
Part Optimisation using CNC Milling Techniques in Engineering Education

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Abstract

Aims/Objectives: Increasing demand for optimised, lightweight, and efficient products has become a necessity in the field of engineering. As such, integrating appropriate design processes into engineering education has become crucial. In this study, the application of Design for Manufacturing, Finite Element Analysis, and Design for Environment principles in the redesign of a motorcycle brake lever was considered. The objective was to enhance its structural performance while reducing material usage compared to the original part.

Results: The re-engineered part achieved a significant reduction in mass, minimizing its environmental impact, while maintaining an acceptable Factor

of Safety (FOS) in comparison to the original design. The Von Mises stress, initially concentrated at a critical arch, was reduced from 54.3 MPa to 27.3 MPa and translated to the pinned region. This effectively eliminated bending moments at critical regions. Additionally, the maximum displacement was reduced, resulting in shorter machining timeframes.

Conclusion: Systematic optimisation demonstrated the possibility of achieving better products with improved safety factors, reduced material usage, and enhanced manufacturing efficiency. The findings and methodologies presented provide critical guidelines for aspiring engineering students and offer valuable insights into the integration of advanced design principles in engineering education.

Keywords. *Manufacturing, Solidworks, FEA, CNC, CAE*

1 Introduction

The finite element method (FEM) is widely used by analysts to conduct parametric studies, size parts, evaluate design scenarios, and predict system behavior under varying loads (1). In the fast-paced manufacturing industry, companies face the challenge of developing high-quality products at reduced costs as it contributes to overall optimisation, reduced carbon footprint while maintaining their competitive edge (2).

To achieve such goals, the integration of computer-aided engineering (CAE), including design for manufacturing (DFM), finite element analysis (FEA), and design for environment (DFE) principles (3), has become increasingly prevalent. This project demonstrates the advantages of applying this integrated approach by presenting a comprehensive workflow for redesigning an existing motorcycle brake lever, serving as a valuable teaching resource for aspiring engineers and technologists in the field of engineering education (4; 5).

The redesign process involved leveraging advanced computer-aided design (CAD) tools, conducting finite element analysis (FEA), and developing optimised tool paths for manufacturing in a computerised numerical control (CNC) mechanical laboratory located at the University of the West Indies, St. Augustine Campus, Trinidad and Tobago. The objective of this project was to enhance the structural performance of the motorcycle brake lever and reduce material usage, while showing how systematic optimisation can lead to improved product outcomes.

Therefore, the project aimed to address both performance and economic aspects of product development. The following sections elaborate on the step-by-step methodology applied, the specific tools and techniques utilised, and the results achieved through the re-engineering process. Furthermore, the paper discusses the implications of the findings and highlights the potential benefits of adopting a similar approach in other engineering and manufacturing scenarios (17).

2 Methodology

The methodology employed for this project involved the use of the Finite Element Analysis (FEA) Modelling technique, which approximates a continuous domain by discretising it into finite elements (6). This approach allows the application of boundary forces and the solution of governing equations at each node of the mesh, enabling accurate analysis of specific parameters using digital computers (7). The FEA methodology provides a powerful tool for solving complex problems on high-dimensional domains that would be challenging to address analytically (8).

To address the environmental impact of the product's life cycle, Design for Environment (DFE) principles were integrated into the redesign process (10; 20). This consideration involved reducing the environmental footprint from raw material extraction during product development to minimising

After finalising the CAD design for milling, the part was saved as an STL file and imported into Boxford’s 3D-GeoCAM software. A suitable cut plane was selected with a z-position set at 50% of the stock material thickness. The stock material dimensions were configured as per Table 2, and suitable cutting tools were chosen.

Table 2: Stock material dimensions setup

Dimension	Value (mm)
X	190
Y	74
Z	15

Efficient material removal and excellent surface finish were achieved using a 90/10 selection strategy for the roughing and finishing passes. Due to the complexity of the lever geometry, a two-stage machining process, namely the top-cut and bottom-cut, was necessary. Figures 2 and 3 illustrate the outcomes of these stages. The cutting tools utilised for the roughing and finishing passes are listed in Table 3.

Table 3: Parameters of selected cutting tools

Tool Type	Description	Dia.
Roughing	OWM–Straight Cutter	6.30mm
Finishing	OWM–Radius Cutter	6.35mm

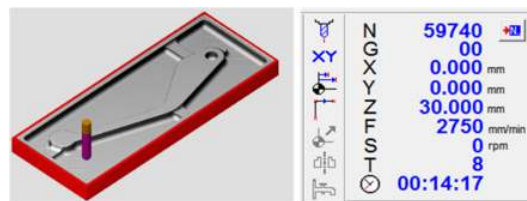


Figure 2: Original design with frame and tabs for machining support (top cut)

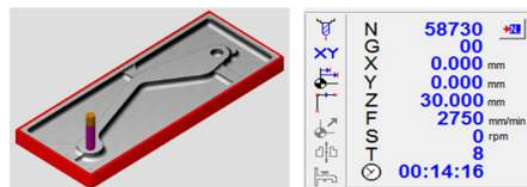


Figure 3: Original design with frame and tabs for machining support (bottom cut)

The machining time for both the top and bottom sides was obtained from the simulation and is shown in Table 4, along with the generated Geometry and Miscellaneous (G&M) codes. After the top-side machining was completed, the part was flipped, and the same process was repeated for the bottom side, maintaining consistent tools and settings except for the cutting plane.

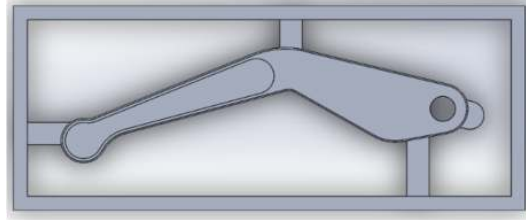


Figure 5: Optimised model with tabs

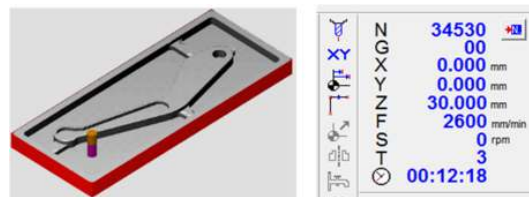


Figure 6: Optimised model with tabs (top cut)

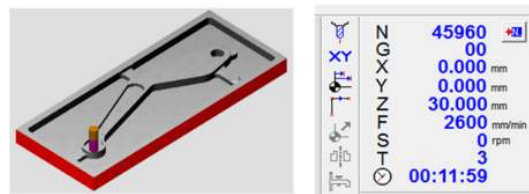


Figure 7: Optimised model with tabs (bottom cut)

Table 6: Parameters of selected cutting tools

Tool Type	Description	Dia.
Roughing	OWM–Straight Cutter	7.90mm
Finishing	OWM–Radius Cutter	6.00mm

Table 7: Machining time for re-engineered part

Machining Operation	Machining Time
Top	00:14:16
Bottom	00:14:17

For facilitating the machining process, tabs were integrated into the design, as shown in Figure 5, which allowed the part to remain attached to the stock material during flipping for machining the opposite side. The tabs, measuring 8mm in width and depth, effectively handled vibrations during milling. Additionally, a clearance amount of 12mm was incorporated at the outermost region to ensure sufficient toolpath clearance throughout the process.

The re-engineering process employed a two-stage machining strategy, namely the top-cut and

bottom-cut, as depicted in Figures 6 and 7. The stock material dimensions and selected cutting tools are shown in Table 5 and Table 6, respectively. The roughing cycle used offset water milling, while the finishing cycle utilised offset milling with compute rest finishing.

Upon completion of the wizard setup, a simulation was conducted, and no collisions were detected. The machining time for the re-engineered part was obtained, as shown in Table 7, along with the generated G&M code. After finishing the top-side machining, the part was flipped, and the same process was repeated for the bottom side, maintaining consistent tools and settings except for the cutting plane. Moreover, the total mass of the re-designed model was found to be less than the constrained maximum outlined in Table 1.

3 Results

Table 8 shows results of the original part, including the maximum displacement (deflection). The Factor of Safety (FOS) was less than one, indicating that it would yield during operation. This result was shown in Figure 8, through the FEA analysis. This suggests that the maximum stresses in the original part exceeded its yield strength, resulting in failure as further demonstrated in Figure 9. In addition, the mass of the original part was measured as 85.10g, which did not meet the redesigned constraints. The Von Mises stress results for the original design are presented in Table 9.

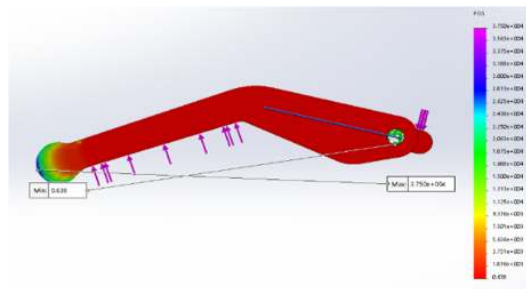


Figure 8: FOS of the original part < 1

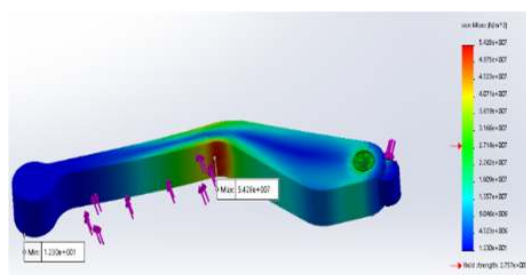


Figure 9: Max. stress in the original part exceeded its yield strength

In perspective, the simulation results for the re-engineered part are presented in Table 10. The re-engineered part achieved an improved Factor of Safety and reduced mass compared to the original design. Figure 10 shows the improved FOS of the re-engineered part, which is greater than one,

Table 8: Results of the original part

Parameter	Original
FOS	0.51
Mass (g)	85.1
Max. Stresses (MPa)	54.3
Max Displacement (mm)	0.58
Machining Time	0:14:16
Surface Finish	'Good'

Table 9: Simulation results of the original design

Parameter	Result Obtained
Max. Stress (Von Mises)	54.3 MPa
Factor of Safety*	0.508
Mass	85.10 g

indicating a more robust design. The applied force on the lever was well distributed throughout the redesigned model, resulting in a significant reduction in maximum stresses and structural instability.

Table 10: Simulation results of Re-engineered Part

Parameter	Result Obtained
Max Stress (Von Mises)	27.3 MPa
Factor of Safety*	1.011
Mass	83.93 g

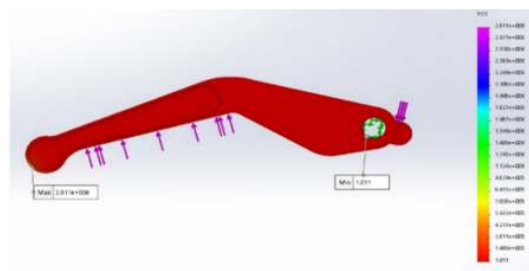


Figure 10: FOS for the re-engineered part > 1

Figure 11 illustrates the maximum stress regions between the original and redesigned parts, which showed the original part was almost three times greater than that of the re-engineered part. This highlights the improvements that were achieved. Table 11 summarises the comparison of results between the original and redesigned parts, highlighting the improvements in terms of FOS, mass, maximum stresses, maximum displacement, machining time, and surface finish.

Finally, Table 12 compares the machining time of original and re-engineered designs. The distribution of maximum stresses throughout the redesigned part is illustrated in Figure 12 while the

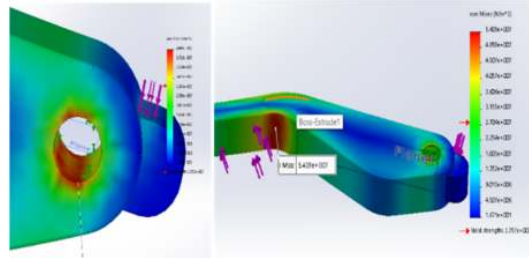


Figure 11: Max. stress moved from mid section to pin region (r) Original part, (l) Redesigned part

Table 11: Results of original and redesigned parts

Parameter	Original	Re-engineered
FOS	0.51	1.01
Mass (g)	85.1	83.9
Max. Stresses (MPa)	54.3	27.3
Max Displacement (mm)	0.58	0.19
Machining Time	0:14:16	0:12:08
Surface Finish	'Good'	'Good'

Table 12: Boxford Tool Machining time simulation for original and re-engineered parts

	Original	Re-eng. 1	Re-eng. 2
Top	00:14:16	00:11:59	00:11:58
Bottom	00:14:17	00:12:18	00:12:17
Total	00:28:33	00:24:17	00:24:16

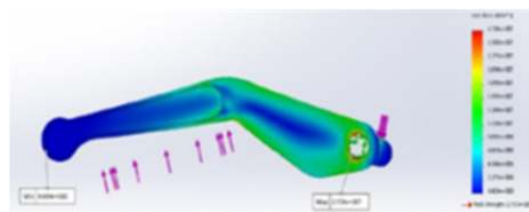


Figure 12: Max. stress distributed of re-designed part

design for environment report is presented in 13.

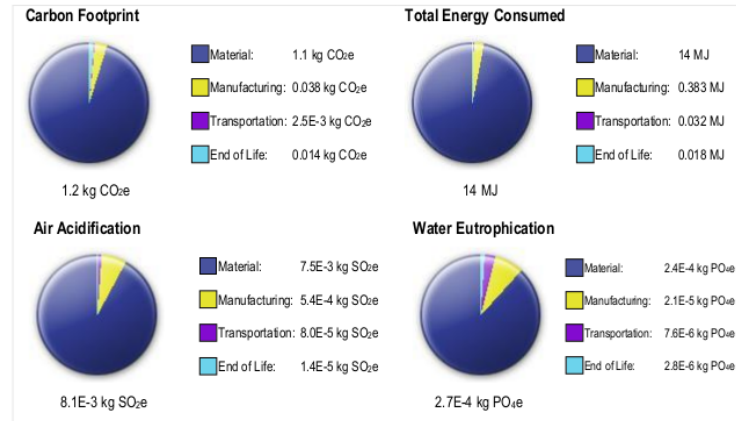


Figure 13: Design for environment results

4 Discussion

The re-engineered process obtained remarkable success in achieving major improvements in the re-designed part compared to the original design. The re-engineered part exhibited reduced maximum stresses and displacements, leading to enhanced structural performance. Additionally, optimisation of the manufacturing process significantly reduced the machining time during production.

The validation of the re-engineered part was carried out through an additional machining iteration, which further confirmed the improved performance that yielded good surface finish without any degradation of the simulated model. The machining timeframes for this can be seen in Table 12. While there was a slight reduction in the length of the part, it was deemed negligible compared to the trade-off for improved structural stability. The decision to reduce the length was justified as it effectively translated the maximum stresses to the pinned supported region, ensuring a satisfactory factor of safety and avoiding any yield stress failures.

The optimality of the redesigned model extended beyond structural improvements, as the assessment of environmental impact using Solidworks sustainability tools have shown. The re-engineered part outperformed the original part in various environmental indicators, including water eutrophication, total energy consumption, carbon footprint, air acidification (see Figure 13), as well as manufacturing timeframes.

This project has provided well-documented procedures and guidelines that can serve as a valuable resource for aspiring engineering students aiming to optimise parts, enhance performance, reduce material usage, and improve manufacturing efficiency in their future engineering projects.

The success of this re-engineering project showcases the potential of using the proposed optimisation approach in engineering education. Incorporating Finite Element Analysis (FEA) Modelling, Design for Environment (DFE) principles, and Advanced CAD/CAM techniques, can help students develop better products with enhanced safety factors and reduced environmental impact. These engineering methodologies not only contribute to sustainable product design but also foster innovation and efficiency in real-world engineering applications.

Future research possibilities lie in exploring similar optimisation strategies for other mechanical components and complex systems for students' second and final year capstone projects. Furthermore, extending the environmental impact assessment to include a life cycle analysis approach would provide a comprehensive understanding of the redesigned part's sustainability and contribute to the broader field of environmentally conscious engineering.

5 Conclusion

The re-engineering of the motorcycle brake lever has resulted in significant advancements that underscore the potential of integrating advanced engineering principles in product design and manufacturing. The following list of points summarises the key contributions of this paper:

- The re-engineered brake lever achieved a significant reduction in mass, minimising its environmental impact, while maintaining an acceptable Factor of Safety (FOS) in comparison to the original design.
- The Von Mises stress, initially concentrated at a critical arch, was reduced from 54.3 MPa to 27.3 MPa and translated to the pinned region, effectively eliminating bending moments at critical regions.
- The maximum displacement was reduced, resulting in shorter machining timeframes and enhancing manufacturing efficiency.
- The redesign process showcased the potential of integrating Finite Element Analysis Modelling, Design for Environment principles, and Advanced CAD/CAM techniques for improved structural performance and reduced environmental impacts.
- The re-engineered part demonstrated better environmental sustainability, outperforming the original design in various environmental indicators.
- The presented methodologies and guidelines provide valuable insights for the aspiring engineering student, fostering innovation and efficiency in real-world engineering applications.
- Future research possibilities include exploring similar optimisation strategies for other mechanical components and complex systems, while incorporating life cycle analysis approaches for comprehensive sustainability assessment.

In conclusion, the re-engineered motorcycle lever exemplifies how innovative engineering approaches can lead to superior product performance, reduced environmental footprint, and invaluable insights for advancing engineering education and industry practices. The continuous pursuit of optimisation and sustainable design principles will undoubtedly shape the future of engineering for a greener and more efficient world.

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