

Topology optimization of a web guiding structure under manufacturing constraints for laser-cut sheet metal fabrication

Otimização topológica de uma estrutura de alinhamento de materiais bobinados com restrições de fabricação para corte a laser

Optimización topológica de una estructura de guiado de material continuo con restricciones de fabricación para corte por láser de chapa metálica

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Emerson de Santana Martins¹
Msc. Edgard Gonçalves Cardoso²
Dr. Leandro Cardoso da Silva³
Msc. Lucas Almeida Willenshofer⁴
Dr. Manuel Patricio da Silva Bisneto⁵
Bruno Yuji Otani Ramalho⁶

ABSTRACT: Industrial web guiding systems require lightweight and rigid structures to ensure accurate positioning while maintaining high dynamic performance. However, conventional design approaches frequently result in oversized components due to the geometric limitations imposed by subtractive manufacturing processes. This study proposes a methodology that integrates topology optimization with Design for Manufacturing (DfM) principles to redesign a guide roller support compatible with laser-cut sheet metal fabrication. The methodology combines finite element analysis, topology optimization using the Solid Isotropic Material with Penalization (SIMP) method, and geometric reconstruction based on manufacturing constraints. The optimized component was validated through static structural simulations using ANSYS Mechanical 2024 R2 under the same loading and boundary conditions adopted for the original design. The proposed solution achieved a 22.79% reduction in mass while maintaining comparable structural performance, with only minor variations in maximum stress, safety factor, and displacement. The results demonstrate that topology optimization can be successfully integrated with conventional manufacturing processes, providing lighter, structurally efficient, and industrially manufacturable components for web guiding applications.

Keywords: topology optimization; web guiding systems; finite element analysis; design for manufacturing; laser cutting.

¹ Postgraduate Student in Industrial Mechanical Projects, Faculdade SENAI-SP, São Paulo, São Paulo, Brazil. E-mail: e_martins11@hotmail.com

² Doctoral Candidate in Energy. Centro Universitário SENAI-SP – Campus Brás, São Paulo, São Paulo, Brazil. E-mail: edgard.cardoso@sp.senai.br

³ Ph.D. in Mechanical Engineering, Centro Universitário SENAI-SP – Campus Brás, São Paulo, São Paulo, Brazil. E-mail: leandro.cardoso@sp.senai.br

⁴ Master's Degree in Mechanical Engineering, Centro Universitário SENAI-SP – Campus Brás, São Paulo, São Paulo, Brazil. E-mail: lucas.willenshofer@sp.senai.br

⁵ Ph.D. in Nanoscience and Advanced Materials, Centro Universitário SENAI-SP – Campus Brás, São Paulo, São Paulo, Brazil. E-mail: manuel.bisneto@sp.senai.br

⁶ MBA in People Management, Technologist in Computer Games and Programming Skills. Universidade Nove de Julho (UNINOVE), São Paulo, São Paulo, Brazil. E-mail: bruno.ramalho@sp.senai.br

1 INTRODUCTION

Industrial automation is a cornerstone of modern manufacturing, improving efficiency, precision, and productivity across several industrial sectors, including packaging, printing, and converting. These industries rely heavily on the processing of continuous web materials, such as paper, plastic films, laminates, and textiles. During production, these materials travel through complex machinery at high speeds, often exceeding several hundred meters per minute. Consequently, even slight lateral deviations can result in severe process failures, including print registration errors, cutting misalignment, and web wrinkling (Roisum, 1998).

To minimize these risks, web guiding systems are incorporated into production lines to continuously monitor and correct the lateral position of the moving web in real time. These systems operate as closed-loop control systems consisting of an edge sensor, a controller that processes the positioning error, and an actuator—electromechanical, hydraulic, or pneumatic—that adjusts the guide structure to maintain the web along its desired path (Roisum; Walker; Jones, 2020). The effectiveness of this corrective action depends not only on the sensing and control strategy but also on the mechanical characteristics of the guide structure. It must be sufficiently stiff to withstand the tensile forces generated by the moving web while remaining lightweight enough to enable the actuator to perform rapid and frequent positioning corrections (Budynas; Nisbett, 2008).

Consequently, the structural design of the web guiding system becomes a critical factor in the overall performance of automated production lines. Traditionally, these structures have been designed using conservative safety factors to maximize rigidity, often resulting in oversized and unnecessarily heavy assemblies. Although this approach improves structural robustness, the additional mass increases system inertia, thereby reducing the dynamic response of the guiding mechanism (Norton, 2013).

As manufacturing advances toward the Industry 4.0 paradigm, where energy efficiency, lightweight structures, and high dynamic performance are essential, traditional engineering approaches are increasingly challenged. Computational engineering techniques, particularly Finite Element Analysis (FEA) and topology optimization, provide powerful alternatives for replacing overdesigned structures with optimized geometries that minimize structural mass while preserving the stiffness required to achieve millimeter-level alignment accuracy (Bendsøe; Sigmund, 2004).

Therefore, this study investigates the application of topology optimization to the structural components of industrial web guiding systems while incorporating manufacturability

constraints associated with their current production process. Since these components are presently manufactured exclusively through subtractive machining to ensure cost control and production scalability, the proposed optimization strategy seeks solutions that are simultaneously lightweight, structurally efficient, and readily manufacturable.

1.1 Research Problem

Industrial web guiding structures are predominantly manufactured using conventional fabrication processes, including laser cutting, subtractive machining, sheet metal bending, and welding. These processes remain the preferred industrial solution because they offer low production costs, high repeatability, and excellent scalability for large-scale manufacturing. However, as noted by Groover (2020), conventional manufacturing methods inherently restrict geometric complexity, limiting the designer's freedom to develop structurally efficient components. Consequently, engineers often compensate for these limitations by adopting conservative designs with additional material to guarantee adequate stiffness, resulting in increased weight and inefficient material utilization.

This design philosophy becomes particularly challenging when advanced structural optimization techniques are introduced into products that must still be manufactured using traditional fabrication processes. According to Bendsøe and Sigmund (2004), topology optimization redistributes material within a prescribed design domain by minimizing structural compliance while satisfying a specified volume constraint. Although this methodology produces highly efficient load paths, the resulting geometries are typically organic, irregular, and difficult to manufacture using conventional subtractive processes. Instead, they are generally more compatible with additive manufacturing technologies.

As a result, a significant gap exists between the theoretical optimum generated by computational optimization algorithms and its practical implementation in industrial production. Closing this gap requires methodologies capable of interpreting topology-optimized geometries and converting them into manufacturable designs that comply with the geometric restrictions imposed by laser-cut steel plates, constant-thickness components, and welded assemblies. Such methodologies must preserve the structural benefits achieved through optimization while ensuring manufacturing feasibility, cost-effectiveness, and production scalability.

Accordingly, this study addresses the following research question: How can a topology-optimized web guiding structure be systematically redesigned for fabrication using laser-cut

carbon steel plates while preserving the structural performance achieved through topology optimization?

1.2 Objectives

The primary objective of this study is to develop and validate a structural optimization methodology for a component of an industrial web guiding system, specifically a guide roller support, by integrating the analytical capabilities of topology optimization with the technical and economic constraints associated with laser-cut sheet metal fabrication.

1.3 Specific Objectives

To achieve the general objective, the following specific objectives were established:

- To perform a static structural analysis of the original guide roller support using ANSYS Mechanical, establishing baseline performance metrics for mass, stress distribution, displacement, and safety factor.
- To carry out topology optimization using the Solid Isotropic Material with Penalization (SIMP) method in order to identify the optimal material distribution and the primary load-transfer paths within the structure (Bendsøe; Sigmund, 2004).
- To interpret the optimized topology and redesign the component according to Design for Manufacturing (DfM) principles, generating a manufacturable geometry that satisfies the constraints imposed by laser cutting of constant-thickness carbon steel plates (Swift; Booker, 2003; Groover, 2020).
- To validate the redesigned component through a second finite element structural analysis, verifying that the proposed design achieves a minimum mass reduction of 20% while maintaining equivalent or improved safety factor, stress distribution, and elastic deformation compared with the original configuration.

1.3 Justification

The accurate alignment of continuous web materials is directly associated with reducing process variability and preventing defects that compromise product quality, such as print registration errors, cutting inaccuracies, and web wrinkling (Roium, 1998). Consequently, the

structural performance of web guiding systems plays a critical role in maintaining stable operation under high-speed manufacturing conditions.

Although these structures are commonly designed to satisfy stiffness requirements, manufacturing cost constraints frequently lead to conservative design practices that result in components with excessive mass. As discussed by Norton (2013), increased structural mass contributes to higher inertia, which, in turn, increases the mechanical loads transmitted to actuators, linear guides, and supporting elements while reducing the dynamic response of the positioning system. These limitations become increasingly significant as production speeds continue to rise.

The application of topology optimization under manufacturing constraints represents a promising strategy for improving the structural efficiency of web guiding components without requiring changes to established production processes. According to Bendsøe and Sigmund (2004), topology optimization enables a more efficient distribution of material by removing regions that contribute minimally to structural stiffness. When the optimized geometry is appropriately redesigned according to Design for Manufacturing (DfM) principles and the limitations of conventional fabrication methods (Swift; Booker, 2003; Groover, 2020), it becomes possible to obtain lighter structures while preserving structural integrity and manufacturability.

The resulting reduction in structural mass decreases system inertia and consequently lowers the dynamic loads acting on actuators and linear guide assemblies. This improvement enhances positioning responsiveness, allowing faster and more accurate alignment corrections. As a result, web guiding systems become capable of operating at higher production speeds while maintaining greater positioning accuracy and improved product quality.

2 THEORETICAL FRAMEWORKS

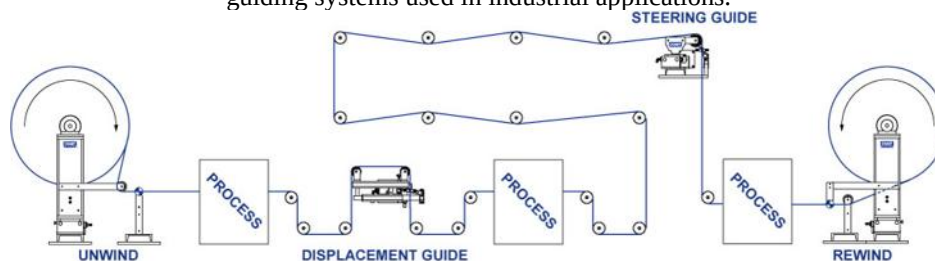
2.1 Fundamentals of Web Guiding Systems

Web guiding systems constitute one of the most important automation technologies employed in continuous web processing industries. Their primary function is to continuously correct the lateral position of the moving web, thereby ensuring process stability and maintaining product quality throughout the production line. According to Coast Controls (2023), industrial web guiding systems can be broadly classified into two main categories:

- Unwind and rewind guides, which laterally reposition the unwind or rewind stand to compensate for web misalignment at the beginning or end of the production process.
- Intermediate guides, which are typically installed immediately upstream of critical manufacturing operations, such as printing, laminating, coating, or slitting. These systems are generally subdivided into displacement guides, preferred where installation space is limited, and steering guides, which are employed in applications with sufficiently long entry spans to provide smooth and accurate web steering (Coast Controls, 2023).

Figure 1 illustrates a typical continuous web processing line and the principal web guiding systems employed throughout the manufacturing process. Depending on their location and function, guiding systems may be installed at the unwinding and rewinding stations to compensate for lateral displacement of the roll, or at intermediate stages to continuously correct the web position before critical operations such as printing, laminating, coating, or slitting. As shown, intermediate guiding systems are generally classified as displacement guides or steering guides according to the mechanism used to restore the web to its desired trajectory (Coast Controls, 2023; Roisum, 1998).

Figure 1. Schematic representation of a continuous web processing line showing the different types of web guiding systems used in industrial applications.



Source: Roisum (1998).

Most industrial web guiding systems operate as closed-loop control systems in which an edge sensor continuously measures the lateral position of the moving web. This positional information is transmitted to a controller, which compares the measured position with a predefined reference and determines the corrective action required. The controller subsequently commands an electromechanical, pneumatic, or hydraulic actuator to reposition the guiding mechanism, thereby actively maintaining the web along its desired trajectory (Roll-2-Roll Technologies, 2025).

Intermediate web guiding systems commonly operate according to the Normal Entry Rule, one of the fundamental principles of web handling. As described by Roll-2-Roll

Technologies (2021), rotating the guide frame through actuator motion generates an entry angle between the moving web and the exit roller axis. Whenever the web approaches a roller at an angle other than perpendicular to its axis, it naturally migrates laterally toward the position that minimizes this angle. Brown (2015) further explains that the lateral velocity of the web is proportional to the roller surface speed multiplied by the web entry angle, making precise control of the guide geometry essential for achieving rapid and stable positioning corrections.

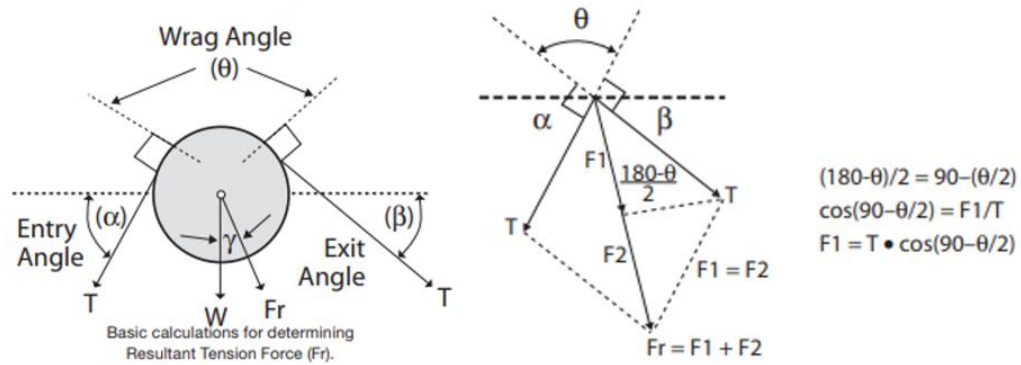
The primary objective of this control strategy is to ensure dimensional accuracy and process stability throughout the production line. Accurate web alignment minimizes print registration errors in printing operations, thickness variations during coating and laminating processes, misalignment during slitting and rewinding, and other defects that directly affect product quality and production efficiency (Chongqing Arise Technology Co., Ltd., 2024).

2.1.1 Structural Requirements

The mechanical structure of a web guiding system must withstand significant static and dynamic loads while maintaining strict limits on displacement and structural deformation to ensure accurate web positioning. Inadequate structural stiffness may compromise the responsiveness of the guiding system, reducing positioning accuracy and increasing the likelihood of process defects. Consequently, the structural design must provide sufficient rigidity without introducing excessive mass that could impair the dynamic performance of the actuator.

According to BLH Nobel (2016), the primary load acting on a web guiding structure originates from the web tension required to transport the material through the production line under controlled conditions. As the web changes direction while passing over the guide rollers, the inlet and outlet tensions generate a resultant force (R) acting on the roller support. This force corresponds to the vector sum of the inlet and outlet tension forces and depends on both the web tension and the wrap angle around the roller. The loading configuration is illustrated in Figure 2, while Equations (1)– (3) describe the calculation of the resultant force acting on the guiding structure.

Figure 2. Schematic representation of the wrap angle calculation based on the web entry and exit angles.



$$R = T \cdot \cos\left(90 - \frac{\theta}{2}\right) + T \cdot \cos\left(90 - \frac{\theta}{2}\right) \quad (1)$$

$$\cos(90 - \theta/2) = \sin(\theta/2) \quad (2)$$

$$R = 2 \cdot T \cdot \sin \frac{\theta}{2} \quad (3)$$

The guide structure must exhibit sufficient structural stiffness to withstand these loads without excessive deformation, since even small elastic deflections may compromise web alignment accuracy. As discussed by Budynas and Nisbett (2008), structural rigidity is a fundamental requirement for maintaining dimensional stability under service loads. However, increasing stiffness solely by adding material often results in unnecessarily heavy structures. According to Norton (2013), excessive structural mass increases system inertia, reducing the dynamic response of moving components and requiring greater actuator effort to achieve the desired positioning. Consequently, oversized guide structures may degrade the performance of the closed-loop control system by limiting acceleration, increasing settling time, and reducing the effectiveness of web position corrections.

2.2 Finite Element Method for Structural Analysis

The Finite Element Method (FEM) is a numerical technique used to obtain approximate solutions for engineering problems governed by partial differential equations. By discretizing a continuous domain into finite elements connected by nodes, FEM transforms complex differential equations into a system of algebraic equations that can be solved numerically.

Owing to its versatility, the method is widely applied in structural analysis, heat transfer, and other engineering fields (Fish; Belytschko, 2007; Alves Filho, 2011; Pedrotti, 2021).

2.2.1 Mesh Discretization and Convergence Analysis

In FEM, the computational domain is divided into a mesh composed of interconnected elements, such as tetrahedral, hexahedral, or shell elements, depending on the geometry and characteristics of the component being analyzed. The accuracy of the numerical solution depends directly on mesh quality and refinement, with progressively finer meshes converging toward the actual structural response (Fish; Belytschko, 2007; Alves Filho, 2011).

To ensure reliable results while avoiding unnecessary computational cost, a mesh convergence study was performed. This procedure consists of evaluating a sequence of progressively refined meshes until variations in the selected response parameters, such as equivalent stress and displacement, become negligible, indicating that the solution is no longer significantly affected by mesh refinement (Patil; Jeyakarthikeyan, 2018; Beisheim; Sinclair; Roache, 2019).

2.2.2 Stiffness Matrix

By combining the equilibrium equations, the strain–displacement relationship, and Hooke's law, the stiffness matrix of each finite element can be derived. This matrix establishes the relationship between the nodal forces acting on the element, (F_e) and the corresponding nodal displacements, (u^e) (Fish; Belytschko, 2007; Alves Filho, 2011).

After assembling all element stiffness matrices and enforcing equilibrium and compatibility conditions at every node, the global structural stiffness matrix is obtained, relating the nodal force vector to the nodal displacement vector according to:

$$\{F\} = [E] \cdot \{U\} \quad (4)$$

where:

$\{F\}$ is the global nodal force vector,

$\{U\}$ is the global nodal displacement vector,

and $[K]$ is the global stiffness matrix of the structure (Fish; Belytschko, 2007; Alves Filho, 2011; Pedrotti, 2021).

2.3 Topology Optimization Theory

Topology optimization aims to determine the optimal material distribution within a prescribed design domain while satisfying loading conditions, support constraints, volume limitations, and manufacturing requirements. According to Bendsøe and Sigmund (2004), the objective is to maximize structural efficiency by removing material from regions that contribute minimally to stiffness. The design domain typically includes non-design regions, such as mounting holes and functional interfaces, which must remain unchanged throughout the optimization process (Patil; Jeyakarthikeyan, 2018).

2.3.1 Compliance Minimization

The most common formulation of topology optimization consists of minimizing the structural compliance while satisfying a prescribed volume constraint. The optimization problem is expressed by the following objective function:

$$C(\mathbf{x}) = \mathbf{f}^T \mathbf{u} = \mathbf{u}^T \mathbf{K} \mathbf{u} \quad (5)$$

where $\mathbf{f}$ is the external load vector, $\mathbf{u}$ is the displacement vector, and $\mathbf{K}$ is the global stiffness matrix (Bendsøe; Sigmund, 2004; Beisheim; Sinclair; Roache, 2019).

In the present study, the optimization process was subjected to constraints on the maximum allowable displacement, the prescribed volume fraction, and the geometric limitations imposed by the component design:

$$u_e \leq u_e^* \quad (6)$$

$$f_v \geq \frac{V_f}{V_0} \quad (7)$$

$$V_f = \sum_{e=1}^{n_e} x_e v_e \quad (8)$$

Where:

u_e is the displacement of element e ,

u_e^* is the allowable displacement,

V_0 is the initial volume,

f_v is the optimized volume,

v_e is the volume of element e ,

and x_e is its design variable (Bendsøe; Sigmund, 2004; Unterberger Filho, 2007; Xu et al., 2012).

2.3.2 SIMP Method

The Solid Isotropic Material with Penalization (SIMP) method is one of the most widely adopted approaches for topology optimization. In this formulation, each finite element is assigned a pseudo-density variable ranging from 0, representing the absence of material, to 1, corresponding to solid material (Bendsøe; Sigmund, 2004). The elastic modulus of each element is interpolated according to:

$$E_e = x_e^p E_0 \quad (9)$$

Where:

E_e is the elastic modulus of the element,

x_e is the element density, p is the penalization factor,

and E_0 is the elastic modulus of the base material.

Intermediate density values are physically undesirable because they represent porous regions that cannot be manufactured using conventional fabrication processes. To discourage these intermediate solutions, the SIMP formulation introduces a penalization exponent. Bendsøe and Sigmund (2004) and Gunwant and Misra (2012) recommend values of $p \geq 3$, as they promote solutions approaching a discrete distribution of solid and void regions while preserving numerical stability under appropriate volume constraints.

2.4 Design for Manufacturing (DfM) and Laser Cutting Manufacturing Constraints

Design for Manufacturing (DfM) is an engineering approach that incorporates manufacturing requirements into the product development process to simplify production, reduce manufacturing costs, and improve product quality. According to Swift and Booker (2003), DfM aims to adapt component geometry to the capabilities and limitations of the selected manufacturing process. In the present study, DfM serves as the link between the geometry generated by topology optimization and a manufacturable component, enabling the optimized design to be reconstructed for fabrication by laser cutting of carbon steel plates while preserving its structural performance (Groover, 2020).

2.4.1 Geometric Constraints for Laser-Cut Components

Laser cutting imposes several geometric constraints that must be considered during the redesign of topology-optimized components.

Constant thickness. Since the component is manufactured from sheet metal, the optimized geometry must be converted into a constant-thickness profile corresponding to the selected plate thickness.

Minimum cutting radius. The minimum achievable internal radius depends on several process parameters, including sheet thickness, laser source (e.g., CO₂ or fiber laser), cutting speed, laser power, and focal position. These parameters directly influence the kerf width, dimensional accuracy, and surface quality of the cut (Wandera, 2010; Orishich; Shulyatyev; Golyshev, 2016).

As a general design guideline, the minimum diameter of internal holes should be at least equal to the sheet thickness to ensure dimensional accuracy and reliable manufacturability (Swift; Booker, 2003; Groover, 2020).

3 METHODS

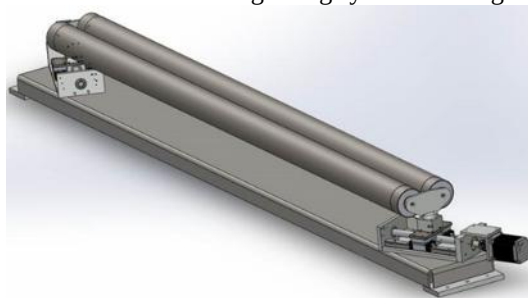
The methodology adopted in this study is based on a numerical-experimental approach, employing ANSYS Mechanical 2024 R2 for structural simulation and topology optimization. The proposed workflow was organized into six sequential stages, beginning with the global structural analysis of the web guiding system and concluding with the validation of the optimized guide roller support redesigned for laser-cut manufacturing.

3.1 Characteristics of the Web Guiding System

The web guiding system investigated in this study is an intermediate guide designed for continuous web processing applications. As illustrated in Figure 3, the system incorporates two guide rollers with dimensions of $\text{Ø}139 \text{ mm} \times 2500 \text{ mm}$, enabling the alignment of web materials up to 2400 mm in width. The guiding mechanism is actuated electromechanically through linear guideways, a ballscrew, and an electric motor. The equipment is intended for medium-tension applications involving paper and paperboard materials with basis weights of up to 105 g/m^2 .

According to the manufacturer's specifications, a web tension of 0.54 kgf/cm , corresponding to the processing of 105 g/m^2 paperboard, was adopted as the design loading condition for the structural simulations.

Figure 3. Illustrative view of the web guiding system investigated in this study.

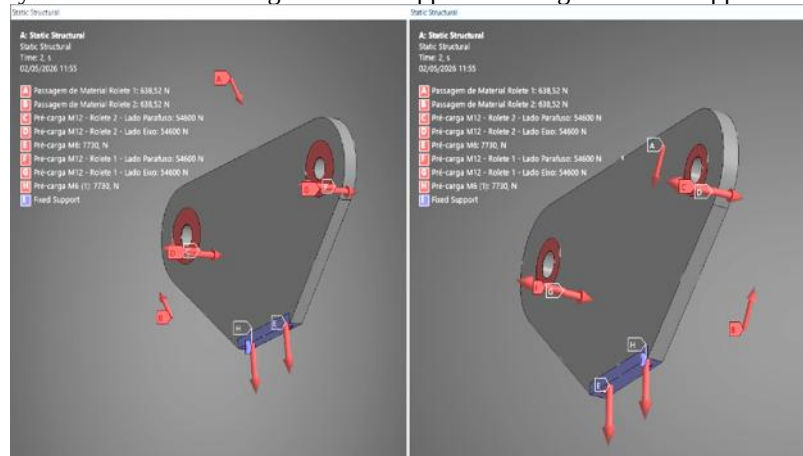


Source: Prepared by the authors.

The guide roller support analyzed in this work is shown in Figure 4, together with its principal dimensions. The mounting interfaces indicated in the figure were used to define the boundary conditions and load application regions adopted in the finite element simulations.

The web path over the guide rollers, illustrated in Figure 5, generates the loading condition applied to the roller support. Considering the maximum web width of 2400 mm, the resultant load acting on the guiding system was calculated as 129.6 kgf, which was adopted as the reference loading condition for all structural analyses.

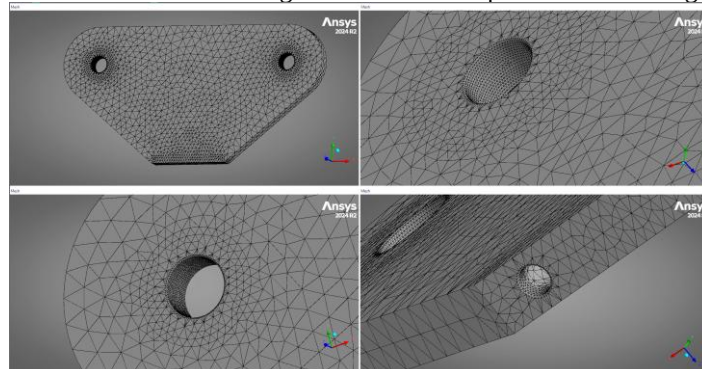
Figure 6. Boundary conditions and loading conditions applied to the guide roller support finite element model.



Source: Prepared by the authors.

The initial finite element mesh was generated using an element size of 4 mm with a Slow transition rate. Local Sizing controls were applied to the same surfaces where loads and boundary conditions were defined in order to improve the numerical accuracy in regions of high stress concentration. The resulting mesh is presented in Figure 7.

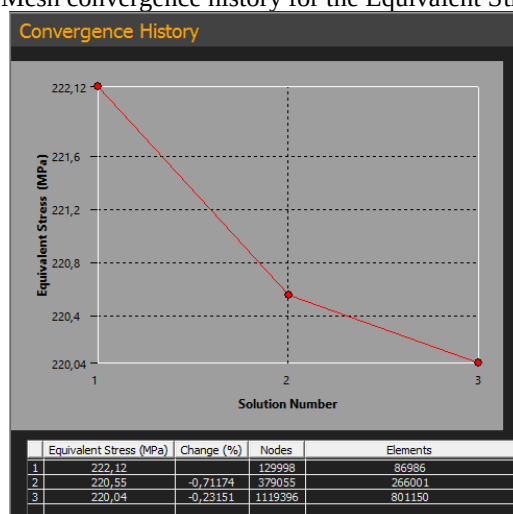
Figure 7. Initial finite element mesh generated from the predefined meshing parameters.



Source: Prepared by the authors.

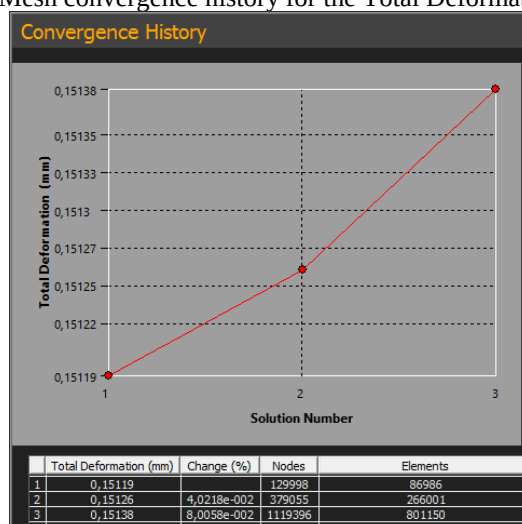
To ensure mesh-independent results, a mesh convergence study was conducted using the Convergence tool available in ANSYS Mechanical 2024 R2. The convergence criteria were defined as a maximum variation of 0.2% for Equivalent Stress and 2.0% for Total Deformation, allowing a maximum of three successive mesh refinements. As shown in Figures 8 and 9, the final refined mesh produced maximum variations of -0.71% for Equivalent Stress and 0.08% for Total Deformation, indicating that the numerical solution had reached satisfactory convergence. The final mesh adopted in the structural analyses is presented in Figure 10. The guide roller support was modeled using the material Carbon Steel 1020, As Rolled, available in the material library of ANSYS Mechanical 2024 R2.

Figure 8. Mesh convergence history for the Equivalent Stress results.



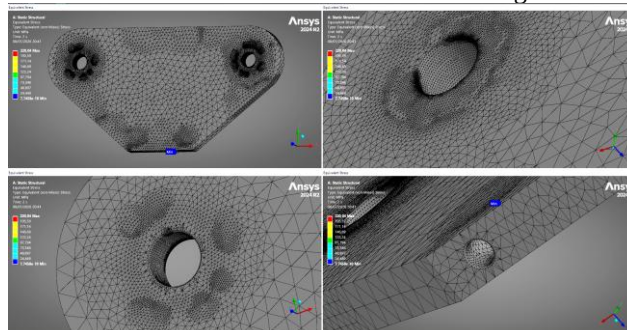
Source: Prepared by the authors.

Figure 9. Mesh convergence history for the Total Deformation results.



Source: Prepared by the authors.

Figure 10. Final finite element mesh obtained after the convergence refinement process.



Source: Prepared by the authors.

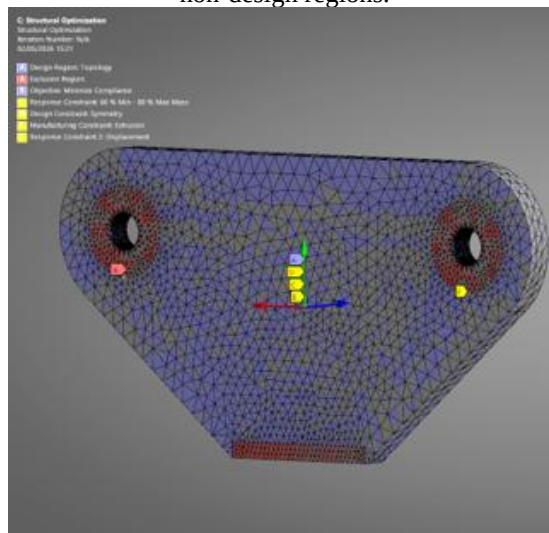
3.3 Topology Optimization

After validating the baseline finite element model, the topology optimization procedure was performed to determine the optimal material distribution within the guide roller support. The optimization setup, including the applied loads, boundary conditions, and design constraints, is illustrated in Figure 11.

The optimization objective was defined as compliance minimization (equivalent to maximizing structural stiffness), while imposing a mass constraint corresponding to 60–80% of the original component mass. Non-design regions were specified to preserve the functional integrity of the mounting holes and contact interfaces, preventing material removal from these critical areas. A symmetry constraint was applied about the YZ plane to ensure assembly flexibility, while an extrusion manufacturing constraint was imposed to produce a constant-thickness geometry compatible with laser-cut sheet metal fabrication.

Finally, displacement constraints were assigned to two nodes located at the guide roller shaft supports. The maximum displacement in the X, Y, and Z directions was limited to 0.1 mm, ensuring that the optimized design satisfied the stiffness requirements established for the application.

Figure 11. Topology optimization setup showing the applied loads, boundary conditions, design constraints, and non-design regions.



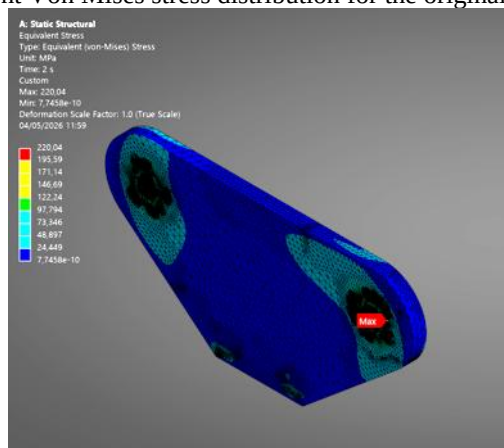
Source: Prepared by the authors.

4 DISCUSSION AND RESULTS

The static structural analysis of the original guide roller support produced the Equivalent Stress distribution shown in Figure 12. The corresponding structural performance metrics, including mass, maximum Von Mises stress, safety factor, and directional displacements, are summarized in Table 1.

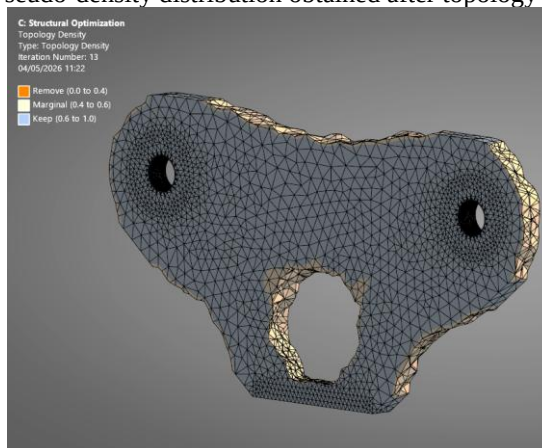
Topology optimization converged after 13 iterations, producing the pseudo-density distribution presented in Figure 13. The optimized topology indicates that most of the removable material is concentrated in the central region of the component, whereas the areas surrounding the mounting interfaces and load transfer paths remain substantially preserved. This behavior demonstrates that the original design contained regions contributing minimally to the structural stiffness.

Figure 12. Equivalent Von Mises stress distribution for the original guide roller support.



Source: Prepared by the authors.

Figure 13. Pseudo-density distribution obtained after topology optimization.



Source: Prepared by the authors.

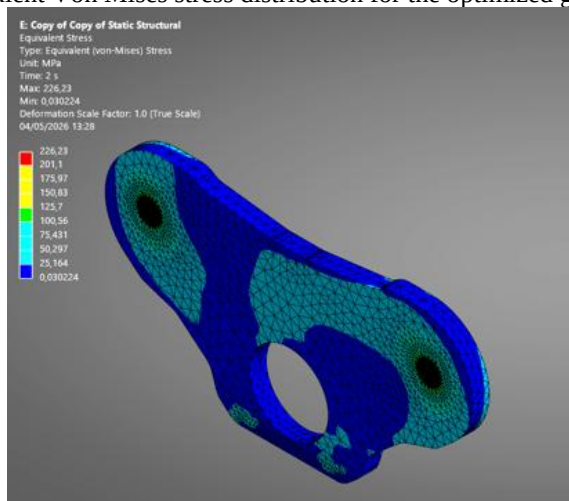
Based on the optimized topology, the component was reconstructed according to the Design for Manufacturing (DfM) methodology described previously. The resulting geometry, shown in Figure 14, preserves the principal load paths identified by the optimization algorithm while satisfying the geometric constraints required for laser-cut sheet metal fabrication.

Figure 14. Reconstructed guide roller support following Design for Manufacturing principles.



Source: Prepared by the authors.

Figure 15. Equivalent Von Mises stress distribution for the optimized guide roller support.



Source: Prepared by the authors.

The redesigned component was subsequently evaluated under the same loading conditions and boundary conditions adopted for the baseline model. The resulting Equivalent Stress distribution is presented in Figure 15, while the quantitative comparison between both designs is summarized in Table 1.

Table 1. Comparison of the structural performance metrics obtained for the original and optimized guide roller supports.

Performance Metric			Original Geometry	Optimized Geometry	Variation (%)
Mass (kg)			1.36	1.05	-22.79
Maximum Von Mises Stress (MPa)			220.04	226.23	+2.81
Minimum Safety Factor			1.49	1.45	-2.68
Maximum	X-Directional	Displacement (mm)	-0.015	-0.021	+40.00
Maximum	Y-Directional	Displacement (mm)	0.015	0.019	+26.67
Maximum Z-Directional Displacement (mm)			0.179	0.179	0.00

Source: Prepared by the authors.

4.1 Structural Performance Evaluation

The proposed redesign achieved a 22.79% reduction in structural mass while preserving the mechanical performance of the component. Although the maximum Von Mises stress increased by 2.81%, the optimized design maintained a minimum safety factor of 1.45, representing only a 2.68% reduction compared with the original configuration. These results indicate that the removed material had a limited contribution to the global stiffness of the structure.

The largest relative increases in displacement occurred along the X and Y directions, reaching 40.0% and 26.67%, respectively. However, these variations correspond to absolute displacement differences of only a few hundredths of a millimeter, remaining well below the displacement limits established during the optimization process. Furthermore, the maximum displacement along the Z direction, which is the primary loading direction, remained unchanged at 0.179 mm, demonstrating that the stiffness required for the web guiding application was successfully preserved despite the significant reduction in structural mass.

Overall, the results demonstrate that the proposed optimization strategy effectively reduced component weight without compromising structural integrity or operational performance.

4.2 Manufacturing Feasibility

Although topology optimization naturally produces organic geometries that are generally incompatible with conventional manufacturing processes, the proposed DfM methodology successfully translated the optimized topology into a manufacturable design. As illustrated in Figure 14, the reconstructed component preserves the principal load paths

identified during optimization while satisfying the geometric constraints imposed by laser-cut sheet metal fabrication, including constant plate thickness, manufacturable internal radii, and minimum hole dimensions. These results demonstrate the feasibility of integrating topology optimization with conventional manufacturing processes without compromising structural performance.

5 FINAL CONSIDERATIONS

This study developed and validated a methodology for redesigning a web guiding system component by integrating topology optimization with Design for Manufacturing (DfM) principles for conventional laser-cut sheet metal fabrication. The proposed approach successfully combined the structural benefits of topology optimization with the manufacturing constraints imposed by subtractive production processes.

The optimized guide roller support achieved a 22.79% reduction in mass while maintaining structural performance comparable to that of the original design. The maximum Von Mises stress increased by only 2.81%, whereas the minimum safety factor decreased by 2.68%. Although the relative increases in displacement along the X and Y directions were higher, their absolute values remained within a few hundredths of a millimeter and therefore below the operational tolerances required for intermediate web guiding systems.

The manufacturing constraints incorporated into the optimization process, together with the subsequent geometric reconstruction based on DfM principles, enabled the optimized topology to be converted into a fully manufacturable component without modifying the existing laser-cut production process. This demonstrates that substantial weight reduction can be achieved while preserving manufacturing feasibility and production costs.

Although the mass reduction obtained for the individual component is moderate, the proposed methodology provides a systematic framework that can be extended to other structural components of industrial web guiding systems and similar automation equipment. Future work should investigate the application of this approach to complete assemblies, incorporating dynamic loading conditions, fatigue analysis, and experimental validation of the optimized components.

Overall, the results demonstrate that simulation-driven structural optimization, combined with manufacturing-oriented redesign, represents an effective strategy for replacing traditional conservative design practices, contributing to the development of lighter, more

efficient, and more competitive industrial automation equipment aligned with the principles of Industry 4.0.

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