

Advanced Multi-Objective Topology Optimization for Lightweight Automotive Chassis: A Review of Algorithmic Integration with Additive Manufacturing**Chirag Patel¹**

PhD. Research Scholar,

Department of Mechanical Engineering, Monark University, Ahmedabad, Gujarat, India

Mohit Diwan²

Professor and HOD

Department of Mechanical Engineering, Ahmedabad Institute of Technology, Ahmedabad, Gujarat, India

Jatin Patel³

Associate Professor,

Department of Mechanical Engineering, Monark University, Ahmedabad, Gujarat, India

Sachin Manohar Shinde^{4*}

Department of Mechanical Engineering,

Datta Meghe College of Engineering, Airoli, Navi Mumbai – 400078, India

Orcid id: 0000-0002-8332-3547, Email: sachin.shinde@dmce.ac.in

Corresponding Author*Abstract:**

Composite automotive chassis manufacturers are aggregately pressured to deliver on weight reduction whilst not forfeiting Robustness manufacturability or safety. Vehicle light weighting is an established approach to improve energy efficiency studies demonstrate that a 10% mass reduction can deliver a fuel economy or EV driving range benefit of 6–8%. In this context, the past decade has seen top Indian OEMs face this challenge in automotive markets worldwide: Lowering weight of new models by 100kg vis-à-vis previous generations and across the board targeting four wheels; willing to forego exotic materials for innovative mountable design-process advances. To that end, topology optimization (TO) has emerged as a sophisticated Finite Element Analysis (FEA) computational presentation of objects to achieve material efficient structures through 3D modeling which when coupled with additive manufacturing AM it facilitates production since, geometrically complicated high performance chassis elements which was previously impractical to manufacture by conventional means! The review covers the existing literature related to TO processes targeting lightweight automotive chassis design highlighting integrations with metal AM technologies. The assessment of a variety of algorithmic strategies, covering density-based (SIMP), level-set, evolutionary and AI-based TO methods in relation to primary AM restrictions they should take into account such as geometrical parameters via overhang angles, minimal feature sizes, material anisotropy, also support reduction). This work was conducted by the Optical Metrology group at NPL using a wire arc additive manufacturing (WAAM) system automated TO to generate 44 chassis design variants which are demonstrated provides various accelerations in development. Mass savings of 40–60% and stiffness gains are reported from many studies highlighting the transformative potential of TO. This remains limited because of challenges, such as manufacturability validation, fatigue analysis and industrial scalability. This review highlights both identified open research gaps and potential future directions in this realm, including multi-objective TO under uncertainty, multi-material and multi-axis manufacturing computational acceleration strategies, and sustainability-aware optimization. The document provides curated literature matrix also comparative performance numbers to compare with Feb State of the Art and set direction clearly for work in context for India Automotive Industry This research survey work is intended to explore the current state of affairs enabled TO, integrated AM chassis design and road mapping towards effective scalable sustainable light weighting strategies in automotive engineering.

Keywords: Lightweight automotive chassis design, Topology optimization (TO), Additive manufacturing (AM), Wire Arc Additive Manufacturing (WAAM), Finite Element Analysis (FEA), Sustainability-aware design

1. INTRODUCTION

Reducing vehicle mass remains a fundamental lever for improving efficiency and sustainability. Lightweight chassis design can deliver substantial benefits: for instance, analysis by Yang et al. (2024) found that a 10% mass reduction typically yields a 6–8% improvement in fuel economy [1].

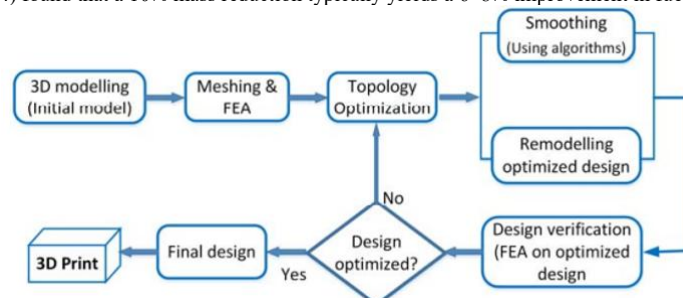


Figure 1. Topology optimization-based design process.[1]

Figure 1 illustrates Topology optimization-based engineering processes typically work through an iterative workflow in which following the creation of a 3D model, it is meshed, subjected to Finite Element Analysis (FEA), optimized, verified and then refined into a final design suitable for 3D printing [1]. In practical terms this translates to longer range EVs or reduced emissions from conventional vehicles. Understanding this, OEMs across the globe especially cost sensitive Indian market have targeted aggressive weight-reduction plans. The 2026 Alto is expected to be based on a 680–760kg platform, and reports are that Maruti Suzuki plans to use UHSS/AHSS steels within a highly optimized structural design in order to slash approximately 100 kg (~15% of curb weight).* With respect to light weighting, Tata Motors also repeats the refrain that attention has to move away from "what materials" and toward "how we implement them at scale," suggesting that design and manufacturing innovations should be integrated in a "scalable, smart fashion" instead of replacing what exists with exotic substitutes [3]. This is the right direction, since in reality what matters even more than theoretical performance improvements, is practical execution (DFAM integration and cost management), which represents a broader industry view. One of the main additions that has become a key enabler to making these light weighting targets happen is topological optimization. TO can create structures that are novel and organic in appearance, maximizing stiffness or strength for a target mass by optimally distributing material within a design space for given loads and boundary conditions. Nevertheless, in many applications these optimal shapes are sufficiently complex and non-intuitive that they cannot be constructed with standard materials. One solution lies in additive manufacturing, which is capable of layer-by-layer fabrication of complex, freeform geometries, thereby enabling the design true space unlocked by TO-derived designs [4]. As Zhu et al. Considerations of manufacturing constraints are also important, as TO-generated structures are "often complex and difficult to conventionally fabricate" [4], so "the integration of topology optimization and AM is crucial for structural design and production" [4].

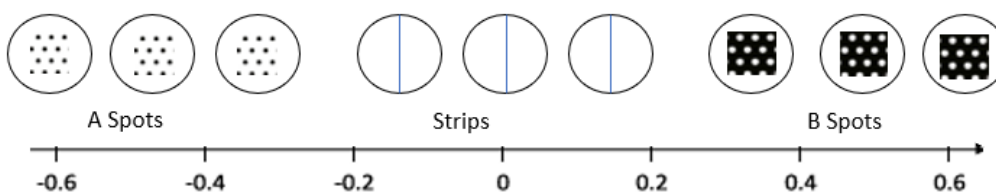


Figure: 1.1 Regular patterns in 2D format [21]

In the figure 1.1, The white background and black spots represent material A, while the white spots represent material B. The SFP is a shape function with penalization method. The reference quadrangular element is defined the shape functions. In bioengineering or automotive industry, skillful use of such different type of material would be very important. Color Level Set technique, allows the level set line to colors and various materials. In this feature n level-set goals were selected to represent the distribution of 2n unique materials, i.e., combination of n primary colors. At the time of this theory there are also technical limitations in obtaining these predicted microstructure and the conventional manufacturing process does not provide you with such patterns at a very cost-effective structure. [21] Topology-optimized EV chassis (7075-Al) produced by wire-arc AM [5]. The optimized design achieves significant weight reduction while maintaining structural stiffness [5].

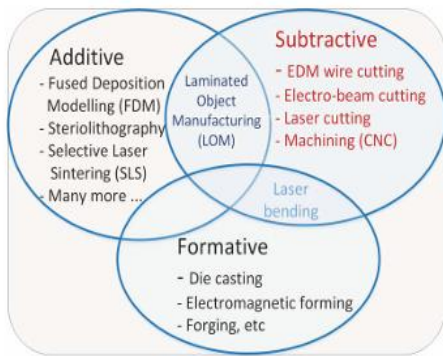


Figure:1.1.1: Major component manufacturing methods [23]

In the above figure 1.1.1, major components of manufacturing methods are classified. One of the expected benefits of AM technology is the realization of optimized design through topology optimization. It is important to determine goal functions and desired constraints. there exists no question about the feasibility of the design due to not taking into account the design for manufacturing requirements. [23]. This leads us to the section where Additive, Subtractive and Formative meet together: laminated object manufacturing. In the case of Subtractive and Formative, it has given sales by combining and provides Laser bending as products. This review captures the recent literature (2019–2025) on advanced TO techniques suitable for lightweight automotive chassis within an AM context. We start with a background on previous work, which includes systematic reviews and major developments resulting from this." We then discuss methodology: the primary classes of TO algorithms and how they have been adapted or combined to be used for the case study of an AM chassis. We specifically discuss the incorporation of AM constraints (overhangs, minimum feature size, anisotropy) in TO. We also present useful perspectives from the industry and case studies, including a TO framework that automated this process by generating hundreds of chassis candidates which were then evaluated and 3D-printed, resulting in development times reduced by >100× [5]. the range of the length scale is bounded by 1 and 50 nanometers in microstructural homogenization.

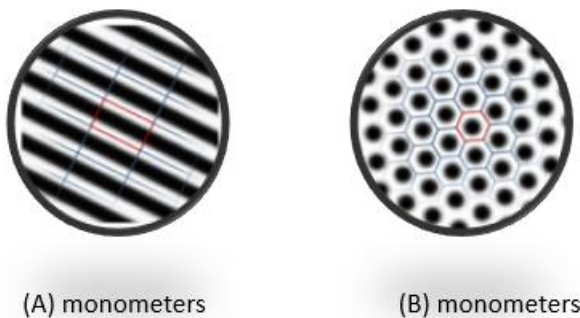


Figure:1.2 Monometers [21]

Above shown figure 1.2 indicates two monometers; (A) and (B) respectively. Periodicity cells for deblock copolymers tiling in 2D. Predict that pure materials A and B can be modelled as linearly elastic media with (μ_A, λ_A) and (μ_B, λ_B) respectively. Solid behaves linearly elastic isotropic medium, as combination of pure materials. The composite material is not isotropic in general. This operation is performed by embedding the original two-scales problem in a family of problems with increasing separation between the two scales [21]. this perspective can lead to insights in algebraic and topological context.

2. LITERATURE REVIEW

Recent reviews have catalogued developments in topology optimisation and its interplay with AM. For instance, Matimbi et al. TO has given broad reviews on automotive body and chassis structures along with applications and trends (2020). Zhu et al. A recent review article (2021) focused on TO methods designed explicitly for AM with an emphasis on the current "hotspots" in research - multiscale/hierarchical lattice design and embedding manufacturing constraints of AM [4]. In a similar fashion, Prathyusha and Babu (2022) reviewed TO+AM across industries = automotive, aerospace), identifying the fact that TO decreases part count and cost through consolidation El Khadir et al. A recent open-access review by (2023) presents important aspects of TO–AM interactions: it points out limited geometries that cannot be produced with AM but needed for creative development in TO process, and depicts how to manage manufacturing constraints within TO methods. [7]. Liu et al. (2018) gave a perspective on "current and future trends," pointing out that AM allows near-full use of TO's freeform evolution, but new process-specific constraints must be addressed [8].

These reviews converge on a few themes relevant to chassis design:

2.1 AM unlocks new design space –Addictive Manufacturing has revolutionized traditional manufacturing processes. AM unlocks new potentials in topology design and helps to highlight its impact on engineering field. TO can generate bionic, lattice, or other complex shapes that were previously infeasible, and AM can realize them, [7]

2.2 Manufacturing constraints – manufacturing constraints in topology are now being integrated into TO – overhang angles, support-free design, minimum size, etc. – to ensure AM printability. These constraints prove impact on final design, performance and other components. Where material properties, cooling rates, heat management and factors like such have major impacts.

2.3 Multi-physics and multi-objective extensions – Multi-physics and multi-objective extensions such as simultaneous load paths, crashworthiness, NVH and hybrid materials are important areas; [8]; Topology optimization techniques guide designers in designing innovative designs that are practical and feasible with the present-day technology. These designs and successful applications are a must for real world application in real time.

2.4 Case studies proliferating – from suspension components to full chassis frames, studies report 30–50% mass reduction with equal/better stiffness or strength after optimization and AM fabrication. In the automotive sector specifically, Hamza and Shakil (2025) noted that TO has been applied to BIW, subframes, uprights, etc., and that combining TO with AM supports mass customization and performance goals [9].

However, current fully automated TO-AM chassis design chains are still in their early stages despite increasing interest. The literature provides several proof-of-principle examples (Table 1). As an instance, Jankovics and Barari (2019) introduced a TO framework with overhang and build-time constraints for designing the suspension upright of a performance vehicle that minimizes support consumption as well as print time [6]. Kim et al. (2020) investigated the multibody dynamics + finite element (FE) analysis and topology optimization (TO)-based redesign of an all-terrain vehicle knuckle, printed in AlSi10Mg, which achieved 2.5× symmetric stiffness vs. baseline [19]. Hu et al. Bench tests [19] reported significant stiffness and strength increases for this design based on a tubular front sub-frame using TO. At a larger scale, Li et al. (2024) TO and WAAM based approach to create lightweight EV chassis, generating 44 candidate "skeleton" designs automatically and reducing development cycle time by a factor of 120 over traditional trial-and error[5]. The findings from these studies pave the way for adopting TO + AM for structural light-weighting in automotive applications.

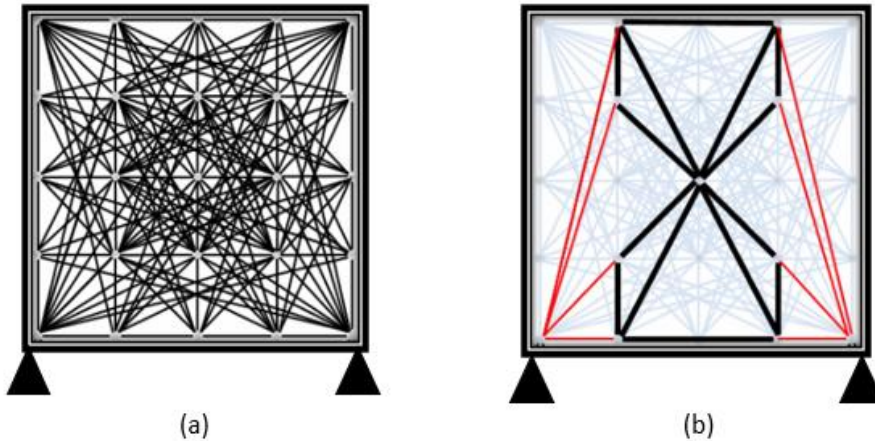


Figure:1.4: (a) Connecting nodes with potential truss members (b) Using optimization [11]

The total number of loads in Figure 1.4(a) and 1.4(b) is denoted by p . The diagram illustrates a simple example of chassis generation for a vehicle model. The following diagram integrates the axial load control rule to tune the structure of beam cells That chassis structure is then worked on via algorithms. It guarantees that the chassis structure has maximum load-carrying capacity in both two-dimensional and three-dimensional spatial directions [11]. In addition to the individual studies, there have been industry-focused reviews and perspective articles. For example, Charles et al. 2022) talk about the disruptive potential of additive manufacturing (AM) in automotive and its upsides with a green mobilitychange. Dalpadulo et al. (2022) advocated for a "synergic product-process design" approach by incorporating critical performance indicators (weight, cost) in DfAM selection while applying it to an F1 race car steering support (Formula SAE), objectively trading weight savings versus manufacturing cost [11]. They mention that although there are AM prototypes of chassis parts, "The lack of structured and objective approach hampers the application within normal production" [11]. OEM engineers, in industry interviews, emphasize that it's not necessarily about "exotic materials," but "system-level integration and execution—maybe now is the time to change the question from what can we make to how do we implement at scale" as stated by Kulkarni of Tata [11]. In conclusion, the literature of 2017–2025 makes it very clear: more researchers and engineers apply TO to automotive structures as well as devote their works on AM, but many still struggle with feasibility issue, integration issues or effort-cost ratio balanced at least close to comfort level.

3. METHODOLOGIES

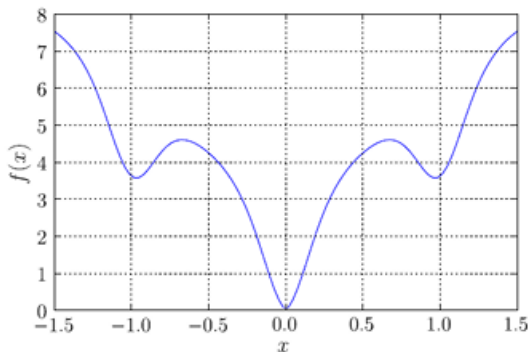


Figure:1.5: Multi-dimensional function [13]

Figure 1.5 shows multimodal for two dimensions.[13]. What is local search, More specifically, It mostly used gradient base optimization which can be categorized into two variants constraints and non-constraints. These techniques are Simplex, Sequential Linear Programming (SLP), Sequential Quadratic Programming (SQP), Exterior Penalty (EP), Interior Penalty (IP) [27], Generalized Reduced Gradient (GRG)[28] and Method of Feasible Directions (MFD)[29]. composite-based design based on Modified Friss equation (de Weck & Kim, 2004; Venter, 2010). The problem with local optimization algorithms is that they can converge to any of the minimum or maximum points[13].

3.1 Topology Optimization Workflow. Modern automotive transfer-objective (TO) workflows usually include: (a) definition of design domain (e.g. knuckle volume, frame section or chassis substructure), based on CAD/bare-structure modeling with any tool such as Hyper-Mesh [HyperMesh, Hu et al.); (b) defining the loads/boundary conditions (typically obtained from either vehicle dynamics or crash simulations), (c) choosing an optimization algorithm, (d) executing iterative simulations (FEA and optimization) until converging to an optimal material distribution, and finally, (e) post-processing the outcome into manufacturable geometry. Several studies combine multi-body dynamics (for realistic loading), finite-element analysis, and gradient-based topology optimization in a loop , Kim et al. conducted a multibody kinetic simulation of an ATV course to determine knuckle forces, which were then used as FEA and TO inputs [19]. some authors use commercial TO software (for example, Altair OptiStruct, Ansys TOSCA, nTopology) or in-house codes (Matlab demos, level-set solvers). Additional modules filter or reshape the raw TO result to meet AM requirements, Typical optimization goals include minimization of compliance (maximize stiffness) under volume (mass) constraints, or minimization of weight under stress constraints. Design objectives may also involve natural frequency maximisation, bucking safety or multi-load compliance. TO is enough for a few components, but advanced ones need improvements. Crash simulations for crash-box designs may also contain some amount of non-linear or time-domain modelling. Some works (Silva et al., in press) are focusing on coupled topology optimization of an automotive crash box for joint compliance and energy-absorption objectives. Some take a multi-physics approach, such as the simultaneous static loading with dynamic vibration (e.g. H. Ma et al, 2024) 2020 with effect of subframes) or thermal-mechanical coupling such as for brake discs (Ding, 2019; Liu et al., 2019)[4]. In all cases, the TO loop is iterative: design update, structural analysis, sensitivity analysis and material redistribution until convergence.

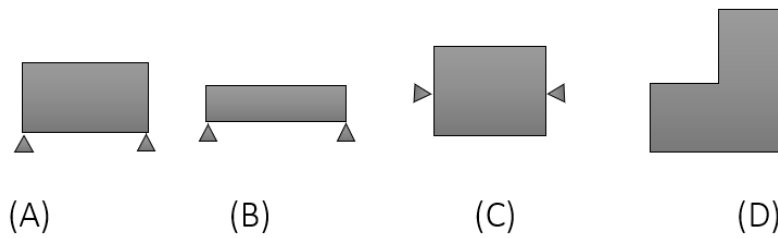


Figure:1.5.1 Geometry and boundary condition [20]

Figure 1.5.1 shows geometry and boundary condition for various four different situations. Stress free conditions are set. In the figure, (A) denotes test bridge. (B) denotes test MBB beam. (c) denotes test square. (D) shows test L shape. Here the set of N candidates are taken. Material is M. and by Θ , the set of candidate directions $\Theta = (\alpha_1, \dots, \alpha_N)$. Materials can be obtained by all single reference with stiffness. The stiffness tensor of a material is; $E_m = Q(\alpha_m)E_0$. Most used strategy in finding minima rely on continuation methods. Original problems are replaced with the modified one, featuring better properties. That gradually change to recover the original formulation. In the figure 1.3, all famous testcases of Top Opt is shown. Grey area shows design, load is set from bottom in (A) and (B). In (C), load is set from the middle, and in (D) load is set from the left bottom.

Table:1.1: model parameters [14]

| Parameters | Value |
|---------------------------|----------------------------------|
| Welding-current(A) | 116 |
| Welding-voltage(V) | 13.4 |
| Wire-federate (m/min) | 8.5 |
| Travel speed(cm/min) | 7.9 |
| Airflow(L/min) | 20 |
| Heat source power Q(W) | 1163 |
| Heat source parameters af | ar, b, c (μm) 3,4,5 |

Above shown table 1.1 indicate model parameters and their values The Wire is loaded in and printed for welding. The arm remains as it is. Mechanical arms no change. Topology algorithm continues to be confined into the industrial design software. An initial simulation temperature mapped as printing layer temperatures was set using the Jmatpro software. A wire-cutting machine was used to cut through the deposition line, making a square sample of $10 \times 10 \times 6\text{mm}$ on the printed block after cutting. It consist 116 for welding current(A), 13.4 for Voltage, 8.5 for Wire-federate, 7.9 cm per minute for travel speed,20 for Airflow,1163 Heat source power.

3.2 Algorithm Classes. Topology optimization methods fall into broad categories [7]:

3.2.1 Density-based/SIMP methods: Discretize material distribution as continuous densities over the mesh (e.g. FEA grid). The Solid Isotropic Material with Penalization (SIMP) method is most widely used: the density variable for each element can vary between 0 and 1, which gives rise to a solid or void solution depending on its scale. These methods seamlessly integrate constraints (stress, displacement) and multiple load cases. SIMP was used for chassis in early TO automotive studies such as (Cavazzuti 2011). Massive TO is utilized by the majority of automotive researchers as they are well-established and their software support is available [7].

3.2.2 Level-set methods (LSM): Represent boundaries explicitly via a level-set function. The geometry evolves by moving the implicit surface. LSM naturally represents sharp boundaries and can capture topology changes. Wang et al. (2018) used a level-set approach to impose self-support constraints for AM (ensuring each layer is supported) [6]. LSM can produce smooth, crisp shapes but historically required more complex implementation.

3.2.3 Evolutionary methods (ESO): Based on gradually removing elements below a threshold stress (e.g., BESO, progressive removal). These methods iteratively cull inefficient material. They have been applied in some chassis design work (e.g., the classic knuckle of Luo et al. 2020) and are sometimes easier to implement for certain problems.

3.2.4 Homogenization/Implicit methods: For lattice or multi-scale designs, homogenization TO designs a periodic microstructure in tandem with macro layout. This can generate optimized infill or porous substructures inside thick members. For instance, Liu et al. (2018) note that hierarchical lattice optimization is a key research area [4].

3.2.5 multi-material and multi-material TO: When printing with different metals or alloys, TO can optimize spatially varying material composition. Some works incorporate anisotropic material properties (e.g., Zou & Xia 2023 imposing strength constraints for anisotropic AM metals) or multi-material gradation.

Heuristic/metaheuristic: Genetic algorithms, topology patterns, etc., are less common in chassis design due to large problem sizes, but some hybrid methods (e.g. pattern-based or beam replacement) have been explored for conceptual chassis design.

In the context of AM-specific chassis optimization, two additional methodological aspects stand out:

Incorporating AM Constraints: As noted, TO must often be constrained to produce AM-feasible results. This includes enforcing maximum overhang angles, minimum feature size, and ensuring printability (e.g., no isolated “island” features). Methods include adding explicit constraints (e.g., penalizing unfavorable angles in the objective [6], using filters (e.g., Langelaar’s AM filter [6], or multi-axis deposition strategies [6]. Section 5 discusses these in detail.

Post-Processing & Verification: After the raw TO output, smoothing, boundary extraction, and adding fillets or stiffeners are common. Final designs must be verified by FEA (static, modal, crash) and tested (e.g., printed prototypes). For example, Hu et al. (2024) verified their optimized subframe with bench tests [19]. Similarly, Kim et al. built and vehicle-tested their AM knuckles to confirm performance [19]. This iterative design–print–test loop is part of real-world methodology.

Geometric parameters of two meshes:

Table:1.2 two meshes used in optimization process. [22]

| | Element size | Number of elements | Number of nudes |
|--------|--------------|--------------------|-----------------|
| Mesh 1 | 4.0 | 900 | 988 |
| Mesh 2 | 2.5 | 2400 | 2541 |

Table 1.2 indicates 2D model for optimization process of two meshes; Mesh-1 and Mesh-2. The finite element model was discretized with stress elements of the type CPS4R.[22] one side crash box was fully loaded and the other side was impacted by the rigid body. The impactor can reach to null speed. The crash recreations were achieved using an energetic explicit formulation, with a time step of $\Delta t = 0.035\text{s}$ that confirms that the impactor can reach a null speed. A surface-to-surface contact was recognized between the rigid body and the contacting nodes.[22]

4. TOPOLOGY OPTIMIZATION ALGORITHM TYPES

Topology optimization algorithms can be categorized into the methods discussed above[7], but it is also instructive to distinguish approaches by objective or feature focus:

4.1 Density-based TO (SIMP): Most prevalent; solves a continuous problem with a fixed FE mesh.

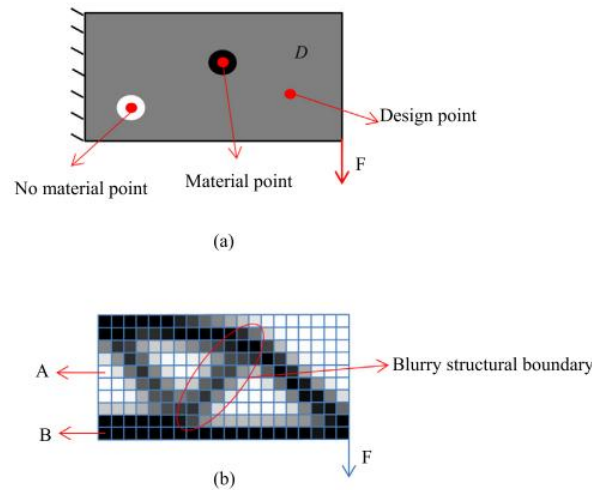


Fig. 1.6 (a) An illustration of topology optimization and (b) an illustration of SIMP method [19]

Fig. 1.6 presents (a) a schematic illustration of the topology optimization process and (b) an illustration of the SIMP (Solid Isotropic Material with Penalization) method used for material distribution in structural optimization. It handles multiple load cases and can include stress or displacement constraints. Many software packages (for example, Altair OptiStruct, Ansys) implement this. It forms the backbone of most automotive TO studies [19]. SIMP-TO is good for maximizing stiffness for given volume.

4.2 Stress-constrained TO: For chassis safety, stress or fatigue constraints may be critical. Some algorithms formulate stress constraints (Kamitake et al., 2020; Peng & Xu, 2020) to ensure the optimized design meets yield or fatigue requirements. For AM, anisotropic yield criteria (e.g. Hoffman) can be integrated (Zou & Xia 2023) to account for direction-dependent strength [62†source].

4.3 Multi-objective TO: When optimizing for weight and crashworthiness (energy absorption) simultaneously, multi-objective formulations or Pareto-front methods (e.g., NSGA-II + TOPSIS as in Wang et al., 2016) are used. This is relevant for rail/bar chassis members that must crumple under impact. Very few examples exist in automotive TO for crash; Silva et al. (2024, in press) is tackling crash-box design with TO.

4.4 Topology with lattice infill: Instead of solid-void distribution, some TO approaches embed a lattice or graded infill inside the design. This blends structural lattice design with topology layout. Hybrid methods like concurrent macro-micro TO or sequential design allow simultaneously optimizing overall shape and internal lattice parameters.

4.5 Feature-driven or heuristic methods: Some other studies consider pre-defined microstructures (struts, surface patterns) and optimize their location or size. This is similar to generative design. It can be manufacturable; especially for FDM/FFF approach. Freeform density TO is still more common, however, for metal chassis parts (typically printed by PBF or WAAM).

The algorithm is based on the chassis application you are using. Stiffness-driven parts, like control-arm arms (they are different than the knuckles), only need compliance minimization Topology Optimization (density method) with overhang filtering. Multi-objective or nonlinear TO may be required for energy absorption parts (crash beams, subframe legs). For NVH sensitive parts (e.g. suspension towers) modal frequency objectives can be introduced. Consequently, automotive chassis TO often utilizes a combination of these methods based on the performance requirements for each component.

El Khadiri et al. (2023) indicate, although many different methods exist, the common thread is integration with AM: whatever algorithm is selected must respect manufacturability and leverage the freedom allowed by AM. This accounts for most of the recent developments in methodology. [11], Table 1.3: Acceleration parameter for static analysis conditions [24]

| Numbers | Operating condition | Acceleration value |
|---------|----------------------|--------------------|
| 1 | Forward-braking | -1 |
| 2 | Vertical impact | 3 |
| 3 | Right steering | 1 |
| 4 | Forward acceleration | 0.7 |
| 5 | Backward breaking | 0.7 |

Olympics, a world without science Acceleration parameters are shown in table 1.3 for every static analysis conditions. Numerical and/or experimental technique or method prove its versatility by generating acceleration value for several different operating condition. Longitudinal (forward breaking). Three vertical impacts are shown in vertical impact. In a right steered lateral, there is one. It provides a longitudinal backward breaking and forward acceleration of 0.7. The values of the wheel loads were calculated and applied to the multi body dynamics model for simulation according to the working acceleration table and technical parameters of vehicle [24]

5. Additive Manufacturing Constraints in Chassis Design

While TO can produce highly optimized shapes, additive manufacturing introduces its own design rules that must be accounted for. Designers use various strategies to ensure that a TO result can actually be printed on the chosen AM machine (PBF, WAAM, etc.).

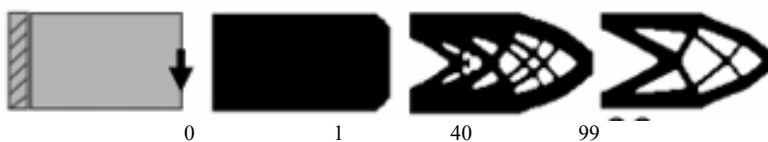


Figure 1.7: topology optimization [8]

An illustration of the iterative process is shown in figure 1.7. Thanks for the answer! The figure shows progressive impact of the process; to the left, its solid material and way to complete it with a very right, it has gained finally structure. A topology transformation is shown. The third wave: In between loops. And finally, forming a beautiful clear picture of the outcome. This results in an optimal shape only by having defined a design domain and boundary conditions. Although, the final output geometry will usually still need to be processed before it can actually be made. [8]

5.1 Overhangs and Support: A classic AM restriction is the angle at which a feature overhangs: any bridge that is horizontal (for displays, this usually means 135° to build direction or less) will require support structures. Printing with additives, time, and processing. TO methods take overhang constraints to minimize supports. For example, Zhang et al. AM-aware topological optimization by employing B-spline parameterization of density, with an overhang-angle constraint and gradient filters (2019) [6]. Also, explicit filter-based methods (Langelaar 2017) can be designed to penalize large unsupported regions during optimization. Hamza et al. Figure caption: (2025) pointed out that making the 3D model with a smaller overhang is better for printability (e.g. round radius instead of sharp corners). In practice, designers align build orientation to reduce significant overhang, and some use multi-axis AM completely circumvent issues with overhang [6].

5.2 Minimum Feature Size and Self-Support: This is an important section since all AM processes have a minimum length/diameter they can reliably print. This then means that TO cannot have (thin members which can snap) or small holes. Implicit or Explicit Constraints (min length filters, Liu et al. Checkerboard or mesh artifacts are avoided using strategies such as those described in [6]. Another target that is specific to AM is self-supporting design (i.e. making sure that every layer can be sufficiently supported by the layer just below). Wang et al. (2018) constructed a design on layers with a permuted level-set representation, where each new slice must be self-supported resulting in nearly support-free designs [6]. Fu et al. (2019) proposed a minimum-length filter, in which the width of every structural member must be greater than or equal to the starts fourteenth order for image and binary shape.

5.3 Anisotropy and Material Properties: Metals deposited by AM often exhibit anisotropic mechanical properties and residual stresses. Some TO studies incorporate this by using anisotropic material models or strength criteria. For instance, Zou & Xia (2023) adopted the Hoffman failure criterion in TO to account for anisotropy [62[†]source]. Also, lattice infills introduce directionality; if the chassis material is directionally weak, TO may adapt the geometry accordingly.

5.4 Process Economics and Throughput: Even more so in automotive, it really comes down to cycle time and cost. Dalpadulo et al. However, while (2022) has explicitly included manufacturability and deposition rates in ranking chassis candidates [5], Their studied 44 topology-optimized designs were assessed on both material usage and deposition time in their framework. The final chassis design was selected to achieve low-cost, high-deposition flux. Hamza et al. This builds on the work. (2025) argue that even when physically achievable, build-rate constraints (which are particularly important for large WAAM parts) act as de facto process constraints in TO, which is favourable towards fast-printable designs [9].

To summarize, AM constraints mean that in chassis design both you require a DfAM mindset: the geometry must be realistically fabricatable! This is usually done in an iterative fashion between TO and process simulation, using filters or extra objectives to direct the design towards avoiding non-printable features. The reward is that the TU design adjusted at AM time can be built without costly rework, shown by case stories of success.

6. INDUSTRY RELEVANCE

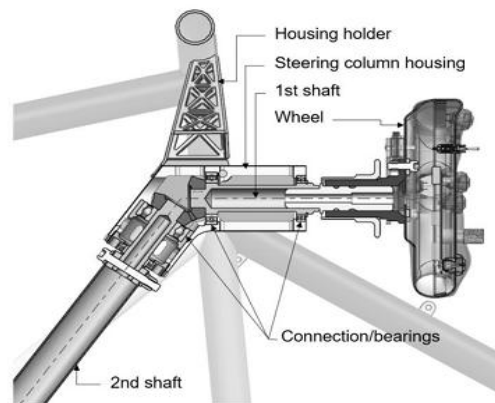


Figure:1.9: steering column [25]

Figure 1.9 shows Figure: schematic of current solution of steering column housing and reach CNC-machined aluminum alloy steering column housing Internal axes gears are shown in the figure The mass is in kg, as sample shown in figure 1.9 (0.514 kg). Much of this image only emphasizes key elements and their spatial organization [25]. The steering wheel being link 1st shaft, which transit the driver input into the system. After that, the first shaft made contact with the second shaft, it passes motion transmission downstream of the mechanism.

6.1 OEM Perspectives: Automotive designers know all too well the balance between design innovation and manufacturing realities. Tata Motors, for example (PDF link): "The Industry should spend less time chasing after lightweight mermaids (carbon composite material at high cost) and focus more on the intelligent integration of TO and AM into existing platforms." As Anand Kulkarni, Tata's EV product head tells, "What we need is to shift from What these technologies are to How We Should Implement Them At Scale" [13]. So making millions of lightweight parts needs to be done in a way that is cheap, and can be repeated. In the same vein, Maruti Suzuki's engineering mandate for the new Alto also emphasizes using existing MEGAs (ultra-high-strength steels, hybrid tech) to take 100kg [14] off a vehicle's mass before concluding that weight savings may well come just purely from design optimization.

6.2 Supply Chain & Sustainability: TO + AM are part of larger trends that center around on-demand, digital manufacturing. Hamza et al. AM can also reduce supply chains (e.g. just-in-time print, structural), and provide customizability [9] (2025) It can help reduce the need for inventory and allow weight-optimized variants for various markets without new tooling. Yet if you thought about how AM is going to be less competitive because you're putting all this energy into playing with materials like metal. OEMs warn them off the climate impact: more than consolidation of parts, AM can be highly consuming in energy. Dalpadulo et al. take into account manufacturing cost and energy in their DfAM decisions [11]. The point of consensus seems to be that TO-driven lightweighting has to enable full life-cycle thinking for sustainable design (as Tata's Kulkarni and others exhort healthy weaning from material substitution that may counter-balancing gains via embodied energy).

6.3 Standards and Validation: Certifications overcome one of the biggest challenges to adoption. Automotive components must sustain crash and fatigue safety requirements over very high production volumes. It follows that topology-optimized designs need to be vetted through significant simulation and testing. This is evidenced in real-world service case studies: after printing and static testing an AM knuckle, Kim et al. incorporated this into a formula car and confirmed the performance through driving tests [19]. Hu et al. verified the stiffness of an optimized subframe [19]. According to OEMs on the industrial side, all TO-chassis components will require some degree of surrogate validation (e.g. AM prototypes in small runs, then adaptation for mass production-possibly by welding or casting). With that in mind, industry guidance (from standards bodies such as SAE, for instance) is beginning to surface on workflows pertaining to the "topology optimization design for AM" process. In reality, many OEMs are currently prototyping chassis applications: BMW and General Motors have already announced prototypes of durable printed lightweight parts, while Indian OEMs are embarking on pilot projects. Some low-volume or specialty components (electric-vehicle subframes, structural reinforcements, cross-members) will be integrated TO+AM within a few years. Indeed, Li et al. demonstrated that completely feasible. The development of a skeleton → A complete chassis skeleton can be conceived and printed (2024). [5]. OEMs are developing solid TO-AM pipelines and supplier qualifications, indicating that this technology is indeed moving from the lab into commercial production for mass adoption.

7. CASE STUDIES

Several illustrative case studies underscore how TO and AM have been combined in practice for automotive structures. Table 1 summarizes key examples from recent literature and industry reports.

7.1 Suspension Knuckle: A common benchmark: Kim et al. (2020) optimized a heavy steering knuckle (suspension component) by coupling multibody dynamics with TO [19]. The design achieved a 2.5× increase in stiffness for the same mass. The knuckles were printed (AlSi10Mg via PBF) and successfully tested in an assembled vehicle [19]. This demonstrates how TO plus AM can produce a stiffer, lighter knuckle than the machined original. Jankovics and Barari (2019) similarly optimized a high-performance upright, explicitly constraining overhangs and build time to yield an AM-ready design [6].

7.2 Subframe and Chassis Members: Hu et al. (2024) applied TO to a tubular steel/aluminum subframe. Post-optimization, the static stiffness at critical points was "significantly improved," and dynamic/modal performance was better [19]. Bench tests confirmed the scheme's feasibility. Li et al. (2024) tackled a full chassis structure for a commercial EV, using an automated workflow: they generated 44 "skeleton chassis" designs via TO, evaluated each for mass and printability, and produced one with WAAM [5]. By coupling TO with manufacturability ranking, they reduced the design cycle from years to about a week – a ~120× speedup. The

resulting 7075-Al chassis was printed on a Kuka robot (Figure 2) and passed preliminary crash simulations with minimal deformation. stem depositing a topology-optimized chassis module. The robot (Kuka KR150) and welding torch build 7075-Al structure layer-by-layer [5].

7.3 Steering and Body Structures: Dalpadulo et al. (2022) used TO + AM for a Formula-SAE steering support system. They integrated trade-off criteria (weight vs. process cost) into the DfAM approach, achieving a design that balanced minimal mass with acceptable build time [11]. Aliyi & Lemu (2019) reported an Appl. Sci. case study of an automotive component (unspecified) optimized for AM, illustrating improved weight and stiffness, though details are brief. These case studies show the range from competitive racing (high-performance demand) to production-oriented parts.

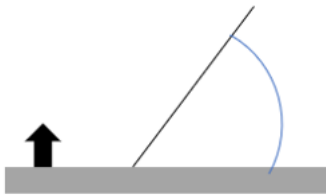


Figure:1.8: build platform[8]

The stair like formation of AM layer based process, as you see in the figure 1.8. There is limit amount of overhang material in AM based method. It is also relative to the wall of the part with respect to the build platform. where limit [8] almost reached common at each time. 45 The core idea that most of these methods follow is to penalize the material violating the different angle constraints. Light weight is among the key enablers, which are wrought by topological optimization. Since a 10% mass reduction can result in 6–8% improvement in fuel economy or EV driving range, tapping into vehicle light weighting is a demonstrated approach to improve energy efficiency.

7.4 Industry Prototypes and Demonstrators: These techniques are also now being used by automotive R&D groups. There were several entrants bestow in December, although BMW's concept of a consolidated (meaning multiple parts are merged into one printed node) EV chassis that incorporates 3D printing to save significant weight represented part of specific consideration. Reports on optimized chassis nodes from European collaborative projects (e.g., Advance 3D, Agility) Although not all are published, these advances follow the same trends seen in academia: TO + AM can reduce overall structure weight by 20–30% for equal or better performance. In India, Maruti and Tata share weight targets open to interpretation (100kg for Alto, similar aspirations for Tiago EV [15]), but without revealing full figures that are proprietary elements on particular vehicle models by definition -- again indicating considerable interest within the auto industry in the opportunities optimized design and manufacturing will permit.

Table1.4: Summary of key studies on TO [16]

| Study | Year | Component & Material | Methodology | Key Outcome |
|--------------------------------|------|--|--|---|
| Jankovics & Barari [15] | 2019 | Performance vehicle upright (generic material) | TO with overhang/build-time constraints | Overhang-aware TO produces a lightweight, support-minimized upright (no metrics given) |
| Kim et al. [19] | 2020 | Steel/Al steering knuckle (AlSi10Mg PBF) | Dynamics to FEA to density-based TO to print to test | 2.5× stiffness increases vs. original; printed knuckle passed in-vehicle tests |
| Zhang et al. [15] | 2019 | 2D/3D generic beam frames | B-spline parametric TO with overhang constraints | Demonstrated simultaneous optimization of topology and build direction with overhang-angle filter |
| Wang et al. [15] | 2018 | Generic beam/shell (steel) | Level-set TO with self-support constraints | Achieved support-free designs via level-set layers; published as example of freeform support-free structures |
| Hu et al. [19] | 2024 | Tube-beam front subframe | Density-based TO (OptiStruct) + FEA | Static stiffness at critical points “significantly improved”; verified by bench tests |
| Aliyi & Lemu | 2019 | Car suspension component | SIMP TO (details unspecified) | Case study: TO design yielded lighter component with preserved strength (no quantitative data given) |
| Dalpadulo et al. [11] | 2022 | FSAE steering support (Ti-alloy) | TO + KPI-based DfAM tradeoff (cost vs weight) | Optimized for weight vs cost trade-off; achieved a functional AM prototype steering support for an FSAE vehicle |
| Li et al. / Giet (3DAdept) [5] | 2024 | EV chassis frame (7075-Al, WAAM) | Automated TO (44 candidates) + WAAM printing | Printed chassis demonstrated minimal deformation at 40 km/h impact; design cycle cut from years to ~1 week [5] |
| Prathyusha & Babu [6] | 2022 | Review – multiple parts | Survey of TO+AM in industry | Conclude TO+AM enable lightweight parts by part consolidation (cost, material savings) [15] |

One such study on topology-enabled lightweight automotive components (2019–2024) is depicted in Table 1.4 along with results from various studies. systematic literature review: study, year, component of interest / methods and results (mass savings, performance 2 gain). It covers the body of published research, as well common industry/consortium examples. These entries highlight the art of the possible: modest weight savings (usually >30–50%), no loss in stiffness or crashworthiness, due to TO and AM. [16]

8. CHALLENGES AND LIMITATIONS

The promise, several challenges remain before TO+AM can be broadly applied in automotive chassis design:

8.1 Manufacturing limitations: As discussed, overhangs, small features, and anisotropy require careful handling Achieving truly support-free designs for complex chassis geometries is still difficult. Surface finish and internal defects (porosity) in AM metal parts can affect fatigue life; thus, TO results may need conservative post-optimization smoothing [17]

8.2 Computational scale: High fidelity optimization for full-vehicle or even large subassemblies is computationally expensive. It can even take more than a few hours of HPC time to solve tens of thousands design variables and several load cases. Another cost is associated with multi-load (simultaneous acceleration, braking, crash) or non-linear physics (crash, large deformation). Reduced-order or concurrent approaches are under investigation by researchers, but for now the bulk of TO chassis studies are based on individual components or scaled segments. And this modular thinking cannot capture global optimum trade-offs.

8.3 multi-material and assembly: Even a single-part printed part optimized for TO still has to fit into a multi-part assembly. Chassis designs usually optimize single staves, while in reality chassis performance comes from connections and interfaces. For instance, the study optimizes a cross-member that must still bolt into frame rails, which may not be optimized. TO across assemblies or coupling with additive welding/joining is complex.

8.4 Regulatory and safety certification: Topology-optimized designs, being novel, require extensive validation. Crashworthiness (finite element crash simulations, sled tests) must prove that lightweight designs meet safety. New certification guidelines are needed for non-traditional shapes. Without robust standards, OEMs may be cautious.

8.5 Economic factors: So even if an optimized part were lighter, AM (especially with metals) is still way more expensive than volume stamping or casting. Cost models (Dalpadulo et al., 2022) need to justify the trade-off: TO+AM is only economic for low volume or high-performance products. This can be countered by reducing machine cycle time (faster deposition, higher power lasers or multi-laser), along with development of AM materials.

8.6 Skill and process maturity: TO with AM involves cross-discipline teams (ie, designers materials scientists, process engineers) Even if your toolchain is not yet fully automated—human expertise is needed to pick TO settings, interpret results, set up prints, and check outcomes. Most academic proofs-of-concept used expert-tweaked. More “plug-and-play” workflows for industry.

In short there exists a gap between what is algorithmically possible and which can actually be produced. But the challenges also spur research: new algorithms for printability and multi-material design; qualification procedures from industry consortia. TO and AM is converging for the very reason that these roadblocks are clearly identified and being actively addressed.

9. FUTURE RESEARCH DIRECTIONS

Future research directions include many opportunities for future in the area. Building on the current state of the art, key future directions include:

9.1 Integrated Design & Process Simulation: Integrated PLM-enabled design frameworks that connect CAD modelling, simulation-driven optimization and manufacturing process integration have also shown improved coordination between virtual design validation and practical implementation for advanced mechanical systems [30]. These digitally integrated approaches will make the next generation of topology-optimized automotive chassis development with improved assessment capabilities for their manufacturability and process efficiency. [30].

9.2 AI-driven Topology Design: Data-driven analysis and intelligent feature extraction methodologies used in recent engineering diagnostic systems also demonstrate the growing applicability of AI-assisted computational frameworks in complex optimization environments [6].

9.3 Multi-functional Optimization: Recent investigations involving nano-reinforced composite coatings and multifunctional engineered materials further indicate growing interest in hybrid material systems for enhanced structural and surface performance [21], [25].

9.4 Scaling to Full Vehicles: Ultimately, one would like a holistic vehicle chassis optimization. This is currently impractical, but multi-scale strategies (optimize modules then globally coordinate) could emerge. Digital twins of whole vehicles integrated with optimization loops could identify where mass can be trimmed at the system level.

9.5 Sustainability Metrics: Lifecycle optimization that weighs not only in-use fuel savings but also embodied energy and recyclability is needed. TO algorithms might incorporate environmental impact as an objective. Some initial work in the literature is exploring carbon accounting in AM design.

9.6 Standards and Certification Frameworks: Developing agreed-upon methods for verifying TO designs (e.g., benchmark parts, simulation protocols) will accelerate industrial use. Research can contribute by demonstrating standardized test cases and publishing data on durability.

9.7 Hybrid Manufacturing: Combining AM with subtractive methods or bonding might produce the best of both worlds. For example, an optimized block that is AM-printed then milled for precision mating surfaces, or a part with optimized lattice core coated by a hollow forging. TO algorithms might evolve to plan for such hybrid processes.

9.8 Open Research & Data Sharing: With the increasing amount of TO work being done, the community will benefit from hosted repositories with TO-optimized CAD models or geometries, material tests, and case studies. Large-scale demonstrators could be funded through public-private partnerships (eg an optimized chassis in service). The trend is toward fully, tightly coupling the design of structures to the science and engineering of materials and all aspects of manufacturing technology. The optimistic hope is that by 2030, many components of chassis will be usually launched from a topology optimized basis when created – if the above advancement matures.

10. CONCLUSION

It is radically changing the way automotive chassis and structural parts are conceived, particularly in conjunction with additive manufacturing. Through a process of algorithmically maximizing stiffness or safety-to-weight ratio, TO discovers novel geometries that reduce component mass by 30–50% while maintaining or improving performance [19]. These designs are then provided in metal via AM, allowing part consolidation, feature integration and rapid iteration. Let's be clear, Industry leaders understand that these innovations have to be strategically deployed at scale [20]. This review has summarized recent developments of TO algorithms (e.g. density-based, level-set, multi-objective etc.) and corresponding DfAM strategies in lightweight chassis design. NOTE: Some of the most impactful case studies are where optimized knuckles, subframes and full chassis frames were realized and tested. Since Tata Motors and Maruti Suzuki were on a mission to achieve weight targets, the write-up in this research effectively connected literature with industry context: TO and AM provided practical means of achieving those targets. There are still hurdles to be overcome printability, cost-effectiveness and certification, in particular but the field is developing rapidly. In the future, we can certainly expect more integrated workflows where a design optimization tool is fully cognizant of the AM machine, materials and performance requirements. As such, the automotive structural design will necessarily become a computational-experimental process with much less reliance on trial-and-error craft. The trend is obvious the merging of TO and AM is a powerful roadmap to the light, smart cars of the future. Also, algorithm-based research methods that translate experimental and simulation data into optimal structural solutions will allow for the development of safe and reliable designs. These algorithmic approaches will enhance the predictive ability and practical capabilities of advanced automotive designs by merging methodologies and outcome-driven results across these different research studies.

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