Diyala Journal of Engineering Sciences

Journal homepage: https://djes.info/index.php/djes

ISSN: 1999-8716 (Print); 2616-6909 (Online)

Influence of Manufacturing Constraints on Generative Design Outcomes: A Lightweight Automotive Brake Pedal Case Study

Mohd Nizam Sudin[1,2*], Mohd Asri Yusuff[1,2], Faiz Redza Ramli[1,2], Abd Rafeq Saleman[1,2], Arzul Arifin[3]

[1] Faculty of Mechanical Technology and Engineering, Universiti Teknikal Malaysia Melaka (UTeM), 76100 Durian Tunggal, Melaka, Malaysia
[2] Centre for Advanced Research on Energy (CARe), Universiti Teknikal Malaysia Melaka (UTeM), 76100 Durian Tunggal, Melaka, Malaysia
[3] Seafarm Innovation Sdn Bhd, 33, Jalan Kristal 7/73, Seksyen 7, 40000 Shah Alam, Selangor

ARTICLE INFO

Article history:
Received: 07/09/2025.
Revised: 19/11/2025.
Accepted: 29/11/2025.
Available online: 10/12/2025.

Keywords:
Generative Design
Design for Manufacturability (DfM)
Topology Optimization
Additive Manufacturing
Automotive Brake Pedal

ABSTRACT

Generative design is a technique that effectively produces lightweight yet structurally robust components. However, the final result is highly dependent upon manufacturing constraints during the design phase. This work investigates how machining, 3D printing, and die casting constraints shape a reengineered car brake pedal. Each option was constructed within Autodesk Fusion 360 using identical loads and fixations and material characteristics. Variations in performance were evaluated by FEA with respect to weight, stress pattern, stiffness, movement under load, and safety margin. In contrast, the greatest mass reduction was attained by the AM-based design; the mass dropped from 1.36 kg to 0.58 kg, a 41.3% drop, while still meeting the minimum required safety margin of at least 2.0. Meanwhile, the average mass for the die-cast design reached 0.70 kg, based on proper taper and thickness rules of the part while maintaining strength. On the contrary, the machined-limited part had the heaviest mass value of 2.77 kg. Nevertheless, it portrayed the highest stiffness; besides that, it attained the highest safety value, FoS = 5.84, highlighting how subtractive manufacturing methods sacrifice mass for durability. Manufacturing limits impact geometric design results by limiting feasible forms while varying mechanical component functionalities. Accordingly, this paper presents an investigation into different manufacturing techniques and their impacts on design solutions, using examples of different techniques to highlight efficiency. Ways of proposing lighter brake pedal designs that are easier to produce involve adjusting material usage while easing assembly steps to enhance feasibility without compromising performance.

1. INTRODUCTION

The main issue and a priority in the design of car parts, such as brake pedals, is weight reduction, since lighter constructions allow improving vehicle performance and increasing safety margins due to a reduced environmental impact. Approaches like lattice structures and topology optimization have demonstrated mass savings of up to about 46.4% without affecting mechanical integrity [1]. For the replacement of conventional steels by aluminum alloys, it can be further expected that vehicle mass decreases, enhancing fuel economy and lowering emissions [2,3], while recent developments of hybrid materials and advanced forming techniques have extended the range of feasible solutions for lightweight construction [4]. Unfortunately, transferring lightweight solutions from concept into production usually reveals various manufacturing limitations, including material and tooling constraints, requirements on draft angles, and constraints related to part orientation. All these issues accentuate the benefit of generative design, which considers manufacturing rules at an early design

*Corresponding author's Email: nizamsudin@utem.edu.my
DOI: 10.24237/djes.2025.18413

stage, and the geometries emerging thereof are not only light but also manufacturable.

Topology optimization is still widely used for mass reduction of structural parts, such as brake pedals, while keeping the design within specifications [5–6]. However, due to its reliance on fixed design envelopes and the tendency to yield complex shapes, substantial rework is often needed before the part can be manufactured [7–8]. Generative design overcomes these limitations by generating multiple design variants directly from the prescribed performance objectives while embedding manufacturability constraints, such as machining tool path accessibility, draft angles for die cast components, and overhang limits for additive manufacturing [9–11]. Such approaches provide design candidates with much fewer modifications to progress the designs towards production [12–13].

Material selection has remained an important factor in GD outcomes since stiffness, weight, durability, and safety performance are controlled by the properties of the selected material and by the fabrication method through which it is processed [10]. For brake pedals, aluminum and titanium alloys and also some high performance polymers present very attractive strength to weight ratios [13, 14]. Regardless of the selected material, designs must fulfill accepted safety standards which conventionally demand a factor of safety above 1.5 for static loading conditions [8, 11]. Each manufacturing process introduces distinct constraints that shape the feasible design space. Additive manufacturing imposes limits related to overhangs, support structures, and build orientation [8, 13]. Die casting requires attention to draft angles, parting line configuration, and minimum wall thickness. Machining places demands related to adequate tool access, minimum radii, and reliable fixturing strategies. Although these constraints reduce the range of possible geometries, they increase the likelihood that the first iteration of the design will be manufacturable [9, 12]. The challenge is to balance design freedom with manufacturing practicality so improvements in performance can be realized in production [14].

The growing use of GD within the automotive industry is indicative of its potential to reduce development cycles and create biomimetic forms that are structurally efficient [15]. However, there are still a few problems to be resolved, including the effective integration of GD with topology and shape optimization, handling multiconstraint conditions, and the need for an early verification of manufacturability during the design workflow rather than post-performance optimization [16]. Many of the current published studies focus on performance metrics in idealized conditions; real-world manufacturing introduces practical considerations such as mold release, tooling access, support minimization, and quality control requirements [17]. This represents a gap in knowledge regarding how manufacturing constraints affect both the geometry generated through GD and the structural response of the resulting designs.

Few comparative analyses consider the machining, AM, and die casting constraints for the same component under the same loads and objectives in the literature [9,11]. Most of the previous work in this area either ignores manufacturing constraints or considers them individually, and therefore it is challenging to comprehend the trade-offs that occur between structural efficiency and manufacturability [12,18]. This work targets this shortcoming using a brake pedal as a case example. For consistent boundary conditions and performance demands, unique GD solutions are derived for each manufacturing route and compared in terms of mass, factor of safety, stress distribution, displacement characteristics, and overall producibility. The objectives are to elucidate the intrinsic trade-off between structural performance and manufacturability and to provide evidence which can help to embrace constraint-driven GD within automotive design processes. The result helps to promote lightweighting activities for modern vehicles, especially regarding sustainable and electric mobility.

2. METHODOLOGY

This research applies a structured generative approach to explore how different fabrication limits affect the shape, strength, or manufacturability of a car brake pedal. The process ran in Autodesk Fusion 360, combining digital modeling, separation of modifiable and fixed zones, assignment of forces and restraints, rule-based design generation, along with stress simulation via FEA. As shown in Figure 1, this outlines the general method used throughout the project.

2,1 CAD model preparation

A basic brake pedal shape was made in Fusion 360, capturing key traits of standard car pedals but cutting extra details. Instead of full realism, just critical parts like the pivot point, foot surface, and force zone were kept. Unneeded elements got eliminated so mesh creation would run smoother while preserving how loads move through the part.

2.2 Design space, preservation regions and obstacle geometries

The design area was set up to explore shapes fully, yet still link to key support and attachment spots. In critical mechanical areas, special zones (see Figure 3(a)) blocked new geometry from forming. Obstacle models (shown in Figure 3(b)), however, kept necessary gaps like room for fitting parts together or moving components remained clear of any structure in the end result.

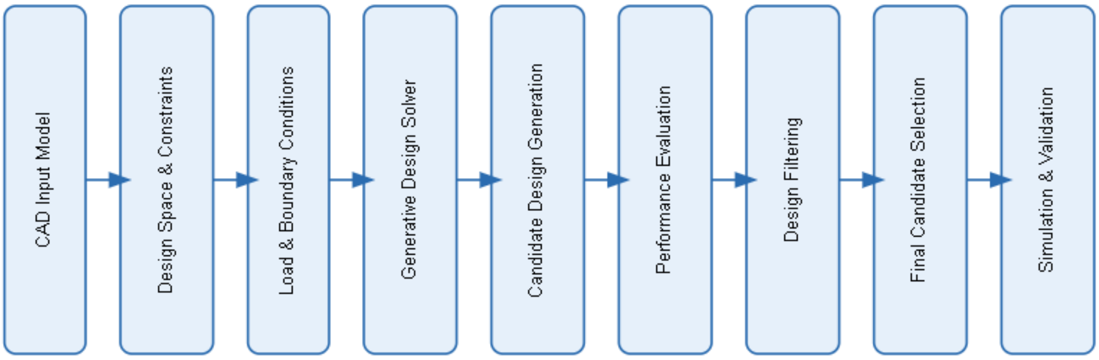


Figure 1. Generative design workflow in Fusion 360 showing setup inputs and evaluation of candidate geometries.

2.3 Loading and boundary Conditions

From prior research [19], braking force needs helped define how the pedal was loaded when checking its design limits. To reflect real-world extremes, data show women typically exert up to 445 N with their right foot while men about 823 N; because of this, the analysis uses 823 N as a cautious estimate for peak demand. The load acted on the pedal's rounded surface, angled at 15° from the main y-axis (set via delta input). This setup matches standard methods used to test critical vehicle parts under high-stress static cases. Guidelines like SAE J1119 outline procedures for brake systems, advising higher-than-normal forces during tests so designs meet required safety levels. This configuration mimics real-world braking performance while meeting standard durability criteria for vehicle brake setups. As shown in Figure 4, the loading pattern and constraints are displayed within the defined design area.

Figure 2. Baseline simplified CAD model of the brake pedal showing key functional features.

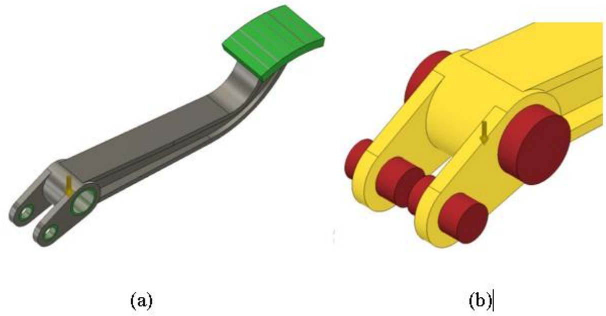


Figure 3. Preserved (green) and obstacle (red) regions used to control geometry growth during generative design.

2.4 Material properties

To check how production limits, affect results, the same metal was used for every design case. The chosen metal was common low-carbon steel from the Autodesk Fusion 360 database. Its Young's modulus was 210 GPa, Poisson's ratio at 0.30, and yield strength at 207 MPa. These are matched against known values for typical car-grade steels. Using only one type of material limits variation due to different choices, thus allowing more clear evaluation of the limits of production.

2.5 Generative design setup

The generative design tool of Autodesk Fusion 360 had the same settings throughout. Set up as in the description of the optimization process to reduce weight but retain at least a safety margin of two, each run used a steady force of 823 N, rather than the dynamic forces described earlier in Section 2.3. Included to make computation easier, this provided an even distribution of shape. A vertical mirror plane was included.

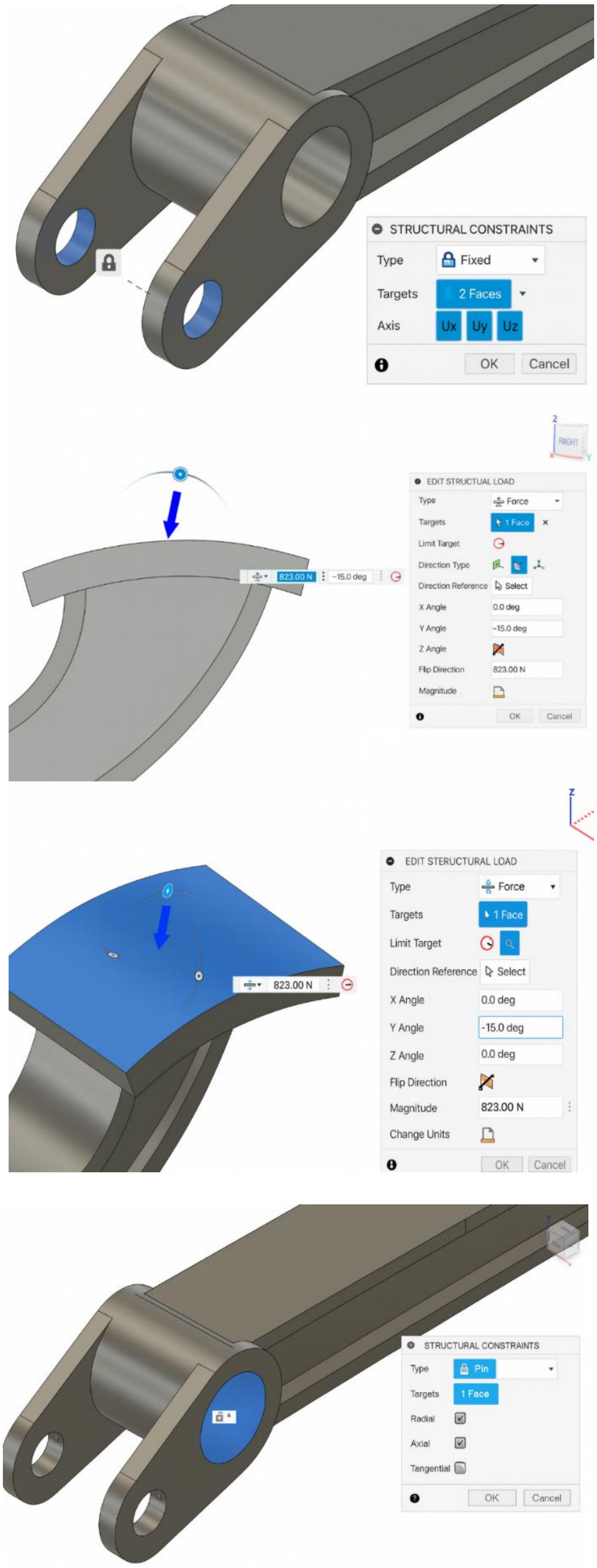


Figure 4. Boundary condition and loading setup for generative design analysis. A static load of 823 N is applied at 15° to the pedal face, while the hinge region is fixed to simulate realistic braking action.

This analysis used the adaptive meshing technique in Fusion 360, with second-order tetrahedral solids for numerical stability. Given the complicated shapes created with generative design, these elements handled the geometry quite well. The produced mesh had approximately 185,000 elements with almost 290,000 nodes. Element size was refined down to around 2 mm near any stress concentration. Convergence was checked through successive refinement of the mesh until less than a 5% change in peak von Mises stress or safety factor was realized between steps. It was at this level that it became a usable stopping point. Solver accuracy was set through default settings from Fusion 360's computation system online. In lieu of fixed error limits as specified by the user, this automatically adjusts refinement.

Only one parameter was varied between the generative design runs, in the form of a predefined production limit, as specified in Table 1. While this rule set defined the minimum draft slopes for die casting, it also provided the other additive fabrication overhang limits and/or the needs for tool access in cutting. The analysis utilized a finely meshed model, as specified in Figure 6.

2.6 Generative run

Every generative setup gave several possible results. Among them, the top choice was the lightest option meeting all required conditions. For every production technique, just those marked "converged" at the end counted as acceptable and kept for review.

2.7 Limitations and assumptions

Static loading alone was used, so dynamic fatigue effects under actual use might be missed. Also, the model relies on simplified material assumptions, ignoring temperature-related and leftover stresses. Later studies could look into optimizing for several goals at once - like durability, sudden forces, and mixed materials.

Table 1: Summary of generative design constraint settings per manufacturing method

Constraint Type	Machining	Additive Manufacturing	Die Casting
Minimum Tool Diameter	10 mm	—	—
Maximum Overhang Angle	—	45°	30°
Draft Angle	—	—	3°
Minimum Wall Thickness	4 mm	2 mm	3 mm

3. RESULTS AND DISCUSSION

3.1 Comparative analysis of GD outcomes under different manufacturing constraints

The generative design study yielded distinctly different geometries for the automotive brake pedal under the three manufacturing constraints considered-additive manufacturing (AM), three-axis machining, and die casting (Figure 5). These differences depict quite clearly how each of the manufacturing routes determines the bounds of the design space and constrains the form that the solver is able to provide. In addition, among the three, AM realized the highest percentage weight reduction, where volumes go as low as 73,903 mm^3 and a final mass of 0.58 kg, which is equivalent to a 41.3% decrease compared with the baseline pedal. In this case, these results are appropriate for the versatility of AM in incorporating internal cavities, load-oriented unit cells, and features impossible with traditional approaches [8, 13]. In contrast, the machining-driven design resulted in the heaviest configuration at 2.77 kg, due to the limitations inherent in the subtractive process, which include the avoidance of undercuts and the need for tool access, both of which impel the solver to thicker, more conservative geometries. Die casting resulted in a midfield solution when it comes to mass at 0.70 kg, balancing mass reduction against drafting and minimum wall-thickness needs.

These design trade-offs were reflected in the mechanical performance results shown in Table 3. All configurations except the machined design resulted in a maximum value of von Mises stress of approximately 103.5 MPa. As a result of larger cross-sectional areas and higher stiffness, the machined version displayed a much lower value of 35.44 MPa. The stress and displacement fields for the AM design (Figure 6) verify that local stress concentrations did not exceed tolerable limits, while the maximum displacement of 1.07 mm is suitable for the given loading conditions. In general, the results confirm that manufacturing constraints affect generative outcomes at a fundamental level rather than being checks applied at the end of the design process, as similarly noted by [9] and [12].

Figure 5. Generative design outcomes for the brake pedal under additive, machining, and die-casting constraints.

Table 2: Comparison of design parameters between each design outcome

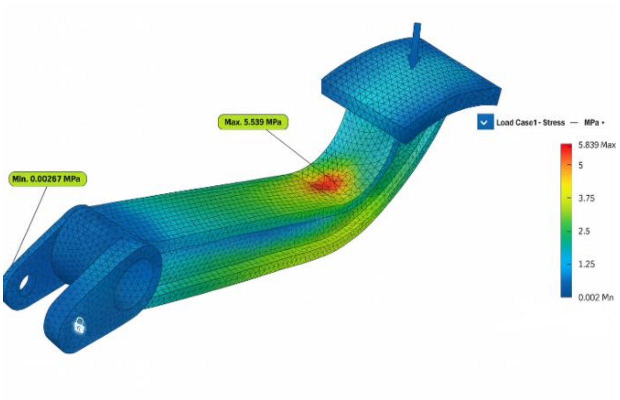
Name	Volume (mm³)	Mass (kg)	Max von Mises stress (MPa)	Min factor of safety	Max displacement global (mm)	Manufacturing method	Processing Status	Recommendation Percentage (%)
Structural Component - Outcome 1	93969.55	0.7376	103.5	2	1.901893922	Additive	Converged	45.73
Structural Component - Outcome 2	73308.68	0.5754	103.5	2	1.108649697	Additive	Converged	76.82

Structural Component - Outcome 3	100050.20	0.7853	103.5	2	1.101113238	Additive	Converged	71.20
Structural Component - Outcome 4	103349.80	0.8112	93.8998072	2.204477	1.722495943	Additive	Completed	41.55
Structural Component - Outcome 5	73902.57	0.5801	103.5	2	1.070173289	Additive	Converged	78.02
Structural Component - Outcome 6	93800.73	0.7363	103.5	2	0.921008967	Additive	Converged	76.20
Structural Component - Outcome 7	352165.60	2.7645	35.4441591	5.840172	0.356996993	3-axis milling	Converged	0
Structural Component - Outcome 8	89190.25	0.7001	103.4999797	2.000003	1.245027455	Die casting	Converged	84.03

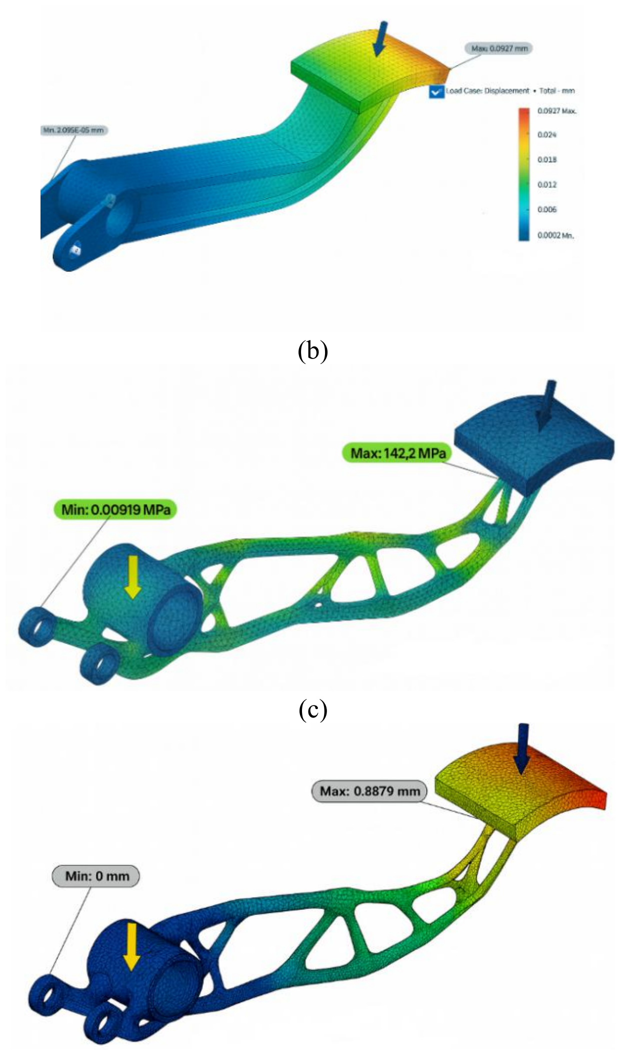
Note: The "Recommendation Percentage" shows the ranking of each outcome by the generative design solver with respect to how well the solution meets the set objectives and constraints-mass, stress, displacement, and manufacturability. Higher values are indicative of more favorable overall performance than other outcomes

Table 3: Comparison of manufacturing methods

Parameters	Additive (Outcome 5)	3-axis milling (Outcome 7)	Die casting (Outcome 8)
Volume (mm³)	73,902.57	352,165.69	89,190.26
Mass (kg)	0.58	2.77	0.70
Max von-misses stress (MPa)	103.5	35.44	103.5
Factor of safety	2	5.84	2
Max displacement (mm)	1.07	0.36	1.25



(a)



(b)

(c)

(d)

Figure 6. FEA results for the baseline and AM-optimized designs: (a) baseline von Mises stress, (b) baseline displacement, (c) AM design peak stress (~142.2 MPa), and (d) AM design displacement (~0.8879 mm) under an 823 N load.

3.2 Selection of the optimal design using weighted objective method

A weighted objective assessment was used, as shown in Table 4, to determine the optimal design for automobiles. Since electric and green vehicle platforms emphasized lightweight construction [2–4], the mass was weighted highest at 50 percent. Stress (20%), factor of safety (15%), and displacement (15%) were thus utilized to weight the structural behavior. Weighted scores shown in Table 5 reveal that the AM design achieved the highest total score (0.670), followed by the machining configuration at 0.610 and die-cast version at 0.577. The AM design had more deflection and a lower safety factor than the machined one but still met the ISO 12143-2:2020 requirements, which require brake components to have a safety factor of at least two. Another AM variant had a weight of 0.585 kg, which was slightly lower, but its safety factor was 1.456, which did not meet the minimum safety requirements for critical structural components in automobile systems. This result highlights the importance of optimization between weight reduction and structural integrity. It agrees with a statement by Sun et al. [11] that weight reduction may lead to a sacrifice in mechanical strength.

Table 4: Evaluation criteria and assigned weights

Evaluation Criteria	Description	Weight (%)
Mass (kg)	Lower mass is preferred for lightweight design	50
Maximum von Mises Stress (MPa)	Lower stress indicates better material utilization	20
Factor of Safety	Higher values indicate greater reliability	15
Maximum Displacement (mm)	Lower displacement reflects better stiffness	15

Table 5: Normalized scores and final weighted score for each design outcome

Criteria	Weight	Min/Max Value	Outcome 05 (Additive)	Outcome 07 (Milling)	Outcome 08 (Die Casting)
Mass (kg)	0.50	Min = 0.58	1.00 × 0.50 = 0.500	0.58/2.77 = 0.209 × 0.50 = 0.105	0.58/0.70 = 0.829 × 0.50 = 0.415
von Mises Stress (MPa)	0.20	Min = 35.44	35.44/103.5 = 0.342 × 0.20 = 0.068	1.00 × 0.20 = 0.200	0.342 × 0.20 = 0.068
Factor of Safety	0.15	Max = 5.84	2.00/5.84 = 0.342 × 0.15 = 0.051	1.00 × 0.15 = 0.150	0.342 × 0.15 = 0.051
Max Displacement (mm)	0.15	Min = 0.36	0.36/1.07 = 0.336 × 0.15 = 0.051	1.00 × 0.15 = 0.150	0.36/1.25 = 0.288 × 0.15 = 0.043
Total Score	1.00		**0.670**	0.610	0.577

Table 6: Comparison of design parameters between initial, optimized and final design

Parameters	Initial design	Optimized design (GD output)	Final design (After refinement)
Design			
Mass (kg)	1.358	0.585	0.583
Volume (mm^3)	1.730E+05	73902.571	74261.175
Factor of safety	35.45	2	1.456
Maximum von-Mises stress (MPa)	5.839	103.5	142.2
Displacement (mm)	0.02971	1.0702	0.8879

3.3 Manufacturing readiness comparison

Cost and manufacturability also play an important role in choosing the best design path. The configuration from AM does reduce the mass the most, but it requires a great amount of post-processing and is a lot more expensive per unit. Similar trends have been observed by Cheng et al. [10] and Kranz et al. [14]. Machining is really accurate when it comes to dimensions; however, it does not use the material very effectively, which increases the cost of parts because a great amount of material needs to be removed. Die casting requires a lot of upfront cash for tooling; however, it has the lowest cost per part for large, high-volume production, so it is a good manufacturing choice for producing cars in large volumes.

These results validate the earlier suggestions by Jaiswal and Gupta [13] that highlighted the need for integrating design-for-manufacturing principles right from the beginning to avoid costly redesigns at a later stage in the cycle. The results of this study show that directly incorporating process constraints into the generative design methodology enables the derivation of geometries which are structurally sound and easily manufacturable, thereby bridging the gap between computational optimization and industrial implementation in practice.

Table 7. Manufacturing feasibility assessment by constraint

Attribute	Machining	Additive Manufacturing	Die Casting
Tool Accessibility	High	Irrelevant	Medium
Support Structures	Not needed	Required	Not needed
Undercuts	Avoided	Allowed	Limited
Draft Angles	Not required	Irrelevant	Mandatory (2°–5°)
Post-Processing Effort	Moderate	High (Support removal)	Low–Moderate
Material Compatibility	High	Depends on printer	Depends on alloy

3.4 Limitations and future work

This work is restricted in scope by the consideration of static loading alone and the assumption of linear elastic material behavior. Real-world brake pedals are subjected to repeated cycles of stress, fatigue, thermal variations, and sometimes even impact. Previous research [8, 17] has established that such factors as thermal stress, fatigue performance, and impact resistance may significantly shift the outcome of the generative design process. In the near future, researchers should expand the comparison scheme to consider dynamic and fatigue analyses, apply a hybrid or multi-material approach where feasible, and validate numerical estimations by physical prototyping. This paper will further develop connections between generative design and sustainable mobility objectives, which will go hand-in-hand with broader industrial application.

4. CONCLUSION

This work systematically investigates the influence of constraints associated with machining, additive manufacture, and die-casting on the topology, structural response, and manufacturability of a generatively designed automotive brake pedal. It is shown that fabrication constraints strongly affect the form and performance of generative design results through keeping material properties, loading conditions, and optimization objectives constant while only altering manufacturing rules related to each respective process.

The additive manufacturing design realized the largest amount of mass reduction amongst the tested configurations, reducing the weight by 41.3% from the baseline pedal. This result illustrates that AM can support complex, material-efficient shapes. However, the rise in displacement and drop in safety factor prove that aggressive lightweighting must be balanced against reliability concerns. The die-cast design compromised by incorporating the appropriate draft angles for mold release, while still managing to save a substantial amount of weight. The machining-based configuration, however, possessed the most mass, yet had the most stiffness, with the largest safety margin. This indicates that the constraints of subtractive manufacturing are naturally conservative. A more detailed analysis of manufacturability and cost shows that the optimum design trajectory is greatly dependent on production volume and performance requirements. Additive manufacturing is particularly well-suited for creating prototypes and low-volume, high-performance components that benefit from a high degree of shape freedom. Machining remains a suitable option for smaller and mid-level production quantities that require tight tolerances and robust structures. Die casting remains the most economical method of producing large quantities. These findings are in line with design for manufacturability concepts, and this work extends previous efforts by providing a side-by-side comparison of three key manufacturing approaches within a common analytic framework. The main contribution this study provides is the clarification that generative design realizes optimal value when framed as a process that should be driven from inception by manufacturability considerations. Indeed, embedding process rules at the conceptual phase increases the synergy between algorithmic optimization and operational readiness-a critical necessity for electric vehicle and sustainable mobility technologies. Future work should expand this approach to include fatigue and dynamic loading responses, hybrid material systems, and full lifecycle assessments including both cost and environmental implications. Experimental testing of the additively and die-cast designed components will also be required to validate the manufacturability of these components and to verify numerical predictions. These will aid in advancing the use of constraint-aware generative design for next-generation lightweight structural components.

ACKNOWLEDGMENT

The authors gratefully acknowledge Universiti Teknikal Malaysia Melaka (UTeM) for the financial support and technical assistance that made this work possible.

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