A review on applications of topology optimization

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ABSTRACT

KEYWORDS

Topology,
Optimization,
Algorithms,
Load.

The main objective of Topology Optimization is optimal distribution of material in a given design space sustaining the applied load under given limiting conditions. It is a widely used design tool. It covers various fields like machine designing, aerospace, nano-optics, architecture, fluids, thermofluids, civil, frequency analysis etc. In this paper, the important role played by the topology optimization in different areas is discussed and focus is given on industrial, defence, space, and fusion application. This paper also gives insight about different types of advanced algorithmic methods used in topology optimization.

1. Introduction

In simple terms, we can describe Topology Optimization as a method used to distribute the material properly in the given domain with the predefined constraints without changing the performance of the material. It comes under structural optimization. Various different types of softwares are available for topology optimization like ANSYS, TOSCA OptiStruct, Nastran, INSPIRE, etc. The product development process of Topology Optimization is explained in below Fig. 1 (Mueller Ottmar, 1999).

Now a days, the significance of Topology Optimization is increasing due to the increasing demand of light weight, material saving, less energy consuming and cost-effective components. From a gear to the structure of sky scrapers, everything is first optimized and then introduced in real world. For instance, the topology optimization of gear is as shown in Fig. 2 (Chinmay Shah, 2018).

2. Algorithms

All these softwares used for topology optimization are executed with the use of finite element methods and optimization techniques based on algorithmic methods like Genetics Algorithms, PSO (Particle Swarm Method), Level Set Method, Homogenization Method, OC (Optimality Criteria Method), MMA (Method of Moving Asymptotes), HCA (Hybrid Cellular Automata), ESO (Evolutionary Structural Optimization), BESO (Bi-directional

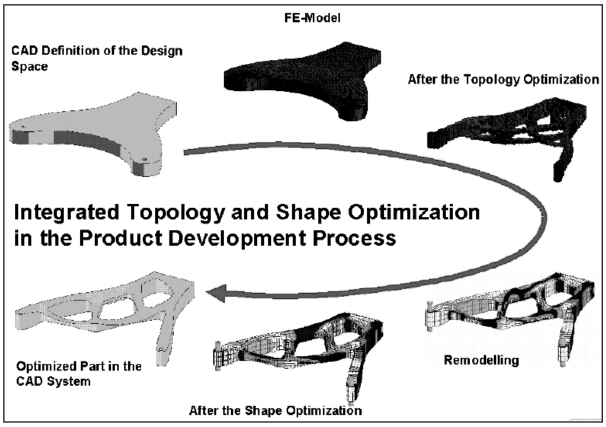

Fig.1. The Product development process.

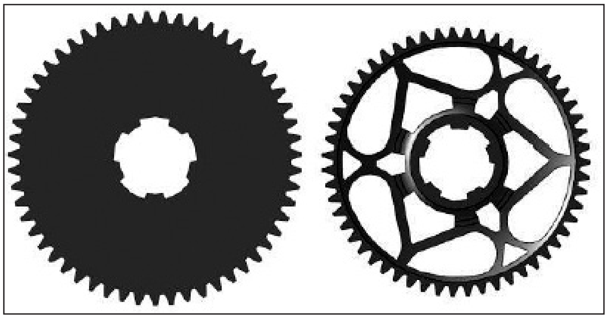

Fig. 2. Topology optimization of spur gear.

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Evolutionary Structural Optimization), SIMP (Solid Isotropic Microstructure with Penalization), SQP (Sequential Quadratic Programming) and many more (Mannai, 2013). In the recent times, the improved versions of these algorithms are applied. For instance, MISQP (Mixed-Integer Sequential Quadratic Programming) which is an upgraded version of SQP is used by ANSYS. These algorithms are either iterative or direct solvers. These methods are compared based on the various parameters like value of compliance, time taken, no. of iterations and the generated shape. Fanni M. et al. (Fanni M., 2013) has compared the SQP, MMA, OC and HCA methods based on compliance values, time consumed and the resulted topological shape in each method. For example, a table of comparison between ESO, Soft-kill BESO, SIMP and Continuation is shown in table 1 (X. Y. Yang, 2015).

These algorithms are also used to combine different tools used in optimization and that also with minimum computational time. Vaheed Nezhadali et al. (Nezhadali, 2011) has done multi-objective optimization of industrial robots in his thesis by integrating FEA using ANSYS with other tools such as Solid works, Dymola and MATLAB.

3. Applications of Topology Optimization

3.1. Industrial application of topology optimization

In his work Dongdong Ge et al. (Dongdong Ge, 2017) has done optimization of body frame of electric car in four working conditions i.e. horizontal bending condition, emergency braking condition, ultimate torsion condition and emergency turn condition. The total mass of lower body frame was reduced from 17.88 Kg to 14.49 Kg i.e. 18.96%. The Optimized design frame is presented in the below Fig. 3 (Dongdong Ge, 2017).

Qiusheng Ma et al. (Qiusheng Ma, 2012) have conducted topology optimization of a high-pressure storage tank with the loading conditions shown in Fig. 4.

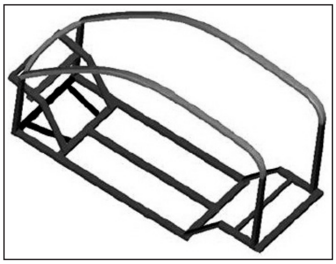

Fig. 3. Detailed design of body frame after optimization.

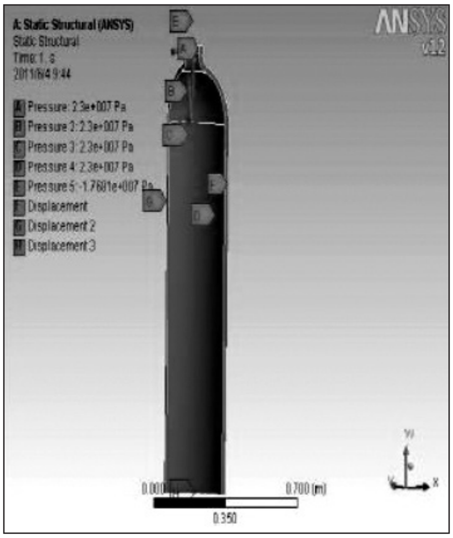

Fig. 4. Load constraints of high-pressure storage tank.

Table 1
Comparison of topology optimization methods.

	Optimization parameters	Total Iteration	Solutions		Error (%)
ESO	ER=1%	67		C=188.91 Nmm	4.12
Soft-kill BESO	ER=2% p=3.0	44		C=183.25 Nmm	1.0
SIMP	move=0.02 p=3.0	37		C=196.48 Nmm	8.29
Continuation	$p_{initial}=1$ $\Delta p=0.1$ $p_{end}=5.0$	337		C=188.44 Nmm	-

The optimized results were set side by side in the below table 2 (Qiusheng Ma, 2012).

Byung Jun Kim et al. (Byung Jun Kim, 2016) did topology optimization of paint robot with the goal of increasing the stiffness of the system using SIMP method. Here part-level metamodel was created relating the stiffness and mass usage. Total strain energy of the robot is reduced from 9817.7 N-mm to 4959.0 N-mm but there was only one limitation i.e. computational time increased from 40 h and 39 min to 50 h and 59 min. Optimized frames of paint robot are showed in the Fig. 5 (Byung Jun Kim, 2016).

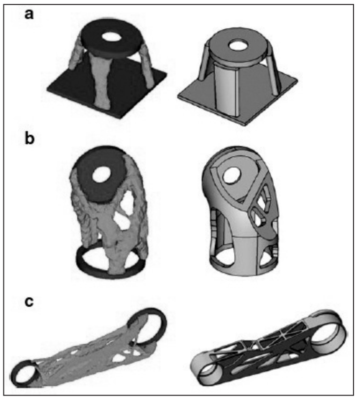

Fig. 5. Topology optimization results and optimization models: (a) Base Frame (b) Lower frame (c) Upper frame.

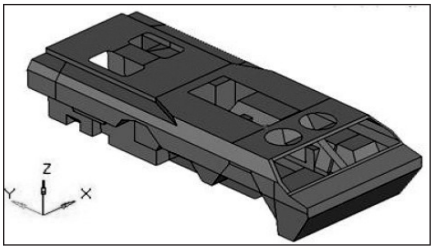

Fig. 6. The original hull structure.

Huang H. & Zhang G et al. (Zhang, 2012) has done optimization of an L-shape arm of Motorman HP-20 using the SIMP method. The difference in weight and displacement of original and optimized arm was 5.2 kg and 0.066 mm respectively (Zhang, 2012).

3.2. Defence application of topology optimization

Topology optimization of hull structure shown in Fig. 6 of wheeled combat vehicle was conducted by Harsh Pingale et al. (Harshal Pingale, 2018) using the SIMP method. Dimensions of vehicle are length=6.3m, breadth=2.5m, height=1.8m and total payload of vehicle consisting of self-weight and external load= 13.5 ton. The optimized model of vehicle is shown in Fig. 7 (Harshal Pingale, 2018).

Nilesh Patel et al. (Rokade, 2018) has done topology optimisation of an Articulating Beam

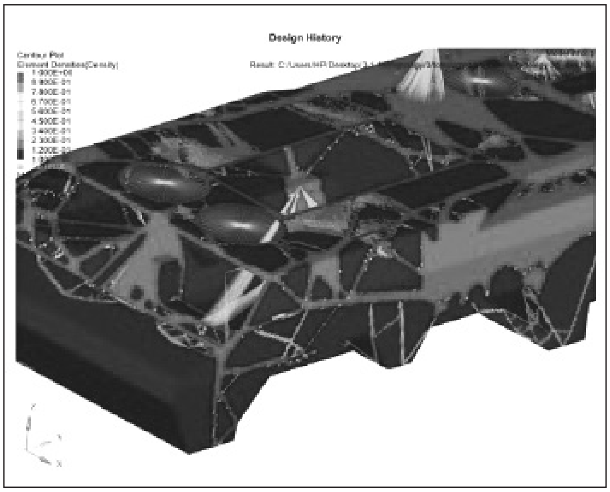

Fig. 7. Topology optimization nephogram of hull structure.

Table 2
Comparison of original & optimized values of high pressure storage tank.

	Mouth thickness [mm]	Tank thickness [mm]	Mouth diameter [mm]	Tank diameter r[mm	Maximum stress [MPa]	Mass of the tank [Kg]	Tank volume [m3]	Loading Rate
Original value	23	18	44.5	185	238.04	242.62	0.142 84	0.058739
Optimization 1	20.523	16.02	40.095	166.69	240.39	193.048	0.141 9	0.073509
Optimization 2	24.123	16.176	48.885	169.05	241.3	198.84	0.142 2	0.071511
Optimization 3	23.223	16.958	42.292	170.24	233.08	209.748	0.142 1	0.067757

of Article Launching System having payload of 15.35 t and volume dimensions as 10.2 x 1.95 x 1.5 m as shown in Fig. 8.

He considered two material displacement plots at articulation of 0° and 20° respectively. The constraints on the articulated beam are as shown in Fig. 9 (Rokade, 2018).

He made two designs, one with circular section and other with rectangular section and compared them. The maximum deflection and maximum stress of both designs were almost nearby. The weight of rectangular section (5.4t) was less than circular section (8.4t). Thus, rectangular section was more relevant compared to circular one which is presented in Fig. 10 below (Rokade, 2018).

3.3. Space application of topology optimization

Meera s. Prasad et al., (Meera S Prasad, 2017) in her work has done topology optimization of launch vehicle, especially the interstage structure having diameter and height of 4 m and aluminum alloy AA 2014 as material using the material distribution method. The interstage structure is as shown in Fig. 11 (Meera S Prasad, 2017). FE ring, AE ring, Bulkhead, Thrust block and a sheet of 1.5mm thickness as outer cover are kept as non-design elements (Meera S Prasad, 2017). The weight of structure was reduced by 65% of the original weight i.e. 2210 kg. The optimized interstage structure is as shown in Fig. 12 (Meera S Prasad, 2017).

Using Right First Time Robust Design (RFTRD) approach, A. R. Srinivas et al., (Srinivas, 2008) has done optimization of spacecraft payload elements with the objective of minimizing the size and mass. In the optimized mounting structure space was saved by 50%, mass was reduced by 20 to 30 % and realization time was improved by 83% (Srinivas, 2008).

3.4. Fusion application of topology optimization

S. Khorasani et al., (Sina Khorasani, 2000) has optimized poloidal field of Damavand Tokamak containing elongated plasma of aspect ratio of about five using genetics algorithm. After the optimization, the energy confinement time was increased by 25%, i.e. from 0.18 ms to 0.25 ms. The poloidal field of Damavand Tokamak before and after optimization is as shown in Fig. 13 (Sina Khorasani, 2000).

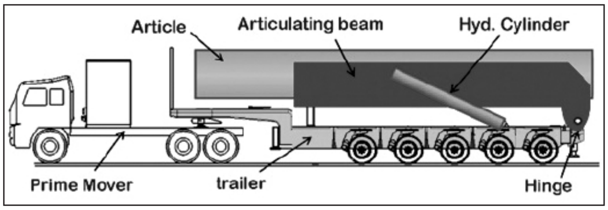

Fig. 8. Articulating beam of an article launching system.

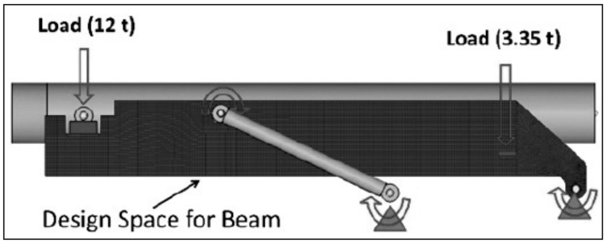

Fig. 9. The constraints of articulating beam.

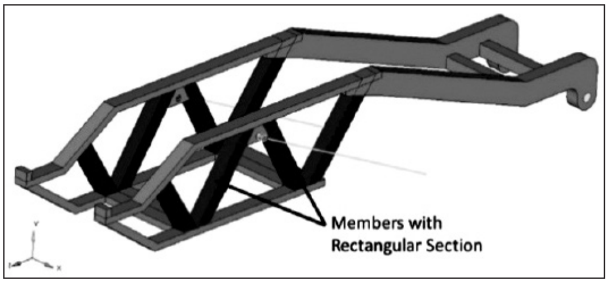

Fig. 10. Articulating beam with rectangular sections.

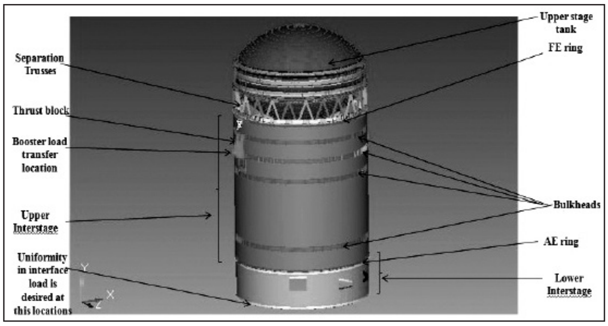

Fig. 11. The Interstage structure.

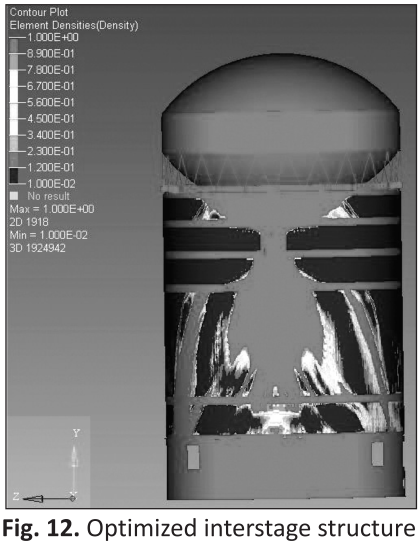

Fig. 12. Optimized interstage structure.

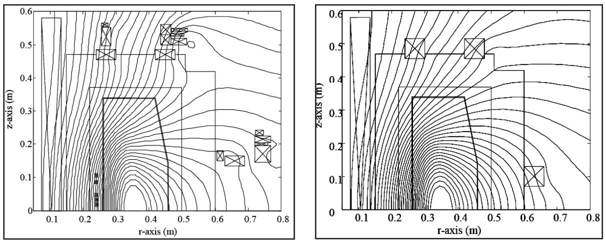

Fig. 13. Before (left) and After (right) optimization poloidal field for damavand tokamak.

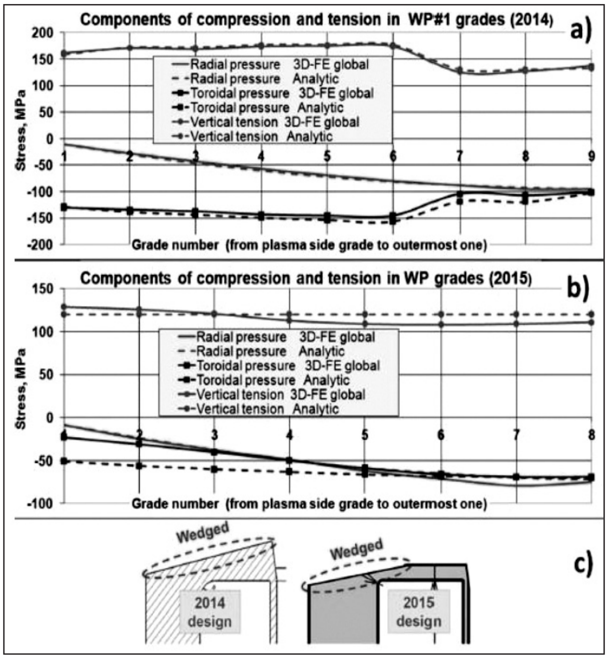

Fig. 14. Distribution of important stress components over homogenized WP grades (2014 & 2015 DEMO TFC layouts).

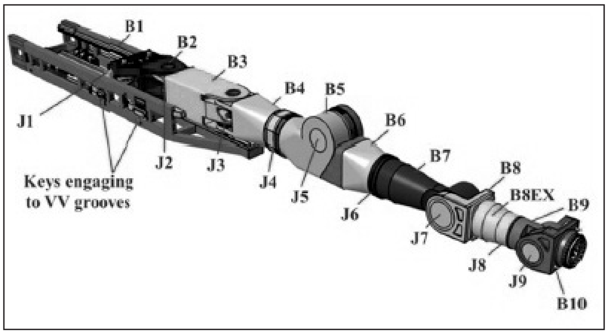

Fig. 15. Components of MPD transporter.

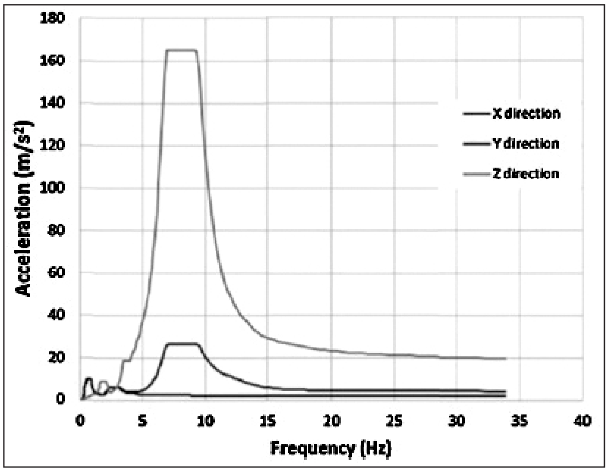

Fig. 16. Frequency response spectrum of MPD transporter.

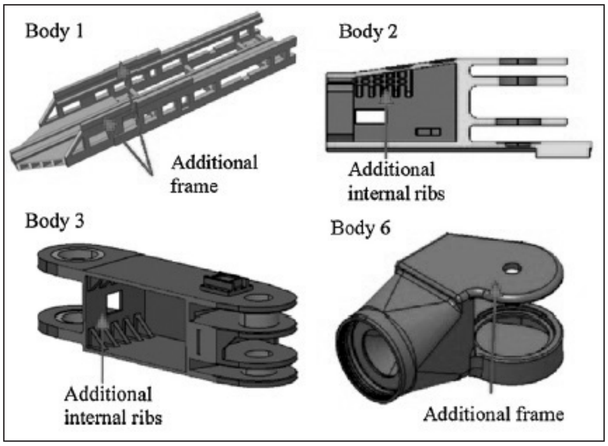

Fig. 17. Components of MPD transporter.

D. Combescure et al., (D. Combescure, 2011) in his work has done structural analysis and optimization of Tokamak ITER complex which is a building of 120 × 80 m with a base isolation system consisting of more than 500 steel reinforced neoprene pads and suggested changes in the dimensions of most relevant structural parts specially giving importance to thicker vertical walls. Panin A. et al., (Panin A., 2017) has developed a calculation tool which under electromagnetic loading determines the mechanical strength of coil and aids in pre-optimization and pre-dimensioning of toroidal field coils. It is presented in below Fig. 14 (Panin A., 2017).

Manoah Stephen et al., (M. S. Manuelraj, 2015) has done structural analysis of ITER multipurpose deployer in which static structural, modal and frequency response spectrum analysis was carried out using iterative solver. At the end of MPD Transporter 2 t payload is considered (M. S. Manuelraj, 2015). The components of MPD Transporter are shown in Fig. 15 (M. S. Manuelraj, 2015).

For the static structural analysis, the loading conditions were distributed into 4 categories. And for the modal analysis, the frequency response spectrum of the mounting location of MPD transporter is as shown in below Fig. 16 (M. S. Manuelraj, 2015).

On the basis of results of static structural analysis and modal analysis, the changes were made in the design of parts containing overstressed locations. For instance, thickness of main structural frame of Body B1 was increased from 20 mm to 30 mm, and the height of the side frames were increased by 150 mm. Similar kind of changes were made to other parts. The improved designs of overstressed parts are presented in Fig. 17 below (M. S. Manuelraj, 2015).

5. Conclusion

This paper in general highlights the use of topology optimization as a pre-processing tool in various applications. Here we can observe that when manipulator and the other components connected with it are optimized, the inertial load of the whole system is reduced without compromising the stiffness of the system. Due to the reduced weight the overall load on the actuators decreases. The material consumption is also reduced making the object cost effective. Thus, due to the favourable outputs topology optimization is extensively used as a design tool.

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Disclaimer

The views and opinions expressed herein do not necessarily reflect those of Institute for Plasma Research, Gandhinagar.

References

1. Kim, B.J., Yun, D.K., Lee, S.H., & Jang, G.-W. (2016, April 12). *Topology Optimization of Industrial Robots for System-Level Stiffness Maximization by using part-level metamodels. Structural and Multidisciplinary Optimization. Springer,* 54(4), 1061-1071. doi:10.1007/s00158-016-1446-x
2. Shah, C., Thigale, S., & Shah, R. (2018, June). Optimizing Weight of a Gear using Topology Optimization. *International Journal of Science, Engineering and Research Technology (IJSETR).* 7(6).
3. Combescure, D., Beltran, F., Rueda, F., Espeche, A., Maqueda, L., Pastor, M., Salgado, S., & Ezeberry, J. (2011 November 6-11). Structural Analysis and Optimization of the ITER Tokamak Complex. *Structural Mechanics in Reactor Technology.* New Delhi.
4. Ge, D., Zhu, L., & Xuan, D. (2017). *Topology Optimization in Electric Car Body Frame based on Optistruct. MATEC Web of Conferences.* EDP Sciences. doi:10.1051/matecconf/201710001016
5. Fanni M., S. M. (2013, December). *Comparison Between Diferent Topology Optimization Methods.* Retrieved from Researchgate: https://www.researchgate.net/publication/265167203_A_Comparison_Between_Different_Topology_Optimization_Methods
6. Harshal Pingale, S. V. (2018). *IRAJ International Conference*, 65-68. Pune.
7. Manuelraj, M.S., Dutta, P., Gotewal, K.K., Rastogi, N., Tesini, A., & Choi, C.-H. (2015). Structural Analysis of ITER Multipurpose Deployer. *Fusion Engineering and Design*. 109-111, doi:http://dx.doi.org/10.1016/j.fusengdes.2015.12.039
8. Kalanchiam, M., & Mannai, B. (2013). Topology Optimization of Aircraft Fuselage. *International Journal of Aerospace and Mechanical Engineering.* 7(5), 820-823.
9. Prasad, M.S., Xavier, S., & Lakshmi, P. (2017, May). Launch Vehicle Topology Optimization using OPTISTRUCT. *International Journal of Advance Engineering & Research Development,* 4(5), 181-186.
10. Ottmar, M., Albers, A., Sauter (1999, January). *Topology Optimization of Large Real World Sructures.* Retrieved from Researchgate: https://www.researchgate.net/publication/36452865_Topology_optimization_of_large_real_world_structures
11. Nezhadali, V. (2011). *Multi-Objective Optimization of Industrial Robots.* M.S. Thesis, Linköping University, Department of Management and Engineering, Sweden, North Europe.
12. Panin A., Biel, W., Philippe, M & Nunio, F. (2017). Mechanical Pre-Dimensioning & Pre-Optimization of the Tokamaks’ Toroidal

Coils Featuring the Winding Pack Layout. *Fusion Engineering and Design.* 124, 77-81.doi:http://dx.doi.org/10.1016/j.fusengdes.2017.04.065

13. Ma, Q.S., Cai, Y., & Tian, D.X. (2012, March 1). Topology Optimization of High Pressure Storage Tank. *Advanced Materials Research. 430-432*, 828-833.doi:10.4028/www.scientific.net/AMR.430-432.828
14. Patel, N., & Rokade, V. (2017). Topology Optimisation and Fabrication Aspects for Light Weight Design of an Articulating Beam of Articulating Launching System. *Defence Science Journal.* 68(1), 26-32. doi:10.14429/dsj.68.11991
15. Amrollahi, R., Minoo, H., Khorasani, S., & Dini, F. (2000, January). *Optimization of Tokamak Poloidal Field Configuration by Genetic Algorithms.* Retrieved from Researchgate: https://www.researchgate.net/publication/228456672_Optimization_of_Tokamak_Poloidal_Field_Configuration_by_Genetic_Algorithms
16. Srinivas, A.R. (2008). Robust Design and Realization of Spacecraft Payload Elements Using OptiStruct as an Optimization Tool. *4 th Indian/ASEAN HTC'08 Conference.* Bangalore.
17. Yang, X.Y., Xie, Y.M., & Steven, G.P. (2005). Evolutionary Methods for Topology Optimisation of Continuous Structures with Design Dependent Loads. Computers and Structures. 83(12-13), 956-963. https://doi.org/10.1016/j.compstruc.2004.10.011
18. Huang, H.B., & Zhang, G. (2012, October). The Topolgy Optimization for L-Shape Arm of Motorman-HP20 Robot. *Applied Mechanics & Materials,* 201-202, 871-874. doi: 10.4028/www.scientific.net/AMM.201-202.871

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