Applied Topology Optimization

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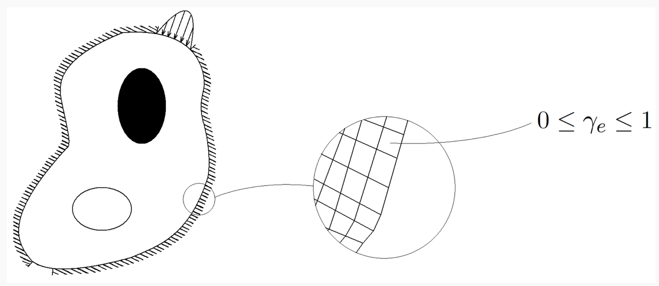
The topology optimization method

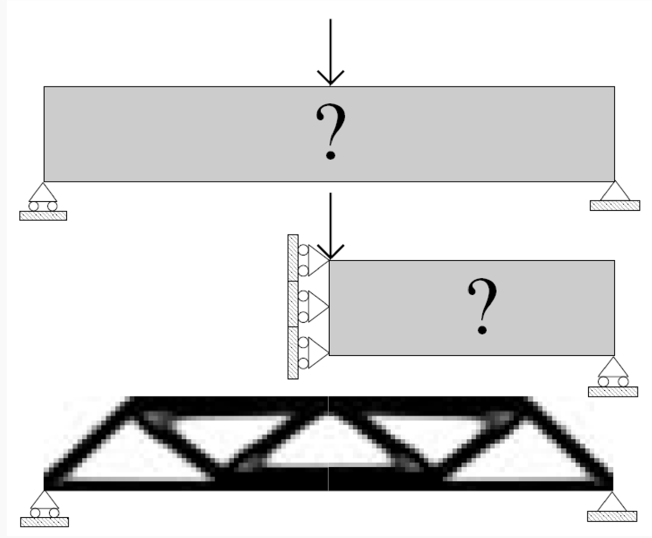
Topology Optimization (TopOpt)

"is a material distribution method for finding optimum layout" [0].

- **Objective:** To minimize compliance $\Phi \equiv$ maximize stiffness (cost function).
- **Constraint:** Volume fraction $\in [0, 1]$.
- **Design domain:** freely chosen.
- **Continuous design variable field:** Density field, γ, is the distribution of material between void and solid in each discretization element.
- **Feasibility:** Optimization problems of magnitude $O(10^9)$ variables solved after $O(10^2) - O(10^3)$ iterations in O(hours) using $O(10^0) - O(10^3)$ cores.



Design parameterization.



TopOpt for the MBB beam - Top: Problem illustration; Middle: Imposing symmetry; Bottom: TopOpt Solution. [1]

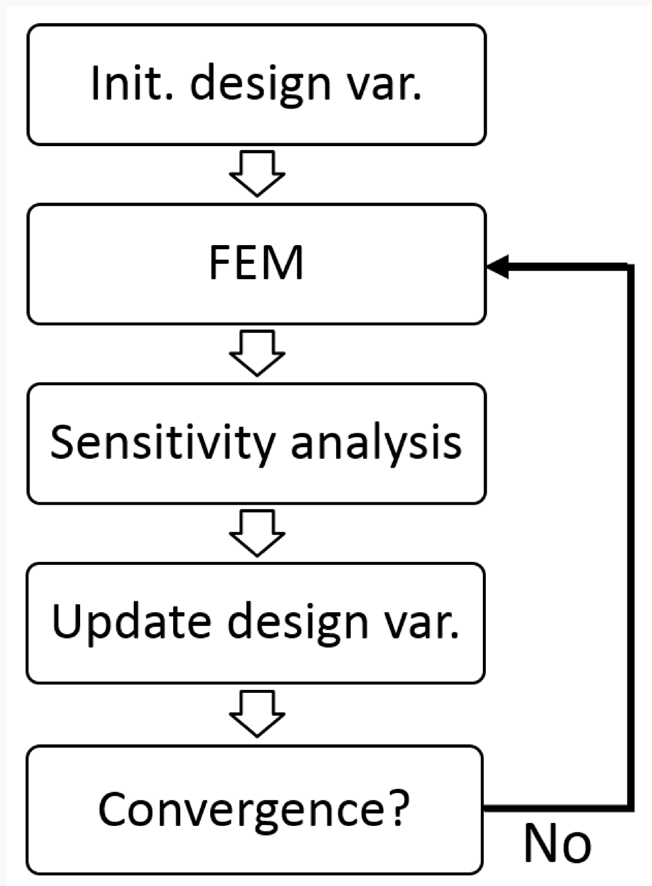
TopOpt utilizes:

- **Sensitivity analysis:** E.g. Method of Moving Asymptotes (MMA) [2] which yields avoidance of mesh-dependency and checker board effects.
  - **Based on:** Sensitivities $\left(\frac{d\cdot}{d\gamma}\right)$ of both cost and constraint functions, which are obtained using *adjoint* analysis.
- Penalizations and filtrations.

TopOpt solution is obtained: when the change ratio of material distribution reaches chosen threshold.

The physical problem:

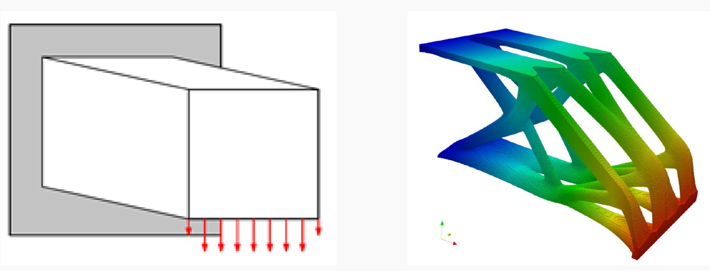
is solved using FEM where elasticity/multi-physics problems are modelled.



A simplified general work diagram for TopOpt.

Loads on cantilever beam

Single load case [3], **Constraint:** $V \leq 12\%$.



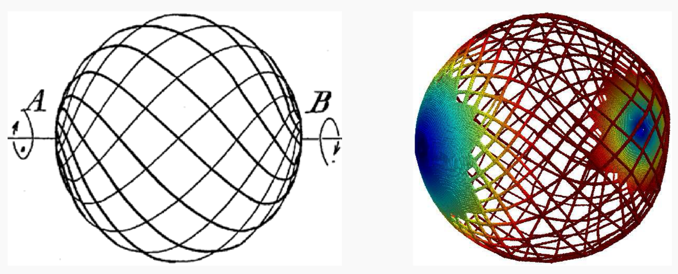
(a) Problem setup **(b)** Solution

(a) Illustration of problem and design domain **(b)** TopOpt solution. Colors indicate displacement magnitudes.

- **# Elements:** $= 480 \times 240 \times 240 \approx 27.6 \cdot 10^6$ (no symmetry imposed).
- **# DOF:** $= 3\times$ # nodes $= 3 \times 481 \times 241 \times 241 \approx 83.8 \cdot 10^6$.
- **Computational time:** 1000 iterations in 12.5 hours (average for var. filter radii) using 24 cores.

Torsions and loads

Torsion only case [3], **Constraint:** $V \leq 0.5\%$.

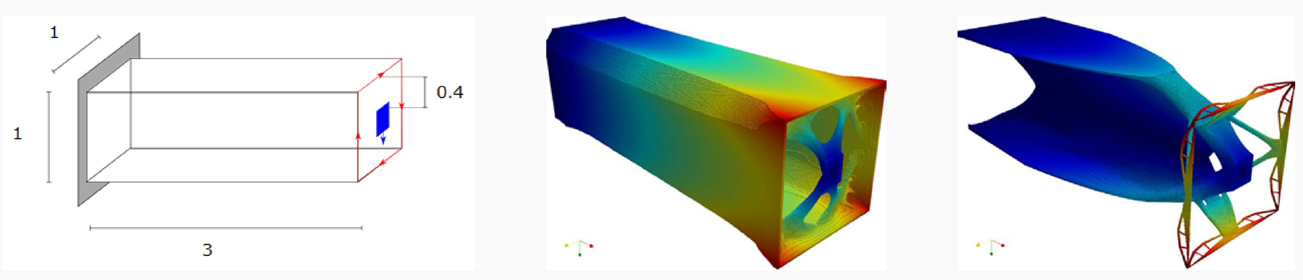


(c) Problem setup **(d)** Solution

(c) Illustration of problem and design domain, **(d)** TopOpt solution.

- **# Elements:** $\approx 82.1 \cdot 10^6$ (no symmetry imposed).
- **Computational time:** 2000 iterations in approx 4.5 hours using 2000 cores.

Multiple load case and torsion [3].



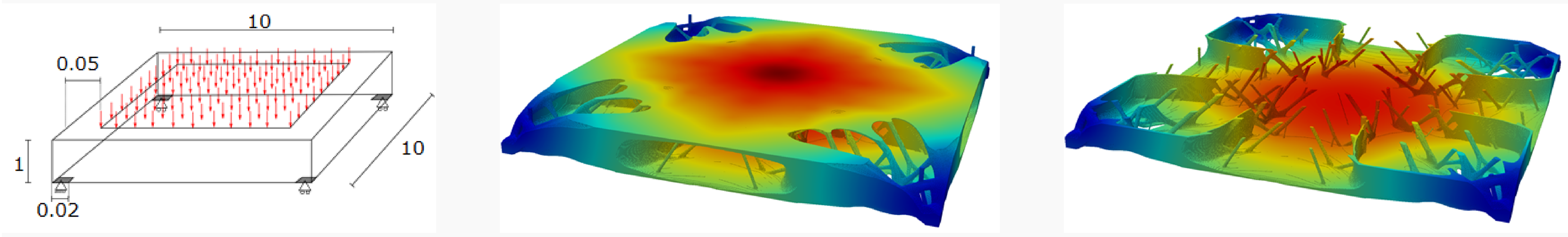
(e) Problem setup **(f)** Solution **(g)** Solution

(e) Illustration of problem and design domain, **(f)** TopOpt solution where torsion=10 and loads=1, **(g)** TopOpt solution where torsion=1 and loads=10.

- **# nodes:** $= 768 \times 256 \times 256 \approx 50.3 \cdot 10^6$ (no symmetry imposed).
- **# DOF:** $= 3\times$ # nodes $= 3 \times 769 \times 257 \times 257 \approx 151 \cdot 10^6$.

Roof supports

Roof support for simple distributed load [3].



(h) Problem setup **(i)** Solution **(j)** Solution

(h) Illustration of problem and design domain, **(i)** TopOpt solution, **(j)** Internal structure view of TopOpt solution.

- **# nodes:** $= 1120 \times 1120 \times 112 \approx 140.5 \cdot 10^6$ (no symmetry imposed).
- **# DOF:** $= 3\times$ # nodes $= 3 \times 1121 \times 1121 \times 113 \approx 421.5 \cdot 10^6$.
- **Computational time:** 1000 iterations in approx 7.8 hours using 2000 cores.

Roof support for the Qatar National Convention Centre [4] **Volfrac=12%:**

(k) Frontal view of TopOpt solution.

(l) Bird's eye view.

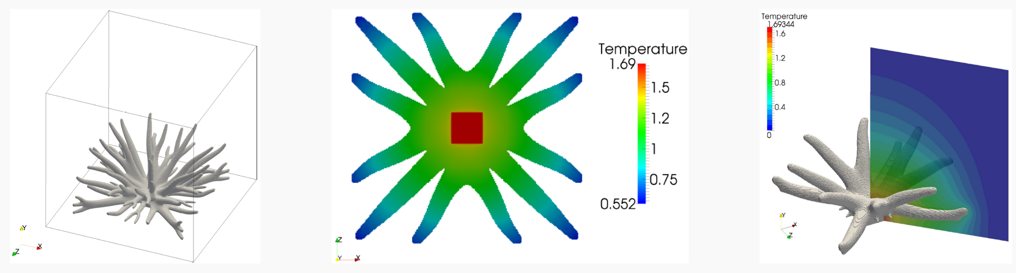
(m) Qatar National Convention Centre (Photo seen on "gulfnews.com".)

(k) Illustration of problem and design domain, **(l)** TopOpt solution, **(m)** Internal structure view of TopOpt solution.

- **# Elements:** $= 512 \times 64 \times 86 \approx 3.1 \cdot 10^6$ (no symmetry imposed).

Heat sink

- **Thermo-fluid case** [5].
- **Aim:** to minimize core temp subject to natural convection cooling.
- The governing equations for the multi-physics are coupled and a steady-state solution is calculated to obtain an optimized material distribution.



(n) Solution in design domain **(o)** 2D view **(p)** Solution in fluid

(n) Solution for mesh size $320 \times 640 \times 320$ **(o)** 2D view for mesh size $160 \times 320 \times 160$ **(p)** TopOpt solution for mesh size $160 \times 320 \times 160$.

- **# Elements:** $\approx 65.5 \cdot 10^6$ **# DOF:** 5·**# nodes:** $\approx 5 \cdot 330.3 \cdot 10^6$
- **Computational time:** 1000 iterations in 107-108 hours using 2560 cores.
- Symmetry exploited, quarter of total problem.

TopOpt large scale visualization challenges

- For large problems, i.e. '$O(10^9)+$' elements, solutions can attain files of magnitude $O(10^2) - O(10^3)$ GB.
- Solution size increases in the presence of higher dimensions as well as additionally imposed physics.
- Visualization is therefore computationally very demanding.
- **Goal:** make it easier to visualize solutions for large scale TopOpt problems.

Considerations:

- Make feasible the interaction with large scale visualization by immersion as with virtual reality frameworks.

What are the alternative methods for large scale visualization for similar problems?

The TopOpt App! [6]

Try the TopOpt apps! Available for:

- iOS and Android.
- Windows, Mac and Linux (see www.topopt.dtu.dk).

(q) App for 2D TopOpt **(r)** App for 3D TopOpt;

References

[0] M.P.Bendsøe & O.Sigmund - *Topology Optimization - Theory, Methods and Applications*, 2004.
[1] Ole Sigmund - *A 99 line topology optimization code written in matlab*, (2001).
[2] Krister Svanberg - *The method of moving asymptotes - A new method for structural optimization*, (1984).
[3] Aage, Andreassen & Lazarov - *Topology optimization using PETSc: An easy-to-use, fully parallel, open source topology optimization framework*, (2015).
[4] - M. Sasaki - *Morphogenesis of flux structure. Architectural Association Publications London*, (2007).
[5] Alexandersen, Sigmund & Aage - *Large scale three-dimensional topology optimisation of heat sinks cooled by natural convection*, arXiv:1508.04596
[6] Aage, Nobel-Jørgensen, Andreasen & Sigmund - *Interactive topology optimization on hand-held devices*, (2013).