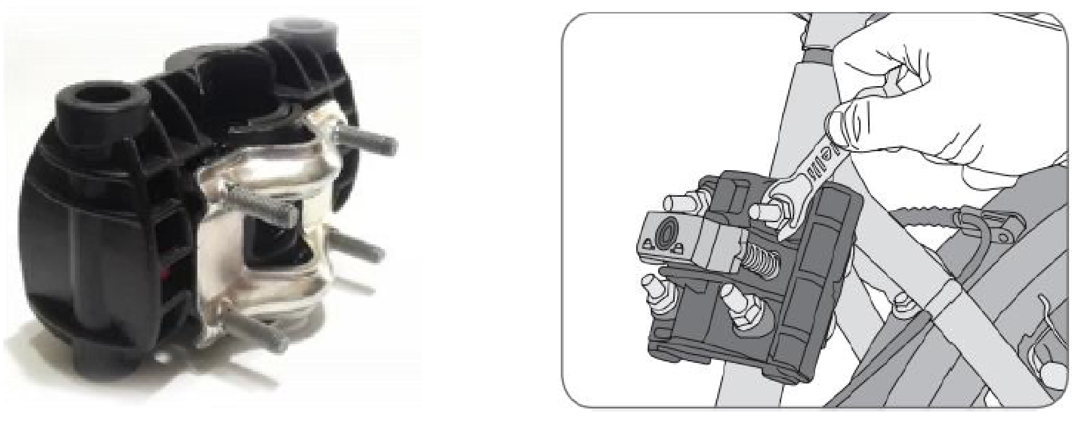


Figure 1. Child seat example [33].

The seat is generally manufactured from a polymeric material and features a geometry and configuration designed to ensure both comfort and safety for the child, with safety being the primary concern in the development of this type of product. To that end, the seat is equipped with components such as:

- A headrest, which provides support for the child's head in the event of an accident, helping to prevent whiplash-type injuries to the cervical spine.
- Footrests, which prevent the child's feet and legs from inadvertently touching the bicycle's rear wheel.
- Safety harnesses, which not only secure the child during transit but also prevent ejection in the event of a collision.
- Padded upholstery, which enhances comfort and contributes to impact absorption.

Regarding the coupling system, most existing products follow a similar functional principle. That is, the coupling system comprises three components: a solid main body made of polymeric material, an elastomeric bushing, and a third element that clamps around the bushing and connects to the main body. The system is observed in Figure 2a. This configuration is mechanically simple but results in a time-consuming assembly process and a negative visual impact. The functional principle relies on compressing the bushing between the seat tube and the two solid components by means of screw tightening, Figure 2b.



(**a**) (**b**)

Figure 2. (**a**) coupling system device [33], (**b**) coupling system assembly demonstration [34].

2.4. Objectives and Specifications

The primary goal is to create a child carrier designed for installation on bicycles, enabling parents who use bicycles as their primary mode of transportation. Additionally, the product must respond to market needs, meaning it must overcome the identified problems and offer specifications that exceed traditional solutions. Thus, in this section, those specifications are described, constituting the second step in the DSR methodology.

O1. The seat must comply with the legislation EN 14344:2004 [35], which guarantees the child's safety during transportation.

O2. The coupling mechanism must ensure that the assembly and disassembly processes occur in less than 10 s and without complications for the user, since it gives a superior advantage over the current market solutions, because it enhances user convenience. Additionally, it must have the capacity to decouple from the seat, allowing the seat to be shared between multiple family users.

O3. The system must be mounted directly on the bicycle frame, which can assume a circular or oval profile, and not in another structural element of the bicycle. And must be capable of withstanding a load of 220 N that simulates the forces produced by a child on transportation.

O4. The coupling mechanism, together with the seat, must withstand 200,000 cycles of lateral loading on a dynamic testing machine, ensuring the equipment's resilience to the conditions of its intended environment.

O5. A locking system must be integrated with the coupling mechanism to prevent the seat from being stolen.

3. Coupling Mechanism Evaluation

Throughout this chapter, various concepts will be presented as potential solutions for the coupling system. Subsequently, a selection table will be used to identify the two most suitable solutions, from which the one that best meets the defined objectives will be chosen

3.1. Conceptualization

In the ideation of a concept to serve as a coupling system, several objectives were considered. However, some of these were given higher priority. The primary purpose was to develop a system that could be easily and quickly assembled and disassembled, preferably without the need for tools. This goal was defined as the most important, as its opposite represents the main shortcoming reported by users of this type of product.

The second objective pertained to enhancing the adaptability of the coupling system to the specific tubular geometry of the frame on which it would be installed. Conventional systems are typically limited to round or oval cross-sections. The increasing prevalence of electric bicycles has introduced a wider range of frame geometries, underscoring the need for a coupling system capable of accommodating diverse profile configurations. Achieving these two principal objectives establishes the foundation upon which the remaining objectives, outlined in the preceding chapter, maintain their relative importance.

When developing new concepts, certain challenges inevitably arise, such as complex manufacturing methods, leading to higher production costs and greater uncertainty in achieving the desired performance. As such, during the conceptualisation of the various coupling systems, two distinct categories were established. In the first category, concepts were based on the existing clamp-style system, which is based on a hinge that clamps, and it will incorporate only minor modifications. In the second category, complete freedom was allowed for the development of entirely new systems.

Accordingly, the following two tables present and describe all the conceptualised systems.

As it can be observed in Table 1, all the concepts are based on the same fundamental principle: two clamp arms connected by a hinge, which act upon the bicycle's seat tube and are secured by a clamping mechanism. Among the various concepts, the primary variation lies in the clamping system itself and its integration with the jaws. The final two concepts are particularly noteworthy, as they combine the advantages of different approaches.

The first of these stands out due to the high degree of micrometric adjustability provided by the threaded element, combined with a compact design and uniform stress distribution. The second concept integrates intuitive operation, robustness, and redundancy (even in the event of failure of the pressure-generating component, the two jaws remain mechanically connected via the ring) while also maintaining a compact form factor. This configuration offers advantages over other options in terms of safety (due to its redundancy), quick assembly, and ergonomics.

Despite the advantages offered by both the first and second systems, all the proposed concepts share a common limitation: the coupling system lacks inherent compatibility with various tubular profiles without the aid of an adapter sleeve. In scenarios where the seat and its coupling mechanism need to be transferred between different bicycles, the user may be required to replace the sleeve. This implies the need to carry additional components, resulting in increased installation time. Moreover, the requirement for interchangeable sleeves necessitates a dedicated fixing mechanism between the sleeve and the coupling system, thereby increasing the system's complexity and potentially its production cost.

With the development of these three new concepts, free from the previous geometric constraints, the aim was to address the issues identified in the solutions presented in Table 1, while also delivering an innovative product that is not complex to manufacture.

In solutions 2A and 2C, due to the internal geometry of the two clamps, it was possible to eliminate the need for additional sleeves when switching from circular to oval tubular profiles. Furthermore, the process was simplified by directly integrating the connection tube into the body of the coupling system. Although solution 2A may potentially present some reliability concerns, the cable-based tightening system stands out as an innovative alternative to conventional pressure-based mechanical fastening methods, an important factor, since an innovative design positively impacts the perception by the consumer, making it more likely to buy the product [36]. In addition, unlike solution 2C, it does not present jamming issues if the connecting rod becomes deformed. Overall, it can be stated that the solutions presented in Table 2 offer significant improvements compared to those listed in Table 1.

Table 1. Concepts regarding the new coupling system, category one with design restrictions.

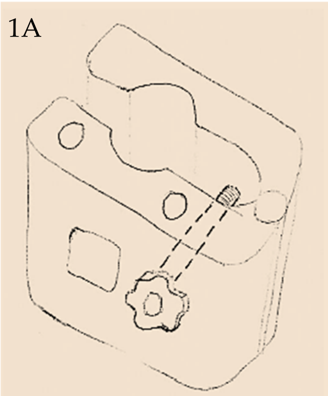
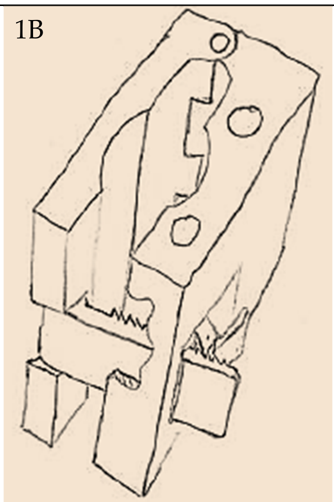
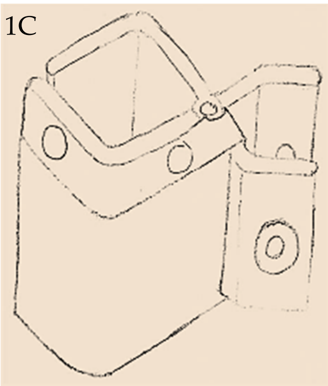
1A 	Description: The system is composed of three primary components. Two of these constitute the main body of the device, functioning as clamping elements that secure the assembly to the bicycle frame. The opening and closing motion of the clamps, as well as the generation of the required clamping force, are achieved through the actuation of a third element—a screw featuring partial threading at its tip. Furthermore, two dedicated holes are incorporated to receive the metal rods that link the seat structure to the clamping mechanism.	Advantages: Allows precise adjustments due to the inclusion of a millimetric screw. Compatible with the existing metal rod connecting the seat. Disadvantages: The tensions are not distributed along the entire body, because the screw only works on one side of the claw. The system is characterised for processing a large volume in the lateral direction, allowing the possibility of causing problems to the user while riding. In case of failure, the system doesn't have a redundant feature that avoids decoupling. Requires the integration of a sleeve to adapt to each different profile type.
1B 	Description: As dictated by the defined condition, this second solution is based on a clamp mechanism connected by a hinge. Unlike the first solution, it does not incorporate a screw to move and tighten the two clamp arms. Instead, it features a polymer body with notches that allow it to mechanically interlock with the opposing clamp, enabling a progressive adjustment of the clamping force applied. Similar to the first solution, there are two openings designed to accommodate the rods that connect the coupling mechanism to the seat.	Advantages: The tension is even distributed along the body. Since the interlock body is on the opposite side compared to the hinge, it allows a lever effect, making it easier for the user to fasten it. Compatible with the existing metal rod connecting the seat. Disadvantages: The notches on the interlock body can suffer premature fatigue or wear due to the assembly cycles. Requires the integration of a sleeve to adapt to each different profile type.
1C 	Description: In this configuration, the initial system was modified to operate similarly to a scissor mechanism. To achieve this behaviour, the hinge was repositioned to the centre of the two clamp arms, while the screw with a threaded tip was relocated to one of the extremities. In this arrangement, when the end containing the screw is opened, the opposite end closes, thereby clamping the mechanism onto the bicycle's tubular profile. As in the previous designs, the two openings serve to accommodate the rods that connect the coupling mechanism to the seat	Advantages: Allows precise adjustments due to the inclusion of a millimetric screw. Compatible with the existing metal rod connecting the seat. The scissors geometry allows the lever effect, making it easier for the user to fasten it. Disadvantages: Due to its unique design, the main body volume is larger than other solutions. Thus, it can interfere with the user's legs while cycling. In case of failure, the system doesn´t have a redundant feature that avoids decupling. Requires the integration of a sleeve to adapt to each different profile type, The geometry has a big eye impact, making it aesthetically unappealing.

Table 1. *Cont.*

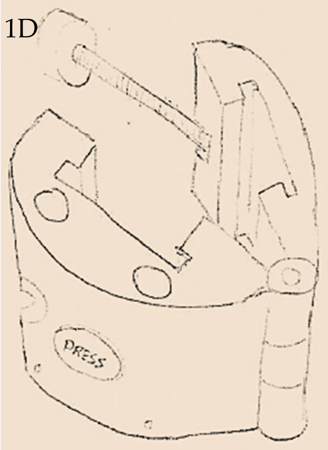
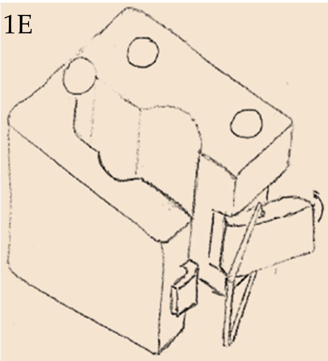
	Description: Similar to the first concept, the movement of the two clamp arms and the corresponding clamping action is achieved through a screw with a threaded tip. However, in this solution, the screw is positioned at the end opposite the hinge to create a lever effect, thereby generating a greater clamping force. Furthermore, in this concept, the screw is attached to a movable component, allowing the coupling system to open fully and thus accommodate larger tubular profiles.	Advantages: Allows precise adjustments due to the inclusion of a millimetric screw. Compatible with the existing metal rod connecting the seat. The tension is even distributed along the body. Disadvantages: In case of failure, the system doesn´t have a redundant feature that avoids decupling. Requires the integration of a sleeve to adapt to each different profile type.
	Description: This concept differentiates itself from others by the specific actuation and tightening method of clamping arms. The solution employs a mechanism commonly found in equipment requiring quick and reliable fastening and unfastening, such as musical instrument cases. A rotating body, pivoting around a fixed axis, drives a ring along the longitudinal direction, which is connected to the opposing clamp arm. This motion brings the two clamp arms together, securing them through applied pressure.	Advantages: Compatible with the existing metal rod connecting the seat. The tension is even distributed along the body. With the use of a pressure mechanism to tighten the system, the user doesn´t need to apply too much strength to close it. Compact design, not interfering with the user while pedalling. Disadvantages: Requires the integration of a sleeve to adapt to each different profile type.

Table 2. Concepts regarding the new coupling system, category two without design restrictions.

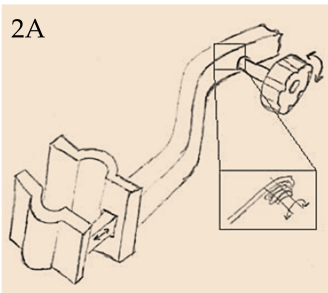
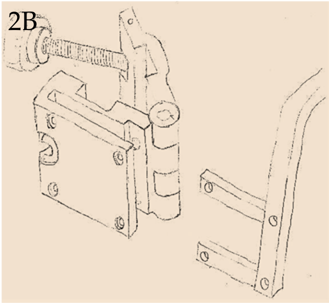
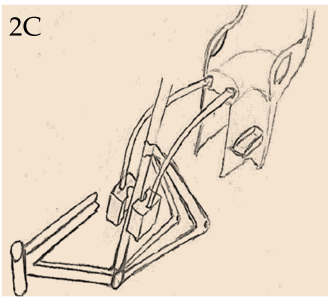
	Description: In this concept, due to the absence of design constraints, the coupling system was completely reimagined. The traditional approach of using a hinge to connect two clamp arms was replaced by a rod connected to a semi-circular element that moves along the tubular component directly attached to the seat. Actuation is achieved through a cable system linked to a pulley, allowing for precise adjustment of the clamping force. The user rotates the system to tighten or release it from the bicycle. Furthermore, this concept allows for direct coupling to the bicycle's seat tube without the need for adapter sleeves, regardless of the tube's profile geometry.	Advantages: Reduced assembly time without complexity. Does not require the integration of sleeves to adapt to different tube profiles. The longitudinal mechanism design allows more convenience to the rider while cycling, since there is no chance of interfering with is legs while cycling. Disadvantages: In case of failure, the system doesn´t have a redundant feature that avoids decoupling. The wire lifespan can be compromised due to the lack of stiffness, due to its continuous stretching during fastening operations. The children's weight can cause a slight deflection on the chair connection tube, causing the jam of the coupling system as its movement relies on the tube interior.

Table 2. *Cont.*

	In the current design, the fundamental geometry of the coupling system was preserved. The hinge linking the two clamp arms continues to incorporate a threaded screw that pivots in conjunction with a rolling element, ensuring the system's closure and clamping force. A notable modification concerns the mounting of the seat's metal rod, which is now inserted horizontally and fixed using four screws. This arrangement facilitates a more uniform force distribution along the main body, thereby mitigating one of the principal issues observed in the majority of previously examined solutions in Table 1.	Advantages: Allows precise adjustments due to the inclusion of a millimetric screw. The connection nature between the coupling system and the tube allows the stresses to be evenly distributed, because the tube couples over a large area. Reduce body volume. Reduced assembly time without complexity.
		Disadvantages: The connection between the tube and the clamping system being positioned only at one side causes its rotation and, therefore, shear stresses on the coupling system. Requires the integration of a sleeve to adapt to each different profile type In case the millimetric screw gets loose by accident, the system doesn´t have a redundant feature that avoids decoupling.
	Description: With the aim of developing a simpler system that would allow for less complex and more cost-effective manufacturing, a mechanism was devised in which the connecting rods to the seat remain permanently attached. Although this approach runs counter to the initial objective of creating a coupling mechanism independent of the seat, thus enabling its attachment to different bicycles without the need for time-consuming disassembly and reassembly, it allows the rods to be over-moulded with polymer to form the main body of the coupling system, thereby enhancing manufacturing efficiency. Due to the distinctive nature of this solution, the installation method differs from those previously presented. Instead of a lateral connection, the system is mounted vertically. In this configuration, the two rods rotate about their axis, allowing each half of the coupling mechanism to open for engagement. The halves are then secured using two crosswise-positioned screws.	Advantages: The manufacturing process is relatively simple, making it cheaper. Does not require the integration of sleeves to adapt to different tube profiles. The assembly procedure is fast.
		Disadvantages: Despite the assembly procedure being fast, it requires the use of tools. he positioning of the system may be challenging, as the chair cannot be detached from the coupling mechanism.

3.2. Concept Selection

With the various proposed solutions outlined, the next step involves the selection of the two most suitable options, one from Table 1 and the other from Table 2. This dual-source selection approach was adopted based on the authors' reasoning that choosing a final mechanism from the complete set of all alternatives would be inappropriate, given that the solutions in Table 1 were developed under specific design constraints.

After selecting the two coupling systems, it is recommended to combine their most favorable characteristics, based on the performance objectives established in the corresponding section. Considering both the considerable number of design alternatives and the broad range of performance criteria, the adoption of a decision matrix was considered the most suitable method to ensure a systematic and objective selection process.

The method chosen for constructing the selection matrix was the one proposed by Ulrich and Eppinger [37], consisting of six stages:

- Preparation of a selection matrix by ordering the design concepts or alternatives along one dimension and the selection criteria along the other.
- Classify each concept following the criteria defined in step 1.
- Attribute a degree of importance to each concept on a relative scale.

- Erase, combine or improve concepts.
- Select one or more concepts.
- Analyse the concepts chosen.

The criteria selection chosen was based on the objectives established for the coupling system to fulfil, which can be synthesised in five categories: reduction of assembly and disassembly time, feasible/cheap manufacturing, low complexity assembly process, safety and innovation. Thus, a mark is attributed to each solution on a scale of 1 (Poor) to 5 (Very good) for each category, based on the predictable performance that might be achieved during operation (Table 3). Although predictions may be inherently approximate and not entirely specific, the underlying knowledge supporting the choices made can lead to accurate and reliable forecasting outcomes.

Table 3. Criteria attribution to each solution.

Solutions	**Selection Criteria**				
	Reduction of Assembly and Disassembly Time	**Feasible/Cheap Manufacturing**	**Low Complexity Assembly Process**	**Safety**	**Innovation**
1A	1	5	3	1	3
1B	3	2	3	4	4
1C	1	5	3	2	3
1D	2	4	2	3	4
1E	3	4	4	5	4
2A	5	1	5	1	5
2B	5	3	4	3	5
2C	2	5	1	5	3

With the scoring assigned to each selection criterion, the next step in the methodology, as outlined by Ulrich and Eppinger [37], involves assigning a weight to reflect the relative impact and importance of each criterion in the context of the coupling device. The assigned weights range from 0 to 1, and their sum must not exceed 1.

Following this principle, the criteria for reducing assembly and disassembly time and achieving a low-complexity assembly process were each assigned a weight of 0.3. This is justified by the fact that, from an objective standpoint, both criteria are directly interrelated and, therefore, should carry equal importance. Regarding the safety criterion, a weight of 0.1 was assigned. Although safety is a critical factor, it is inherently addressed in the development of the proposed solutions, which are required to comply with safety standards set by regulatory bodies. As such, its relative weight may be lower compared to other criteria, given that compliance is assumed as a baseline condition. For the innovation criterion, a weight of 0.2 was defined, based on its positive influence on customer perception during the purchasing decision. Lastly, the criterion Feasible/cheap manufacturing was assigned a weight of 0.1. While it is indeed an important factor, given its direct influence on profit margins per unit, if a mechanism can be developed that is both easier and faster to assemble, combined with an innovative solution (the two most heavily weighted criteria), it is possible to attract a larger customer base and more confidently adjust the final product price, thereby offsetting any potential increase in production costs associated with the coupling mechanism.

To know which solution of each table is better, judging by the criteria defined, the following equations are used:

$$b = \frac{a}{Higher\ score\ between\ all\ concepts} \times 100 \tag{1}$$

where: b is the solution score, about all solutions and a the assigned weight to each solution

$$c = w_i \times b_i \tag{2}$$

where: c is the relative weight for each solution, w_i the weight defined for a specific criterion and $c = w_i \times b_i$ the solution score obtained from Equation (1)

$$y = \sum(w_i \times b_i) \tag{3}$$

where: y is the performance indicator resulting from the analysis.

Below.

Table 4 summarises all the calculations made and the performance results for each solution.

Table 4. Representation of the selection matrix to choose the best solution.

		Reduction of Assembly and Disassembly Time		**Low Complexity Assembly Process**		**Feasible/Cheap Manufacturing**		**Safety**		**Innovation**		**Performance Result**
Coupling Mechanism Solution		$\omega_1 = 0.3$		$\omega_2 = 0.3$		$\omega_3 = 0.1$		$\omega_4 = 0.1$		$\omega_5 = 0.2$		γ
1A	$\frac{a}{b}$ c	$\frac{1}{20\%}$	6	$\frac{3}{60\%}$	18	$\frac{5}{100\%}$	10	$\frac{1}{20\%}$	2	$\frac{3}{60\%}$	12	48
1B	$\frac{a}{b}$ c	$\frac{3}{60\%}$	18	$\frac{3}{60\%}$	18	$\frac{2}{40\%}$	4	$\frac{4}{80\%}$	8	$\frac{4}{80\%}$	16	64
1C	$\frac{a}{b}$ c	$\frac{1}{20\%}$	6	$\frac{3}{60\%}$	18	$\frac{5}{100\%}$	10	$\frac{2}{40\%}$	4	$\frac{3}{60\%}$	12	50
1D	$\frac{a}{b}$ c	$\frac{2}{40\%}$	12	$\frac{2}{40\%}$	12	$\frac{4}{80\%}$	8	$\frac{3}{60\%}$	6	$\frac{4}{80\%}$	16	54
1E	$\frac{a}{b}$ c	$\frac{3}{60\%}$	18	$\frac{4}{80\%}$	24	$\frac{4}{80\%}$	8	$\frac{5}{100\%}$	10	$\frac{4}{80\%}$	16	76
2A	$\frac{a}{b}$ c	$\frac{5}{100\%}$	30	$\frac{5}{100\%}$	30	$\frac{1}{20\%}$	2	$\frac{1}{20\%}$	2	$\frac{5}{100\%}$	20	84
2B	$\frac{a}{b}$ c	$\frac{5}{80\%}$	30	$\frac{4}{60\%}$	24	$\frac{3}{60\%}$	6	$\frac{3}{60\%}$	6	$\frac{5}{100\%}$	20	86
2C	$\frac{a}{b}$ c	$\frac{2}{40\%}$	12	$\frac{1}{20\%}$	6	$\frac{5}{100\%}$	10	$\frac{5}{100\%}$	10	$\frac{3}{60\%}$	12	50

From the table, it is evident that among the concepts developed with design constraints, concept 1E achieved the best performance based on the defined criteria, while among the unconstrained solutions, concept 2B emerged as the most promising. The 1E mechanism, when compared to others within the same category (Table 1), stood out primarily for incorporating a simple and rapid clamping system, capable of attaching the seat to the seat tube with a single action. In contrast, the remaining solutions rely on fastening a bolt, which requires more time. Moreover, in terms of safety and innovation, 1E also received high scores, comparable to those of mechanism 2B, resulting in a balanced and high overall rating for 2B as well. For this reason, both solutions stand out from the others within their respective categories. Regarding the analysis of mechanism 2B as the most promising among the solutions in Table 2, it does not differ significantly from concept 2A. Both achieve strong performance across most criteria. However, 2B scored higher in terms of safety and feasibility. In terms of safety, the lower score of 2A is attributed to its reliance on a cable-and-pulley system to generate the clamping force. In the event of cable failure or slippage within the pulley, the user would be directly exposed to risk. In contrast, 2B employs a more reliable mechanism based on a threaded screw. Regarding feasibility, the use of a cable in 2A introduces manufacturing constraints, as the assembly of this component must be carried out manually by an operator rather than through an automated process, due to the restrictive geometry and dimensions of the cable mounting area.

3.3. Development Approach

Although the two concepts have been selected as coupling systems for a bicycle child seat, they are not yet sufficiently developed or fully aligned with all the defined objectives to be considered final products. Therefore, based on the selected concepts, this section presents a gradual development approach aimed at merging the positive aspects of solutions 1E and 2B and implementing the necessary improvements to arrive at a final product suitable for market introduction and compliant with the established objectives.

As a starting point, given that concept 2B achieved the highest overall score and presented the most promising design, a prototype was produced using additive manufacturing, although the final components will be manufactured by injection moulding, as highlighted further in Section 4. This prototype was installed on a child seat and coupled to a bicycle to gather initial user impressions and inform the subsequent improvement process.

Following fabrication and assembly, as shown in Figure 3, it became apparent that the prototype possesses a relatively large volume, which is both aesthetically unappealing and may interfere with the rider during pedaling. Nevertheless, employing a single rod to connect the system to the seat improves the overall visual integration. Regarding assembly time, tests conducted across multiple users revealed an average assembly time of 10 s, representing a significant improvement of approximately 97.78% compared to the 5 to 10 min typically required by conventional systems currently available on the market. From this initial evaluation, it can be concluded that improvements should focus on reducing the overall volume of the coupling system. Beyond the aesthetic impact, the image also illustrates how the limited space between the seat tube and the rear tyre complicates installation. Furthermore, there is noticeable interference between the child seat and the bicycle tyre.

(**a**) (**b**) (**c**)

Figure 3. (**a**) Coupling system prototype, (**b**) front view of the coupling system installed on a child bicycle seat, (**c**) side view of the coupling system installed on a child bicycle seat.

The first aspect to be addressed in the design evolution was the connecting tube between the child seat and the coupling system. Although it presented a clean and visually appealing appearance, the mechanical connection between the tube and the seat revealed a degree of fragility. Due to its circular geometry, the connection was susceptible to rotational slippage over time, particularly as the polymeric material of the child seat underwent wear. This could result in the seat rotating around the axis of the connecting tube during use. To mitigate this issue, a rectangular base was added to the end of the tube, secured with a pin, which in turn is connected to the child seat (Figure 4b). This modification increases mechanical stability and prevents undesired rotational movement. Furthermore, as previously noted in the preliminary analysis, there was interference between the child seat and the bicycle tyre, which also complicated the mounting process. To address this, the geometry of the tube was redesigned by incorporating curved elements, as shown in Figure 2a. This change enables the seat to be mounted using a lateral trajectory, thereby facilitating installation and eliminating interference with the bicycle tyre.

However, the inclusion of additional components should, whenever possible, be avoided to minimize part count and simplify the manufacturing process. Therefore, another approach was designed to follow this good engineering practice but also to interfere as little as possible with the seat structure, since it is already in compliance with safety regulations. This results in the installation of two tubes instead of using only one tube, allowing the platform to be removed and the direct installation of the two tubes on the seat, like in Figure 4c, without any concerns concerning structural integrity.

(**a**) (**b**) (**c**)

Figure 4. Coupling system, (**a**) mounted on the child seat, (**b**) coupling system with a platform to be attached to the seat, (**c**) double tube system connected to the coupling system.

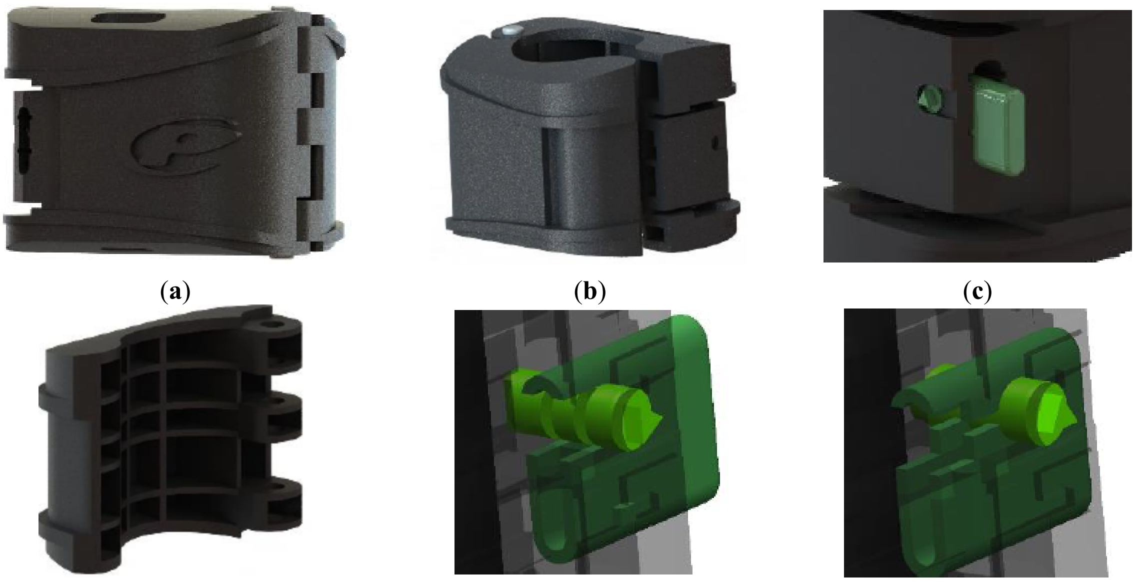
The clamping system using a micrometric screw allows for precise installation and fastening of the coupling mechanism to the seat tube. However, its geometry causes the screw to protrude beyond the body of the clamp block, potentially interfering with the user or with bicycle components such as brake and gear cables. Moreover, this system applies clamping force in very localised areas of each jaw, resulting in non-uniform pressure distribution. This may lead to improper coupling between the system and the seat tube, causing slippage and localised stress concentrations within the body of the mechanism, thereby increasing the risk of premature failure. As a result, the screw-based clamping system was eliminated and replaced with the mechanical pressure-based solution used in prototype 1E. To further optimise the distribution of clamping forces across the structure, the cross-sectional area of the lever responsible for actuation was increased, Figure 5a. Additionally, the traditional metallic ring typically used in such systems, previously discussed, was replaced with a polymer component. For structural reinforcement, the clamping lever is connected to a metallic insert, which is over-moulded by the body of the system, as shown in Figure 5b. To ensure compliance with the EN 14344:2004 [35] standard, a locking mechanism was incorporated into the connecting tube, similar to those found in conventional commercially available systems, as demonstrated in Figure 5c. The operating sequence involves pressing a button, which retracts two locking pins; the tube is then inserted, and upon releasing the button, the pins move back into position, engaging with the tube and immobilizing it.

(**a**) (**b**) (**c**)

Figure 5. (**a**) coupling system with the mechanical pressure locker, (**b**) metal insert in which the mechanism is supported, (**c**) tube locker button.

With the prototype nearly finalised in terms of its internal mechanism, the next step involved optimising the geometry and overall design of the system to enhance its aesthetic appeal and ensure it could be manufactured using injection moulding. To achieve this, sharp edges were rounded, and unnecessary material volumes were removed, Figure 6a–c. To reduce the system's weight, solid sections were replaced with structural ribs, see Figure 6d. Additionally, to prevent issues during the mould release process, large flat surfaces were minimised by introducing a 2° draft angle to them (Figure 6b).

To fulfil the requirement of incorporating an anti-theft mechanism, a security feature was added to the clamping lever. Specifically, a button (shown in green in Figure 6c) was integrated into the lever and is mechanically linked to a pin. Depending on the rotational position of the pin, it either allows (Figure 6f) or prevents (Figure 6e) the button from being pressed. When enabled, pressing the button permits the movement of the lever, thereby allowing the child seat to be removed. This pin can only be rotated using a dedicated personal key held by the user.



(**a**) (**b**) (**c**)

(**d**) (**e**) (**f**)

Figure 6. Final coupling system design (**a**) frontal view, (**b**) overview, (**c**) locker button, (**d**) left claw interior, (**e**) pin on locking position, (**f**) pin on unlocking position**.**

4. Structural Integrity Assessment by FEM Analysis

To verify the integrity of the components used, which are manufactured by injection moulding to ensure mass-scale production availability, and to assess whether they can withstand the loads to which they will be subjected during use, a Finite Element Method (FEM) analysis was carried out using SolidWorks simulation software. As specified in the relevant standard EN 14344:2004 [35], which outlines the testing procedures required for validation, the most critical loading scenario for the child seat involves lateral forces. These result from the combined effect of the child's weight and inertial forces. In Figure 7, the vector representing the lateral load is denoted by the letter "F".

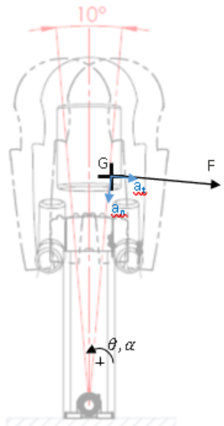


Figure 7. Lateral movement cinematic representation regarding the chair when subjected to lateral motion.

To know the value of lateral force to be applied on the chair to run the simulations, first, it is imperative to calculate the acceleration to which the chair is subjected. To assess the value, Equation (4) is written based on the EN 14344:2004 standard [35].

$$\vec{\theta}(t) = -\frac{\pi}{36} \times \sin(2\pi t) \tag{4}$$

where: $(\vec{\theta})$ expresses the phase angle in the sinusoidal equation and (t) the time.

By double differentiation of Equation (4), the acceleration equation is obtained, and calculating the acceleration for the instant of 0.75 s, which corresponds to the acceleration instant of the chair for 10° (Figure 5), the following value of acceleration is attained:

$$\vec{\alpha}(0.75) = -3.445\ rad/s^2 \tag{5}$$

With the value obtained from Equation (5), the tangential acceleration is obtained with Equation (6).

$$a_t = \alpha.r = 3.445 \times 0{,}825 = 2.842\ m/s^2 \tag{6}$$

where r is the distance between the centre of mass and the rotation axis. In this case, 0.875 m.

Lastly, with Newton's equation, using a mass of 26 kg (child's average weight plus the seat mass), the force is calculated.

$$F = m.a_t = 26 \times 2{,}842 = 74\ N \tag{7}$$

The next step involved defining the boundary conditions, materials and applying the load to proceed with the simulation. Moreover, the analysis to be performed is a static analysis to understand if the child seat system withstands the load calculated in Equation (7). To optimize computational resources, the seat was replaced by a simplified plate model, onto which the two connecting rods were defined as fixed supports (Figure 8). Regarding the mesh applied to the model, it was adopted a mesh with tetrahedral elements to all components with a fine degree of refinement, set by the own program.

In the model, three materials were selected according to experience with a similar system (Table 5).

Both connecting rods were modelled as welded joints at their interfaces Figure 9a, and as fixed at the connections with the simulated seat plate and the coupling system. The interaction between each jaw of the coupling mechanism and the pin, which enables its rotation, is defined as a pin-type connection (Figure 9b), allowing rotation and deformation while preventing translational movement. For the interface between the coupling system and the seat tube, a rough contact was applied to eliminate slippage between the parts, Figure 9c.

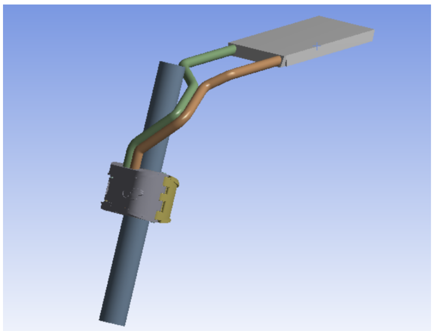
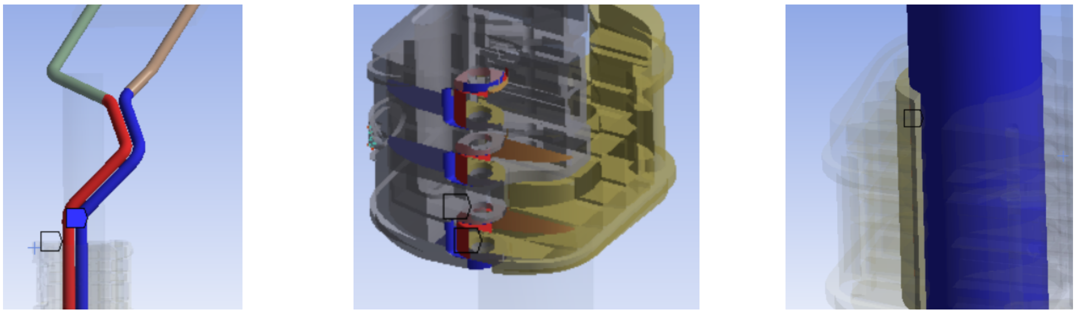


Figure 8. Coupling system with the seat simplification by its substitution with a plate.

Table 5. Material attribution to each child seat component.

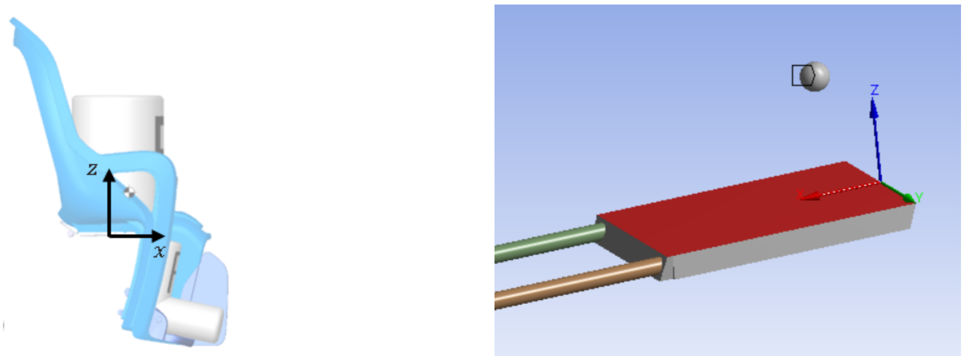
Material	Density [g/cm^3]	Young's Modulus [38]	Poisson Coefficient	Tensile Strength [MPa]	Respective Components
Steel S355	7.86	210	0.29	355	Connecting rod
Thermoplastic Polyurethane	1.24	1.69	0.38	63.2	Camping claws bushings
PA6 + 35% of glass fiber	1.41	11.4	0.4	150	Clamping claws



(**a**) (**b**) (**c**)

Figure 9. Boundary conditions: (**a**) welding connection, (**b**) pin connection, (**c**) grip connection.

To simulate the mass of the child, as represented in Figure 8a, a remote centre of gravity was introduced at the coordinates (40.15; 0; 83.91) mm, as shown in Figure 10b.



(**a**) (**b**)

Figure 10. (**a**) Representation of the centre of mass on the chair, (**b**) the equivalent mass as remote centre of gravity on the simulation.

To further simplify the simulation, the mechanical clamping levers were removed and replaced by preloads of 1000 N, representing the forces typically exerted by the levers on the system body. Subsequently, a lateral load of 74 N, calculated according to the specified Equation (7), was applied to the side of the plate simulating the child seat, as illustrated in Figure 11 by a red arrow.

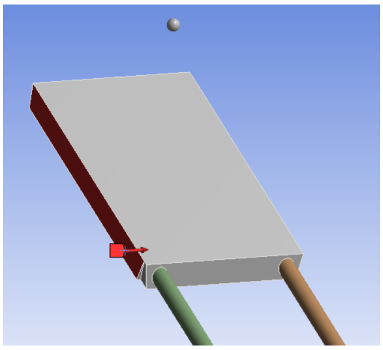


Figure 11. Lateral load application on the plate simulating the seat.

Following the simulation, it was observed that the maximum stress reached approximately 384.85 MPa in the connecting rod, exceeding the yield strength of the material from which it is made (S355 structural steel, with a yield strength of 355 MPa), as demonstrated in Figure 12. The maximum stress observed in the coupling system was approximately 38.409 MPa (Figure 13), resulting in a safety factor of 2.8, above the proposed threshold of 2.5. Regarding deformations, these were found to be very low, indicating high stiffness and structural integrity of the system. This is considered a positive factor, as it enhances the perceived safety and reliability for users.

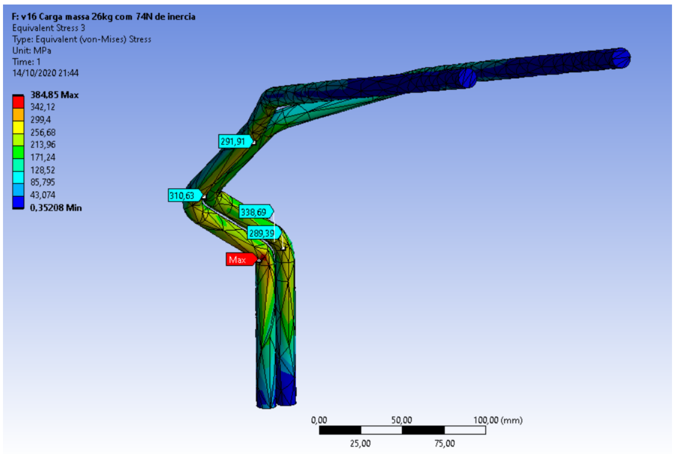


Figure 12. Maximum tension verified on the system, being localised on the connection tube.

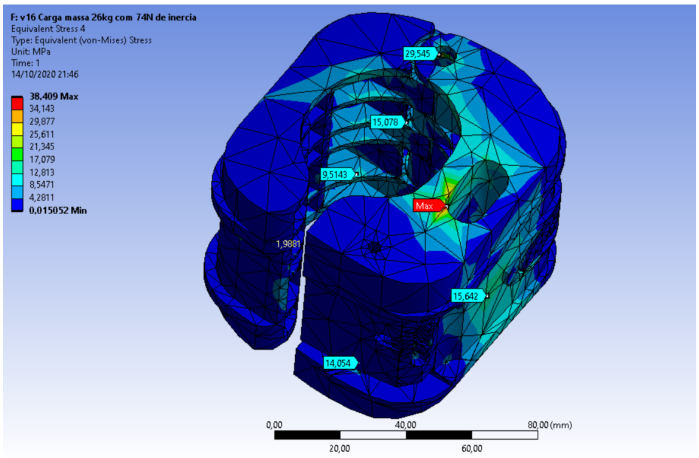


Figure 13. Max tenson verified on the coupling system.

To address the issue of high tensions, the curvature of the connecting rod was reduced, Figure 14, and its wall thickness increased to 4 mm. Furthermore, to further improve the structural integrity of each clamp, the reinforcing ribs were enlarged. As a result of these modifications, the stress in the rod was decreased to approximately 123 MPa, mainly at the welded joint between the two rods (Figure 15). Additionally, the maximum stress in the coupling system was lowered to 24.69 MPa, yielding a safety factor of 4.5.

(**a**) (**b**)

Figure 14. Connection rod curvature relaxation, (**a**) before the relaxation procedure, (**b**) after the relaxation is completed.

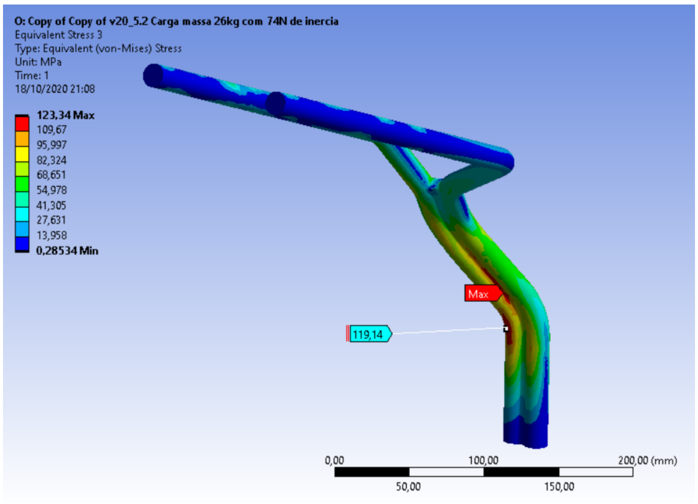


Figure 15. Representation of the maximum stress encountered after the improvements have been made.

With the FEM analysis validation done, regarding stress resilience, the final prototype is represented in Figure 16.

(**a**) (**b**) (**c**)

Figure 16. (**a**) final prototype, (**b**) closed coupling system detail, (**c**) open coupling system detail.

5. Cost Analysis

By adopting the coupling system Design Science Research (DSR), it was possible to achieve the objectives established initially, as outlined in the next Section 6, making the solution developed in this study outperform the existing market solutions (Table 6). Therefore, a commercial opportunity is created to sell it to the public. However, despite the superior technical features, they cannot constitute themselves as the decisive factor in approving the coupling mechanism for market release, since the cost of producing it could be high enough to deter manufacturers from fabricating it. Thus, through this section, a cost analysis will be conducted based on the author's experience in the field to assess investment costs and provide a more comprehensive perspective for potential implementers.

Table 6. Coupling mechanism and the respective child seat technical information.

Technical Information		Design Information	
Maximum child weight	22 kg		Safety harness
Coupling mechanism lifetime.	Capable of withstanding 200,000 cycles of lateral load (22 kg).	Safety components	Head rest
Regulation	In compliance with the norm EN 14344:2004		Feet holders
Clamping claws material	PA6+35% of glass fibre	Bike frame profile compatibility	Oval and circular
Assembly time	10 s	Type of clamping mechanism	Lever-actuated system

The analysis of Table 7 revealed that the coupling system can be produced for €5.25. Considering that the average child carrier seat, which incorporates the coupling system, is sold for €78.96 [33,34], the production cost corresponds to only 6.64% of the total price. Therefore, the price of the coupling system does not significantly impact the total cost of the product, making the concept viable when only considering the production cost. On the other hand, the initial investment is quite high (128,500 € in Table 8). However, if it is considered that in 2021 the global production of bicycles was 193 million units [39] and considering that 80% percent of these units 20% are going to be equipped with a child bike carrier (80/20 Pareto rule), which corresponds to 30,880,000 units, each child seat only needs to be sold for 0.04 € (128,500 divided by 30,800,000) to pay off the initial costs in one year. Despite this estimation being overly optimistic, it stands out the potential viability for manufacturers to produce this coupling system.

Table 7. Components production cost.

Components	Quantity	Cost per Unit [€]
Front claw body	1	0.75
Back claw body	1	0.60
Internal bushing	4	0.07
Unlocking button	1	0.10
Unlocking button spring	1	0.01
Anti-theft key	1	0.05
Pin for the anti-theft lock system	1	0.05
Connecting rod	1	3.00
M8 Axel for the lever clamping system	1	0.25
Lever handle	1	0.30
Crank of the lever	2	0.05
Pin for the crank lever	1	0.02
Total		5.25

Table 8. Production tools investment cost.

Description	Cost [€]
Front claw body mould	45,000
Back claw body mould	30,000
Internal bushing mould	25,000
Unlocking button mould	6000
Mould for the anti-theft pin system	3000
Assembly line	8800
Prototype samples	1000
Mould testing	2000
Coupling system legal certification	4000
Safety manual development	3700
Total	128,500

6. Conclusions

Through the implementation of the Design Science Research (DSR) methodology, a critical analysis of existing coupling systems was carried out, identifying their shortcomings. This procedure enabled the fulfilment of the proposed objectives through a continuous development process, culminating in the creation of a new coupling system.

The initial presentation of multiple conceptual solutions for the coupling system, illustrated with graphical elements and supported by detailed descriptions of each mechanism, provided a broad overview of potential approaches. This analysis allowed for a comparative evaluation of the strengths and weaknesses of each concept, which proved highly informative and beneficial. Subsequently, a selection matrix method was employed to identify the two most promising solutions. By combining the selected concepts and refining them in line with the design objectives, a final solution was developed that met the outlined requirements. By maintaining the original child seat unchanged and utilising its existing interface points to attach the newly developed coupling system, Objective 1 was automatically fulfilled, as the seat was already compliant with the relevant safety standards.

Furthermore, replacing the conventional bolt-based clamping mechanism with a lever-actuated system that generates mechanical pressure enabled a significant reduction in both assembly time and complexity, to just 5 s, representing a 99.47% decrease relative to the original mechanism (fulfilling Objective 2). The integration of a single-key locking mechanism qualifies the system as theft-resistant, thereby meeting Objective 5. An initial finite element analysis (FEA) revealed that the original design and wall thickness of the connection tube were insufficiently conservative, as it failed to withstand the loads defined by Objectives 3 and 4. Following a re-design, by reducing the tube's curvature and increasing its wall thickness, it became possible to satisfy both Objectives 3 and 4, as well as to ensure the required structural stability.

Moreover, when comparing the novel mechanism developed in this study with the solutions established on the market, clear improvements were achieved, positioning this study's concept ahead of the others. Regarding the appearance, with the addition of curvature elements and refining the mechanism aesthetics to have a clean design, it conditions the potential client behaviour in choosing it over the others, maximising the revenue. In addition, with the improvement of the conventional bolt system for a lever-actuated mechanism, besides enhancing the overall clamping mechanism appearance, since the use of bolts can transmit an archaic look, it mainly had an impact on the assembly time reduction of the seat on the bicycle, surpassing the market solutions. In terms of ergonomics, an improvement was also achieved when comparing with the traditional market solutions, via the positioning of the seat tubes together on the same side, which makes the system more compact, thus facilitating additional space for the rider. The clamping geometry adopted, combining oval and circular profiles, mitigated the incompatibility that market solutions typically exhibit when applied to diverse bicycle frame geometries.

Author Contributions

F.J.G.S.: conceptualization, methodology, data curation, visualization, supervision, resources; R.D.S.G.C.: methodology, data curation, visualization, supervision; D.A.: investigation, data curation, visualization, writing original draft; N.S.: data curation, visualization, writing—reviewing and editing; T.P.: data curation, visualization, writing—reviewing and editing: J.C.S.: writing—reviewing and editing; R.P.M.: writing—reviewing and editing. All authors have read and agreed to the published version of the manuscript.

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Informed Consent Statement

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Data Availability Statement

Not applicable.

Conflicts of Interest

The authors declare no conflict of interest. Given their editorial roles, Francisco J. G. Silva (Editor-in-Chief) and Raul D. S. G. Campilho (Senior Consulting Board) had no involvement in the peer review of this paper and had no access to information regarding its peer-review process. Full responsibility for the editorial process of this paper was delegated to another editor of the journal.

Use of AI and AI-Assisted Technologies

No AI tools were utilized for this paper.

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