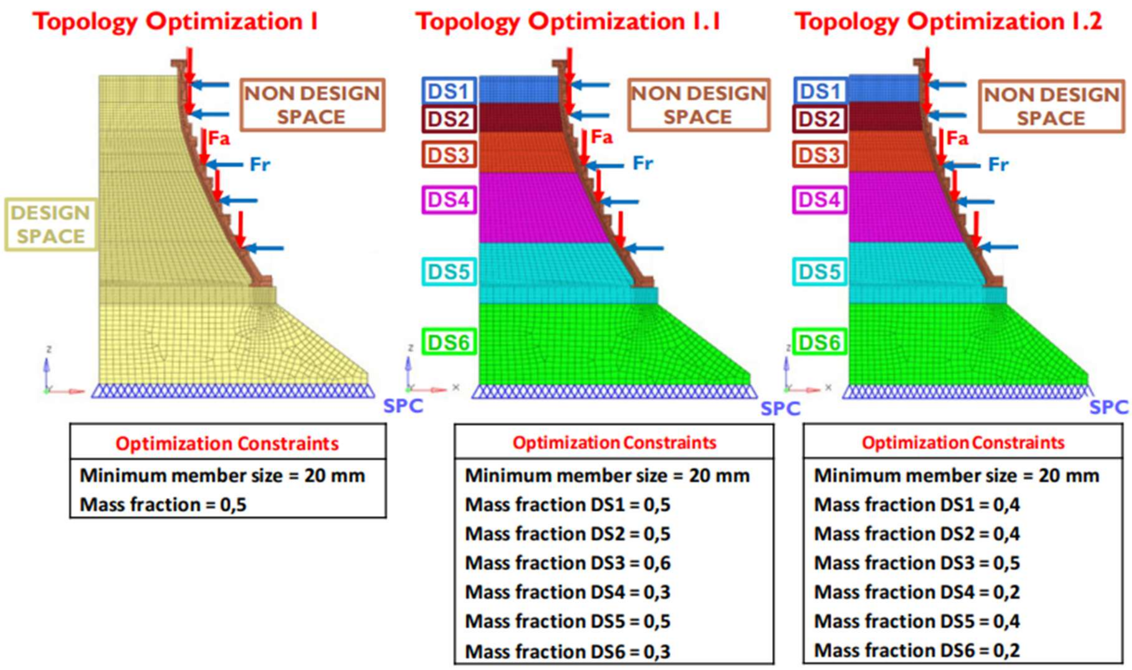
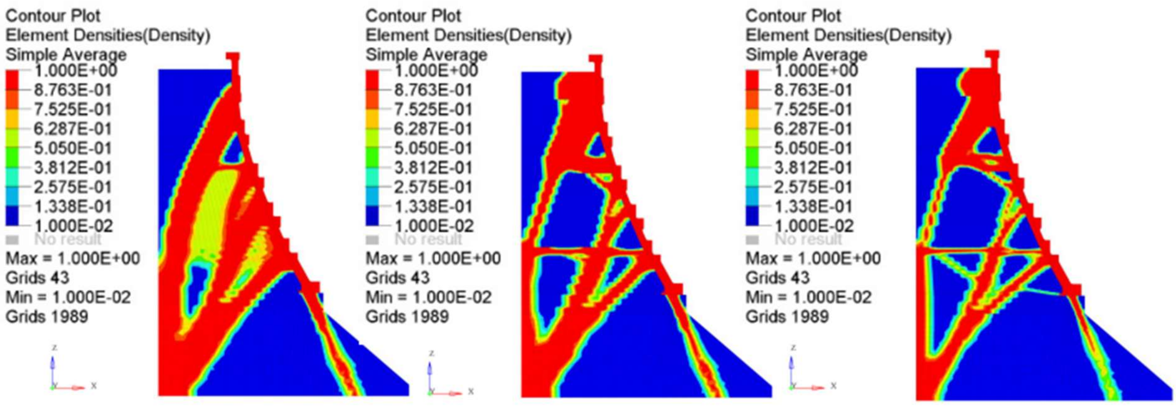
removed, solid regions where it was structurally necessary, and intermediate regions where a lattice infill was appropriate.



Element density contour plots for three 2D topology optimisation case studies, showing the material distribution converging towards discrete solid-void designs.



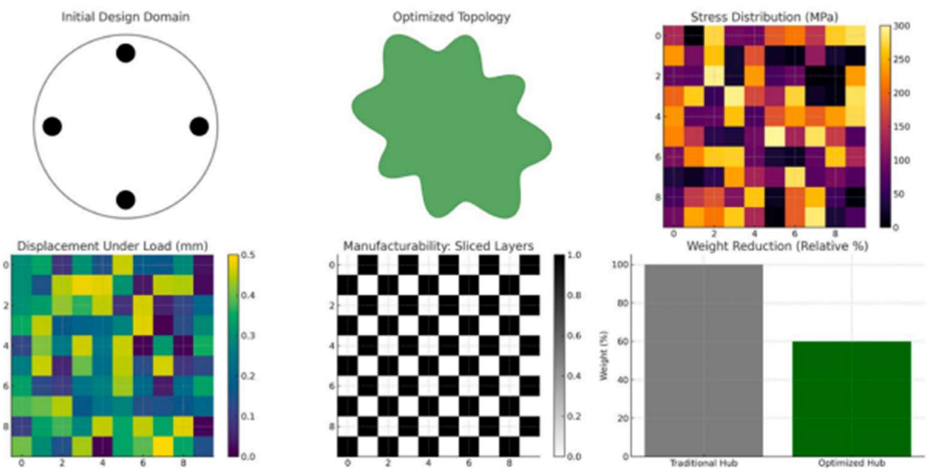
3D topology optimisation results from Calabrese et al. showing the TO4 case with 51.5 percent mass reduction, with solid, lattice and void regions identified.

A notable and honest finding of their work was that the addition of lattice structures in the initial design did not, in their linear static analysis, materially reduce the maximum displacement - the values were essentially unchanged across all case studies. This confirmed that the elements the optimiser had assigned low density were genuinely structurally redundant, and validated the optimisation result. Their achieved mass reduction on one three-dimensional case reached 51.5 percent.

3.2 Keerthi Kumar N et al. (2025): Reinforcement-Learning-Based Topology Optimisation

This paper represents the AI-driven frontier of the field. The authors integrate topology optimisation with deep reinforcement learning, specifically a Proximal Policy Optimisation (PPO) agent, to generate lightweight, manufacturable structures. The agent learns optimal material layouts within a design space by trial and error, receiving feedback in the form of compliance, stress and displacement data computed by finite element analysis - a physics-informed reward loop.

Two elements of their formulation were directly adopted as the acceptance criteria for the present project. Their design is constrained by a maximum Von Mises stress of 300 MPa and a maximum displacement of 0.5 mm; the 0.5 mm displacement limit is used here as the machining-tolerance acceptance criterion. Their reward function penalises any design that violates these constraints heavily, ensuring that the learned designs are mechanically feasible and not merely light.

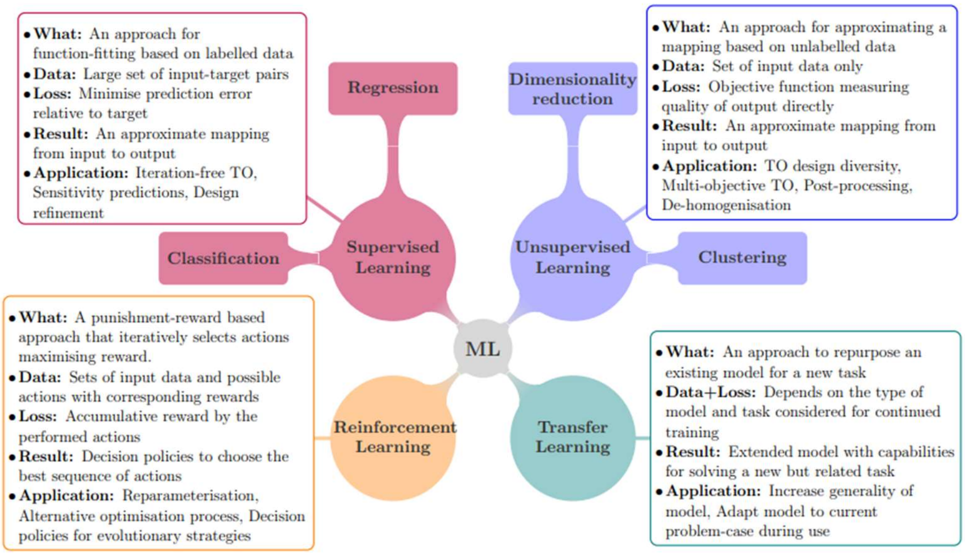


Their reported results are instructive as a benchmark. The method achieved up to 40 percent weight reduction while maintaining compliance, outperforming conventional SIMP and level-set techniques on the standardised Topology Optimisation Dataset, and was validated on a real wheel-hub geometry. The pipeline incorporated Signed Distance Field smoothing to remove voxel-level aliasing before exporting an STL file for additive manufacturing - a post-processing step relevant to any physical realisation of the optimised fixture.

3.3 Woldseth, Aage, Bærentzen & Sigmund (2022): On the Use of Artificial Neural Networks in Topology Optimisation

This review is the critical counterweight to the enthusiasm of the previous paper, and it directly motivates the second theme of this project - the interpretation of non-intuitive AI geometries. The authors survey the rapidly growing body of work applying neural networks to topology optimisation and reach a sober conclusion: direct-design models that attempt to map boundary conditions straight to an optimised structure, bypassing iteration, tend to produce poor designs, are expensive to train, and are severely restricted in the range of problems and mesh resolutions they can handle.

Their most important technical argument, reproduced here because it underlies the whole difficulty of interpreting AI geometries, concerns sensitivity to boundary conditions. They demonstrate that a very small change in the load - a load angle perturbed by one-hundredth of a radian - can change the optimal structure completely, from a single vertical bar into a braced two-member structure. The compliance of the original single-bar design under the perturbed load rises by nine orders of magnitude; it effectively collapses. This means the mapping from problem to optimal structure is riddled with discontinuities, which is precisely why AI-generated geometries are non-intuitive and why an unbounded number of training examples would be needed to learn them reliably.



The authors further observe that AI-based methods commonly produce structures with residual grey-scale intermediate densities and a tendency towards disconnected members and blurred boundaries, losing the fine features that conventional SIMP captures. Their recommendation is that the goal of iteration-free topology optimisation should be set aside, and that AI effort should instead be directed at reducing the cost of the expensive components within the conventional iterative process. For this project, the paper's lasting contribution is a vocabulary and a diagnostic lens for the structural-determinants analysis.

Category/ Level	Supports	Mesh	Loads	Test≈Train
0	fixed	small fixed	single-point restricted	sampled from the same limited pool
1	few (2-3 or very similar)	larger fixed	single-point many options	small difference (i.e. changing supports marginally resulting in small visual difference)
2	some (multiple options, but still similar problems)	limited variation possible (i.e. 2-3 choices for different aspect-ratios or resolutions)	multiple limited (i.e. ≤10 loads or placements restricted domain boundary)	some difference (i.e. definite difference aspect-ratios or loads)
3	many (a set of clearly different options)	many (some flexibility both in terms of shape and resolution)	multiple many (either no upper bound on no. loads or no restriction on placements)	medium difference (i.e. ensured difference loads and BCs)
4	any (method appears applicable to any set of reasonable support options)	any (complete mesh-independence)	any (no restrictions apply)	significant difference (BCs, loads, mesh-shape and resolution different)
Weight	3	2	3	1

3.4 Synthesis of the Three Works

Paper	Contribution to this project	What was adopted
Calabrese et al. (2017)	Method for fixture TO on thin-walled parts	BC philosophy, min member size, solid-lattice reasoning
Keerthi Kumar N et al. (2025)	AI generative TO benchmark	0.5 mm displacement & stress acceptance limits, 40% mass target
Woldseth et al. (2022)	Critical limits of AI in TO	Diagnostic lens for non-intuitive geometry analysis