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Redesigning The Mountain Bikes Rocker Arm Linkage Via Topology Optimization

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Abstract

This project applies reverse engineering (RE) and topology optimization (TO) to redesign a mountain bike (MTB) rocker arm. The project aims to improve structural performance, reduce weight, and ensure optimal functionality below challenging restrictions. To capture the complex geometry of the current component with high accuracy, the Shining3D Combo Plus scanner is used to gather data. Then, to rebuild surfaces and repair flaws, the cloud data was processed in Geomagic Wrap, yielding a flawless, watertight polygonal model. Later, to verify dimensional precision and the smooth, permanent integration of the redesigned component into the bicycle frame, the prototype was imported into Autodesk Fusion 360 and converted into an entirely parametric CAD model. Altair Inspire was manipulated by the TO stage to apply a realistic 1200N load to reduce non-critical substructures, resulting in a lightweight structure with sufficient strength. The optimized aluminium design was validated through Finite Element Analysis (FEA), showing a maximum Von Mises stress of 120.806 MPa, a maximum displacement of 0.188 mm, and a safety factor of 3.0. The outcomes determined that another component is similarly weight-efficient and structurally robust under high working loads. The definitive stage of validation and manufacturability, utilizing the Bambu Lab X1 Carbon printer for optimized design via Fused Deposition Modelling (FDM) 3D printing. This established an even transition from simulation-driven redesign to physical prototyping, with printed models confirming the geometric accuracy and assembly tolerances of the redesigned part, indicating that the multifaceted, optimized topology will likely be manufactured and assembled into a useful product.

Keywords: Reverse engineering, topology optimization, mechanical design, Finite Element Analysis, Additive Manufacturing.

1. Introduction

Topology optimization (TO) is an advanced computational design method that optimizes the efficient distribution of material within a proposed design province to meet specific performance objectives and constraints (Tang et al., 2024). Contrasting conventional size or form optimization, which relies on predefined geometries, TO is freed from the initial arrangement, allowing the emergence of entirely new structural designs (Shin et al., 2022). This freedom in definitive proposals enables engineers to reduce weight by increasing stiffness, making it a significant tool in weight-conscious manufacturing, such as in aerospace, automotive, and civil engineering (Sigmund, 2020). The mathematical establishments of structural optimization date back to Michell's 1904 criterion for best possible truss structures (Tang et al., 2024). Nevertheless, modern numerical TO was introduced by Bendsøe & Kikuchi (2003), who adopted the homogenization approach to discover optimal material designs via Finite Element Analysis (FEA). Subsequently, the field has evolved into distinct numerical frameworks, including density-based methods such as Solid Isotropic Material with Penalization (SIMP), level-set methods (LSM), and evolutionary structural optimization (ESO/BESO) (El Khadiri et al., 2023 & Nathan et al., 2020).

In In the meantime, reverse engineering (RE) is defined as the method of removing the surface geometry of a substantial component and transforming it into a complete three-dimensional (3D) digital model (Lee et al., 2021). This typically involves utilizing 3D scanning equipment and point cloud data to create an editable CAD representation (Rochefort-Beaudoin et al., 2025). Conversely, TO is a mathematical approach that optimizes the distribution of materials within a predefined design domain to meet specific performance objectives, typically reducing weight while maintaining structural integrity (Sigmund, 2020). The combination of RE and TO is poised to transform cutting-edge contemporary mechanical engineering, with remarkable potential for component redesign. The process from conceptualization to physical production of traditional design follows a straight-line track; the reorganization of RE and TO allows technologists to skip the physical component, digitalize the condition geometry, and apply mathematical algorithms to enhance its structural performance (Pang & Fard, 2020). This combination is predominantly serious in high-impact sectors, likely aerospace and energy, where technical documentation for prior components is often out of date or absent, manufactured via RE methodology for refining mechanical systems (Nathan et al., 2020).

Elsewhere, weight reserves, the purpose of the TO for rocker arm linkages, is important for confirming long-lasting structural reliability under the most demanding loading conditions, such as landing shocks or high-speed cornering. Conventional, detailed, or complicated associations repeatedly demonstrate stress concentrations at sharp corners or at uniform-breadth sectors that do not align with the actual load paths.TO enables supplementary consistent stress spreading by digitally aligning visible strengths with the fundamental stress paths (Tyflopoulos & Steinert, 2020). The academic significance of this optimization likewise includes inventions relevant to Additive Manufacturing (AM). However, rocker arms for inheritance are made by CNC milling or forging; the difficult, hollow, or lattice structures constructed by TO can be manufactured through Direct Metal Laser Sintering (DMLS). This permits the fabrication of compositionally graded material components tailored to the specific kinematics of an individual bike structure, indicating a shift from mass production to mass customization in the cycling industry (Wu et al., 2021).

2. Literature Review

The incorporated workflow, combining RE with TO, yields an accurate, multi-phase arrangement that converts a substantial relic component into a high-performance digital resource. The procedure begins with data acquisition, during which advanced 3D scanning technologies, such as laser or structured-light scanners, capture the detailed exterior and internal geometries of the body part as a high-density point cloud (Pang & Fard, 2020). This raw information is later digitally rebuilt, a process that generates a point cloud and links it to an irrefutable 3D CAD model that serves as the preliminary design area (Al-Habaibeh, A., 2023). After the digital model is recognized, imitation and validation are performed using FEA to establish a standard for the portion's current mechanical performance, including stress distributions and natural frequencies (Pang & Fard, 2020). Even in these borderline circumstances, distinct TO procedures, such as SIMP or level-set methods, remain useful for reallocating or eliminating outmoded material, iteratively purifying the structure to achieve precise objectives, such as mass minimization or stiffness maximization (Manios et al., 2019). The concluding phase, besides frequently recording a stimulating phase, remains geometry deportation, in which the subsequent original compactness charts are rehabilitated into even, parametric CAD surfaces specifically aimed at traditional manufacturing or AM (Fan et al., 2022).

In modern times, the combination of TO with AM is expected to revolutionize the fabrication of dense, bio-inspired, and multi-gauge structures that were previously impossible to produce (Wu et al., 2021). The current study is increasingly focused on Multiphysics challenges, such as fluid-thermal connections and electromagnetic effects, and on integrating machine learning to reduce the substantial computational costs conventionally associated with iterative optimization sequences (Alexandersen & Andreasen, 2020 & Shin et al., 2022).

Then, the structural optimization of a mountain bike (MTB) rocker arm linkage via TO is a critical aspect of high-performance sporting engineering, particularly given its role in the vehicle's dynamic response and suspension kinematics. During the critical intermediate phase, the rocker arm must withstand extensive multi-axial fatigue loads while exerting high torsional stiffness to guarantee precise rear-wheel motion (Manios et al., 2019).

Tayong et al. (2023) showed the evaluates its mechanical performance and durability toward the structural outcomes for the rear swing arm (RSA) employing displacement, the Max Von Mises stress, and the factor of safety, and:

i. Displacement: This parameter estimates the RSA stiffness, through numerical displaying indicating a maximum displacement magnitude of almost 0.30 mm below a static load of 2500 N. The outcomes implied that a smaller displacement will commonly be associated with greater structural stiffness.
ii. Factor of Safety (SF): Actually, it is decided at 3 for systematic calculations; based on data in industry standards for motorcycles, the factor of safety is refined to 1.5. This change enables a more efficient approach to achieving a lightweight design while confirming that the structure preserves its resistance to extreme conditions.
iii. Max Von Mises Stress: Based on the material properties of the 7075 T651 aluminium alloy, the study shows that stress applications surpassing the

503 MPa yield strength are mainly established throughout individualities identical fixing points and axle passages.

The considered search for process efficiency, aimed at maximizing the stiffness-to-weight ratio to enhance the bike's overall handling and acceleration, clarifies the situation: structural performance through TO is not merely a matter of material reduction (Pang & Fard, 2020). In MTB design, the rocker arm contributes to the system's weight rather than to its total mass. Reducing this mass is fundamental to increasing the suspension's sensitivity, allowing the rear wheel to react more quickly to high-frequency terrain irregularities (Manios et al., 2019). Using density-based optimization methods comparable to SIMP, inventors can identify and eliminate material from regions of low strain energy, resulting in organic, bio-inspired geometries that traditional subtractive manufacturing cannot readily achieve (Sigmund, 2020). This decrease in mass, when combined with conserved or mounted stiffness, is associated with reduced rider fatigue and increased power on technical terrain.

3. Methodology

In this project, the redesign of mechanical linkages (the MTB rocker arm) facilitates TO, as demonstrated in Fig. 1. The project's development advocates sustainable engineering practices by reducing material waste and energy consumption, and by extending the product's lifespan through more effective design. Therefore, in the context of reverse engineering, TO not only replicates the geometry of a remaining product but also improves its performance by applying advanced computational methods to construct optimized sustainable designs. 5 stages of project development are indicated: 3D scanning, surface reconstruction, reverse engineering, TO, and validation.

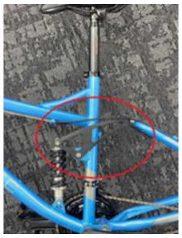
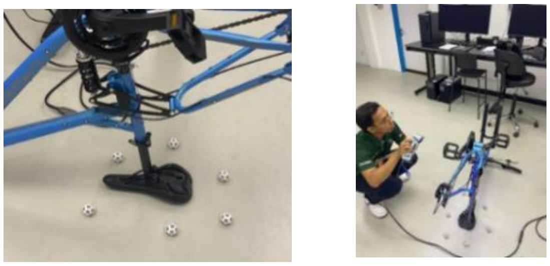


Fig.1: MTB rocker arm to enhance its stiffness

3.1 3D Scanning

For 3D Scanning, a Shining3D Combo Plus scanner was employed to capture the component's specific dimensions, contours, and surface specifications. This sophisticated scanning technology uses light or laser-generated techniques to create a dense cloud of data points, which is converted into a high-resolution digital 3D model. Improving the fabrication of such a scanner will deliver cutting-edge capabilities and enable the smoothest geometry. This digital representation, intended to serve as the basis for reverse engineering, eliminates the need for physical dimensions for can be time-consuming and prone to error. Below indicates step for 3D scanning the bicycle linkage:

1. i. Preparation of the Component: Stickers and reflective pointers are sited arranged the bicycle frame and surrounding the linkage spot to perform as reference points. It is important to combine several scans to reconstruct the object in 3D space, as illustrated in Fig. 2(a).
2. ii. Scanning Process: The scanner predicted constructed light prototypes versus the exterior, and sensors documented the light warped over the object. By moving the scanner around the component, the system gathers a dense cloud of data points and infers the component's accurate surface geometry, as illustrated in Fig. 2(b).



(a) (b)

Fig. 2: (a) Preparation of component and (b) scanning process

3.2 Surface Reconstruction

The digital reconstruction of the rocker arm was completed using a high-resolution scanning workflow with the Shining3D Combo Plus. The Geomagic Wrapware was used to validate geometric truthfulness with full integration with Computer-Aided Design (CAD); these accurate datasets experienced rigorous computational analysis. This process involved the post-processing stage, comprising gap resolution, noise removal, and the combination of multiple viewpoints to construct a watertight mesh that preserves critical surface descriptions and dimensional precision. Lastly, the RE method encourages robust design optimization by providing a high-reliability digital model suitable for complex engineering analysis and adaptation. As determined in Fig. 3, the main frame of the MTB arm linkage was captured. Fig. 4 defines the rocker arm component to be redesigned. The validation of the procedure in Geomagic Wrap is systematic below.

i. Importing into Geomagic Wrap
   The scanned data of the bicycle frame and linkage were imported into Geomagic Wrap for surface reconstruction, transforming the initial mesh into a practical digital model. This process is intensive in developing geometric precision, confirming that the resulting high-fidelity demonstrates appropriate performance for unified arrangement and extended movement within Computer-Aided Design (CAD) circumstances.

ii. Repairing Irregularities
   During the primary scanning stage, data acquisition events included sensor access and

surface reflection, with mesh flawlessness characterized by holes, intervals, and surface breaks. To resolve these issues, a suite of restoration algorithms ensued, used to fill in missing provinces and sections by solving the exterior of the bicycle frame and linkage. This post-treatment phase was important for certifying geometric stability and dimensional accuracy, ensuring a watertight mesh suitable for subsequent REand downstream modelling.

iii. Creating Axis and Alignment
To guarantee three-dimensional consistency throughout the digitized geometry, a universal orientation was established to enable exact recording of the scanned data. This arrangement phase was initially important for showing precise dimensions, accommodating successive design adaptations, and confirming overall interoperability with downstream CAD systems.

iv. Exporting for Reverse Engineering
Upon completion of the reconstruction and repair phases, the refined geometry was exported in STL (Standard Tessellation Language) format to enable subsequent downstream processing. Given its broad compatibility with diverse Computer-Aided Design (CAD) environments, the STL file serves as the foundational mesh for the REworkflow. Ultimately, this export ensures the digitized geometry functions as a robust reference, facilitating highly precise CAD modelling and iterative design optimization.

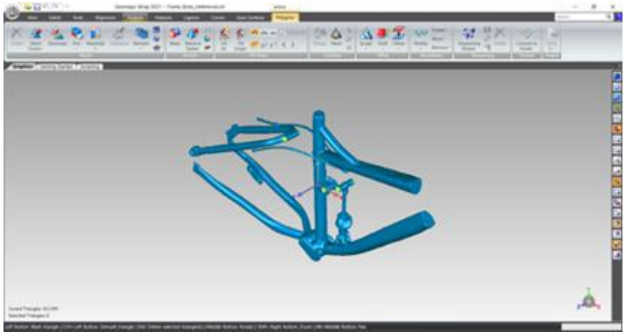


Fig. 3: The main frame of the MTB without the arm linkage

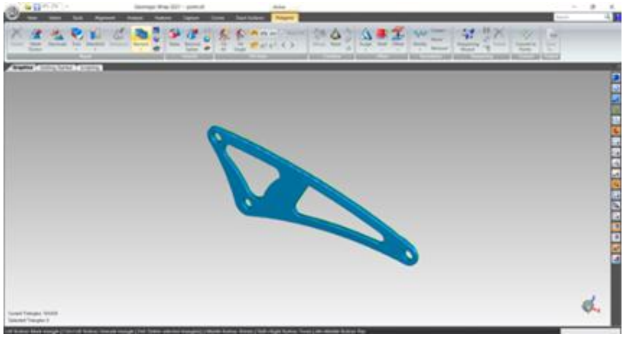


Fig. 4: The MTB rocker arm component is designated for redesigning

3.3 Reverse Engineering

Following the finalization of surface reconstruction in Geomagic Wrap, the geometry is transferred to a parametric Computer-Aided Design (CAD) environment, namely Autodesk Fusion 360. This transition facilitates the progression from fixed, triangulated mesh data to a dynamic, feature-based solid model of the bicycle linkage. By employing geometric referencing techniques such as sketching, extruding, and lofting, the scanned geometry is systematically rebuilt into a rule-driven framework, strictly governed by dimensional constraints and functional parameters.

In contrast to static mesh data, this parametric method preserves design intent and enables the effective optimization of critical features, including linkage dimensions and hole diameters, while supporting progressive downstream engineering tasks, such as kinematic analysis and finite element optimization. Eventually, participating in Fusion 360 hooks into the REpipeline, bridging the gap between empirical data acquisition and functional design, guaranteeing the final model is both a high-reliability imitation and a multipurpose tool for reiterative product development. As illustrated in Fig. 5, the Parametric CAD Model of Bicycle Linkage Plate in Autodesk Fusion 360, while Fig. 6 shows the Assembled Parametric CAD Model of Bicycle Linkage in Autodesk Fusion 360.

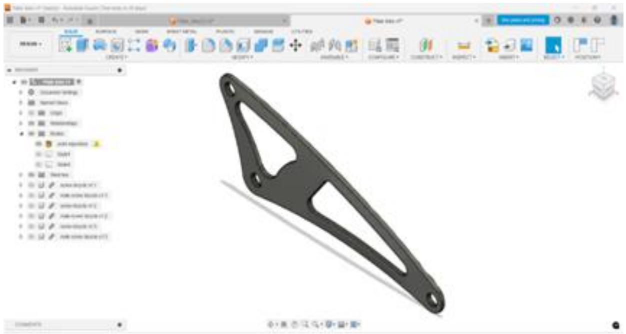


Fig. 5: The parametric CAD model of the MTB rocker arm plate in Autodesk Fusion 360

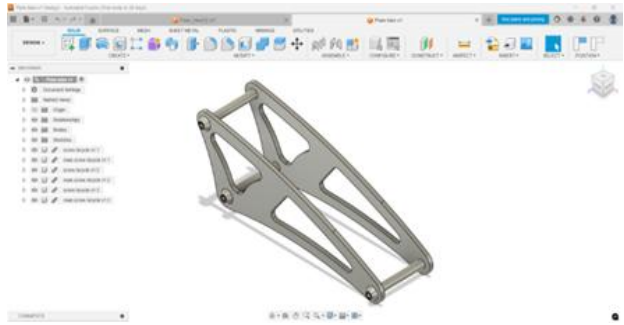


Fig. 6: The assembled parametric CAD model of the MTB rocker arm in Autodesk Fusion 360

The incorporation of the topology-optimized rocker arm plate obsessed by a parametric CAD frame accelerates accurate confirmation of the component's geometric devotion within the broader suspension assembly. The approach is facilitated by considering the structural arrangement, including load allocation and manufacturability, through physical implementation. This modelling dynamically associates swivel positions and shock absorbers. Finally, the computational combination utilities provide a detailed association between conceptual redesign and functional performance, confirming MTB suspension and structural performance. Fig. 7 shows the incorporation of a parametric CAD model of the MTB rocker arm plate into the rear suspension linkage system.

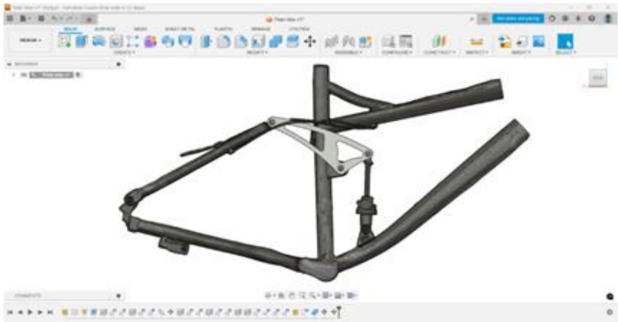


Fig. 7: Illustrates the incorporation of a parametric CAD model of the MTB rocker arm plate.

3.4 Topology Optimization

Transitioning the design from minimal geometric imitation to high-performance assembly via TO in Altair Inspire represents a significant stage in the structural modification of the reverse-engineered rocker arm. Simulating a 1200N operational load and imposing boundary conditions at the pivot points, the computer software's algorithms abolished redundant material to strengthen primary load paths. The method yields a geometry with an enhanced stiffness-to-weight ratio, successfully reducing mass without compromising the safety of the mechanical components. The resulting design attains toughness and cycling performance, providing a validated foundation for assembly. There is a subsequent TO method for the MTB rocker arm.

i. Material Property Selection

The material properties for the bicycle linkage are selected during the first procedure. The 7075 T651 aluminium alloys were selected for their lightweight, strong properties. The Mechanical properties of 7075 T651 aluminium alloys, which are convincing in Young's modulus, Poisson's ratio, and yield strength, were quantified to guarantee the desired option.

ii. Application of Boundary Conditions

The representative boundary circumstances were applied to duplicate operative situations, with pivoted points remaining constrained to simulate a fixed attachment to the bicycle frame. Next, exterior loads were used to characterize the forces conveyed from the bicycle frame and the rider's weight, as illustrated in Fig. 8.

iii. Topology Optimization

To minimize weight and improve stiffness while preserving structural integrity, the TO was conducted. The optimization algorithm analytically removed non-indispensable material from low-stress areas, confirming that key load-bearing tracks remained complete, as illustrated in Fig. 9.

iv. Geometry Refinement

The optimized geometry was then refined and integrated into a manufacturable prototype, which process comprised smoothing uneven surfaces, strengthening thin areas, and reshaping complex outlines that are compatible with manufacturing and assembly developments, as illustrated in Fig. 10.

Fig. 8: Illustrates the boundary conditions of constrained pivot points to simulate a fixed attachment to the bicycle frame

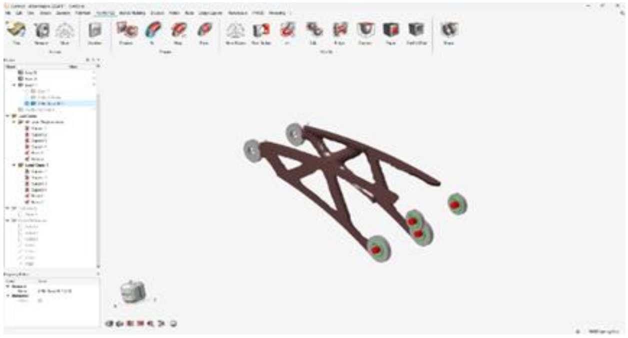


Fig. 9: Illustrates the TO conducted to minimize weight and improve stiffness while preserving structural integrity

Fig. 10: Illustrates the optimized geometry, which was subsequently refined to produce a manufacturable prototype

4. Results

The results and discussion present the mechanical results from a finite element structural analysis (FEA) to calculate the linkage under loading. Validation of the MTB Rocker Arm Linkage to identify potential failure zones, stress concentrations, and deformation regions, providing the basis for design optimization.

To validate stress, deformation, and factor of safety to achieve limits under predictable loading conditions, the process began by reassessing the optimized geometry from FEA. The analysis correspondingly approves that material usage and weight reductions do not compromise structural integrity and functionality. Altair Inspire software was used to perturb the similar boundary conditions during TO, and the analysis was conducted with aluminium as the study material and applied loads of 1200N. The results indicate a displacement of 0.188mm, which is lower than the 0.30mm result reported by Tayong (2023). This lower displacement is commonly associated with higher structural stiffness, as shown on Fig. 11. While the factor of safety is 3.0, which is better than the factor of safety 1.5 based on experimental data and industry standards for motorcycles, as shown in Fig. 12. Lastly, the maximum von Mises stress was about 120.806 MPa, corresponding to the 7075 T651 aluminium alloy, as shown in Fig. 13. The result was lower than the 503 MPa yield strength reported by Tayong (2023). The structural analysis designates a direct linear relationship between the applied load and the subsequent mechanical response of the rear swing arm. The maximum Von Mises stress is 120.806 MPa when subjected to a static force of 1200 N. Alternatively, increasing the practical load to 2500N results in a significantly higher stress of 503 MPa, which exceeds the yield strength and imposes careful regard of the factor of safety to make sure structural integrity.

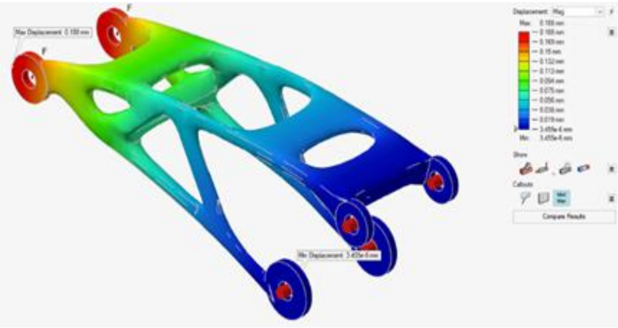


Fig. 11: Illustrates the results, indicating the displacement is 0.188mm

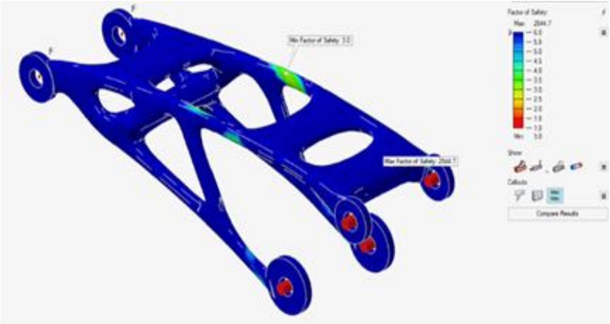


Fig. 12: Illustrated factor of safety of 3.0

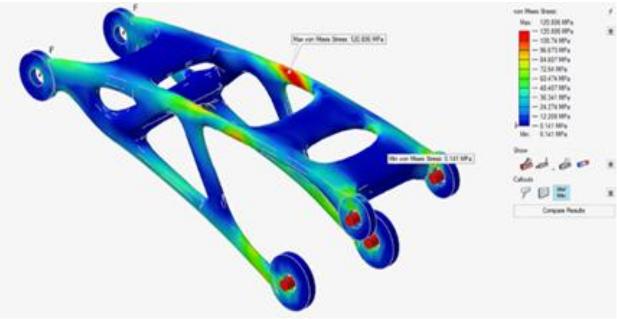


Fig. 13: Illustrated Max Von Mises stress resulted in about 120.806 Mpa

The superior geometry, categorized through calculated material retaining laterally primary load trails and the elimination of non-essential areas, attains an optimal equilibrium of strength, stiffness, and manufacturability, complete simulation-driven design, promising the component is structurally robust, nevertheless lightweight, aimed at incorporation into the bicycle frame. Fig. 14 illustrates the optimized bicycle linkage assembly model created through TO, which was applied to reduce weight, while preserving structural integrity. Additionally, Fig. 15 illustrates the combination of the MTB rocker arm in the interior of the whole bicycle frame assembly, highlighting its role in the suspension linkage system.

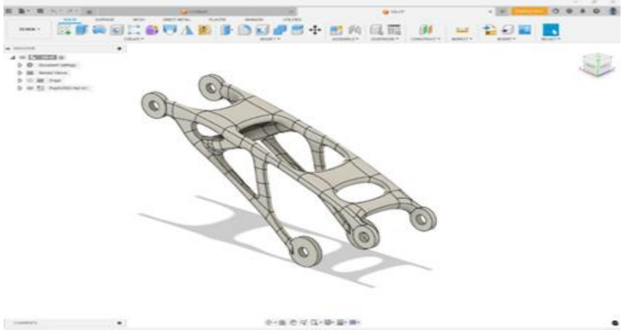


Fig. 14: Illustrates the optimized bicycle linkage assembly created through TO

Fig. 15: Illustrates the combination of the MTB rocker arm in the whole bicycle frame

5. Discussion

The conclusive phase of validation and manufacturability, using the Bambu Lab X1 Carbon printer for optimized design through Fused Deposition Modelling (FDM) 3D printing. The prototype was printed using the material extrusion AM process, which is commonly known as FDM Technology. Printing was performed by preparing the parts in slicing software and selecting the orientation to print the prototype. The orientation will affect the total printing time, material consumption, support structures and surface resolution. Thus, with these four considerations, the part orientation is shown on Fig. 16.

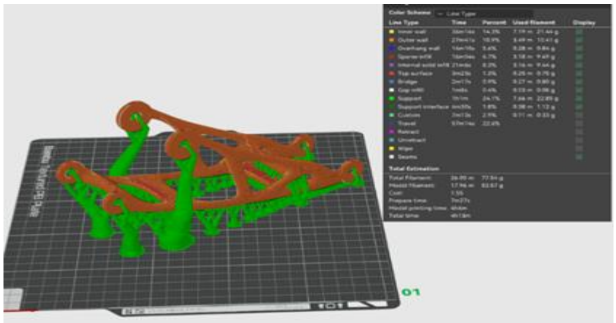


Fig. 16: Illustrates the orientation of the prototype during 3D printing

Finally, the prototype of the product yielded from TO, as illustrated in Fig. 17, shows 3D-printed prototypes, which play a critical role in the cutting-edge expansion of the MTB rocker arm linkage by providing physical validation of the simulation-driven design. As illustrated in Fig. 16, the prototype was done for 3D printing to confirm the geometric accuracy and assembly tolerances of the redesigned part, indicating that the multifaceted, optimized topology will likely be manufactured and assembled into a useful product.

Fig. 17: Illustrates the prototype done for 3D printing

6. Conclusion

According to the study, concerning the redesign of the MTB rocker arm linkage, there were subsequent conclusions equally drawn:

i. **Design Methodology Integrated:** The combination of RE and TO delivers a robust outline for changing inherited physical components into high-performance digital properties.

ii. **Structural Optimization and Weight Reduction:** By affecting load 1200N via the optimization stage, non-critical structures were eliminated to produce a lightweight geometry without ignoring the component's strength or stiffness.

iii. **Validation for Performance:** The results showed a maximum displacement of 0.188 mm, a safety factor of 3.0, and a maximum Von Mises stress of 120.806 MPa, as indicated by FEA, which established the structural integrity of the optimized design.

iv. **Improved Dynamic Response:** To accept the rear wheel to counter more efficiently to high-frequency terrain irregularities, reducing the mass of the rocker arms will increase suspension compliance.

v. **Digital Accuracy:** To confirm the formation of a watertight, parametric CAD model with high-dimensional accuracy, use Geomagic Wrap and Autodesk Fusion 360 for advanced 3D scanning and surface reconstruction tools.

vi. **Prototyping and Manufacturability:** Physical validation via FDM 3D printing established the geometric precision and assembly acceptances for the complex, optimized topology, representative of its enthusiasm for incorporation into the bicycle frame.

vii. **Engineering or Sustainability:** The study supports sustainable practices by encompassing product lifetimes and reducing waste material through computational design developments rather than subtractive manufacturing.

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Author Contributions: The research was carried out successfully with contributions from all authors.

Conflicts of Interest: The authors declare no conflict of interest.

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