STM JOURNALS

Recent Trends in Civil Engineering & Technology
ISSN: 2249-8753 (Online), ISSN: 2321-6476 (Print)
Volume 7, Issue 1
www.stmjournals.com

Multi Population Search Engines for Topology Optimization of Continuum Structures

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Abstract
This paper deals with the complex design domains which usually require higher computational effort, and further tuning of parameters for algorithms is not practicable in terms of time and effort required. Multi search engines can be one such option wherein the search particles in groups are searching the design domain. Aqua search metaheuristic optimization algorithm is used to effectively explore and exploit the search domain. It is observed that this process of intensification and diversification is very effective to locate the optimum distribution of material in the given domain using two search engines in parallel. The overall computational effort required to optimize is reduced. Few problems have been solved and the results compared.

Keywords: *Aqua search, topology, search engine, continuum structures, multi population, optimization*

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INTRODUCTION

A structural engineer dream is to design, analyze and build a structure which can withstand the loading, sustain for a longer time and which is not only safe but also economical to build, provide green environment to live in, and which can promote and serve mankind needs. Any structure designed for a specific purpose has to undergo through this rigorous process before it takes the final form. In the quest for value creation, an engineer has to use his innovation abilities to design a structure that will be the hallmark in the field of structural engineering.

The knowledge of optimization which includes, structural mechanics, mathematics, computer science, and information technology to address the real time problems and design a structure which is not only cost effective but also innovative and that lasts forever. This complete process of designing a real time structure starts from preparing a mathematical model, perform analysis and arrive at the topology optimization [1]. Topology optimization sets the direction of the final design, a broad view of the design. Although not a clear ready to build output, it further needs shape optimization to smoothen the structure and prepare a final design which can be used in real time. Performing this entire process is quite expensive in terms of time and cost.

The entire process of optimization can be optimized in three ways:

- First: developing a better optimization algorithm: Aqua search algorithm can explore and exploit the search domain quite efficiently over FFA [2].
- Second: improving the C++ programming language which can efficiently use the available computational resources.
- Finally third way is access to high end performance computing servers, which can be quite costly.

This paper falls into the category of developing the program to efficiently make use of the available limited hardware resources. Multi search engines [3] is one such area where in the search operations can be performed in parallel [4]. In this paper, two search engines are used, each consisting of a population, in Aqua search algorithm terminology we can address them as divers who will locate the optimum. This is one of a kind of parallel computing. After a certain interval, the information pertaining to the best design can be exchanged between these groups and there after the process continues.

THEORY

The initial period during which Michel (1904) and Maxwell (1894) made their pioneering studies in the field. The techniques apply only to limited types of discrete structures and constraints (Hemp 1973). Following these initial works, the field of structural topology optimization fell relatively dormant for many decades.

A second period occurred during the 1960's and 1970's in which time, interest in structural optimization was re-kindled by the initial developments of high-speed computers. During this period, many important theoretical results for general optimization methods and numerical implementations were first presented, and difficulties in structural topology optimization were given extensive attention.

A third period during the 1980's and 1990's has been characterized by extremely dramatic growth in computing technologies. While theoretical work on structural topology optimization has continued, numerical techniques for structural topology optimization have been further refined, developed, and applied to larger-scale, more realistic structures. During this third period, while advances in discrete topology optimization continued, novel continuum structural topology optimization methods were also introduced and developed quite extensively.

In the olden days, a structure subjected to large external loading was built with heavy members having solid sections and the entire cross section material in the member was not effectively used to safely transmit the load. These age old structures were quite expensive and built of stone or lime and usually took several long years to build. Optimizing such structures for the amount of material required and hence the cost incurred has been the topic of interest for several years now.

New theories have been proposed and newer ways to optimize the structures to minimize the weight as objective function along with other constraint parameters such as stress, deflections have been increasingly in use [5]. With the increasing understanding of structural performance, the response of the structure subjected to different types of loading conditions, people begin to realize that the structures can be optimized in terms of material required and hence reducing costs. The knowledge of structural optimization is gaining ground, and structural designs are improving in terms of both getting lighter and with increased strength. There is no one such approach that can be used to optimize structures. Several theories were proposed and many of them were best of their times and withstood the test of times. For instance, during the 1800s, structures designed by Michell are still being used in the literature as ones of the pioneering designs. The central idea is to reduce costs, increase the structural performance given material, loading and boundary conditions.

Normally, optimization needs lot of computational effort. In those days where there were no computers, people used to design and redesign on paper. The field of structural optimization went cold for several decades during the mid 19th century. With the advent of computers during the latter half of 1950's, slowly the field began to gain some ground. With the increasing computational power being available at lower prices, more and more people began to contribute to this field of study, structural optimization. The computers play a vital role in both, computing and designing the optimum structural design for a given set of conditions. Structural optimization is the way of making an assemblage sustains loads. For instance, think of a situation where load is to be transmitted from a region in space to a support. One has to perform an optimization to design a structure that performs the load transmission in an efficient way using a lighter structure which is safe as well. Along with the weight, there can also be other constraints such as stresses, displacements and/or geometry.

There are three major components for any structural optimization problem. They are:

1. Formulation of a mathematical model,
2. Representation, and
3. Optimization method.

In addition to the above, one can also consider economy, aesthetics, functionality and following is a brief discussion of these [5]:

Functionality

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The main intended purpose of the structure. Say, a bridge, one needs to know how long, how many lanes, loading expected.

Conceptual Design
In addition to the functionality, one also needs to know what type of bridge; a truss bridge, a suspension bridge, or an arch bridge.

Optimization
The next step would be the optimization step, wherein within the chosen type one has to design the bridge within the constraints for low cost and least material.

Further Details
They can include aesthetics, social factors etc.
Repeat the process iteratively until a design satisfying the constraints is converged. Using a computer based finite element method, can help to develop an optimum design in an effective way [6]. The optimum design of a structure has to satisfy these and also at the minimum cost as well. Simply said, the mathematical formulation of all the measurable factors in an optimization problem for designing an optimum structure whose main task is to carry loads by satisfying all the constraints can be termed as structural optimization [5].
Mathematically, an optimization problem consists of:

- **Objective Function (f)**
A function useful to classify a design for every possible value of f, indicates the level of acceptability of design. f can be a measure of the weight.
- **Design Variable (x)**
It is a vector/function to represent a choice of material or geometry which can be altered during an optimization process.
- **State Variable (y)**
For a given x, y is a function that represents the response of the structure. A general form can be minimize f(x, y) subject to design constraints f(x), behavioural constraints y (such as displacements), and equilibrium constraints.

After the hallmark paper of AGM Michell in 1904, structural optimization took a new beginning. The field of optimization went cold during the mid 1900's. With the advent of computers in the 1960s, the field of optimization gained momentum. This area of research is about 50 odd years old, fairly newer field of research compared with the other areas of civil engineering. John Holland proposed Genetic algorithms in the year 1975. The field of optimization rejuvenated and several researchers have proposed optimization algorithms during these many years and following is the brief list of a few of them [7].

Table: History of the Optimisation Algorithms

Number	Year	Algorithms since 1975
1	1975	Holland proposed Genetic Algorithms (GA)
2	1977	Glover proposed Scatter Search (SS)
3	1980	Smith genetic programming
4	1983	Kirk Patrick's Simulated Annealing (SA)
5	1986	Glover and McMillan offered Tabu Search (TS)
6	1986	Farmer *et al*. suggested the Artificial Immune System (AIS)
7	1988	Koza registered first patent on Genetic Programming
8	1989	Evolver provided the first Optimization Software using GA
9	1989	Moscate presented Memetic Algorithm
10	1992	Dorigo proposed Ant Colony Optimization (ACO)
11	1993	Fonseca and Flemming provided Multi Objective GA
12	1994	Battiti and Tecchiolli introduced Reactive Search Optimization
13	1995	Kennedy and Eberhardt proposed PSO
14	1997	Storn and Price proposed Differential Evolution
15	1997	Rubenstien presented Cross Entropy Method
16	1999	Tillard and Voss proposed POPMUSIC

Number	Year	Algorithms since 1975
17	2000	Snyman Leap Frog Algorithm
18	2001	Geem provided Harmony Search
19	2001	Hansetha and Aanestad offered Bootstrap Algorithm
20	2004	Nakrani and Tovey presented Bees Optimization
21	2005	Krishnanand and Ghose introduced Glow Worm Optimization
22	2005	Karaboga proposed Artificial Bee Colony Algorithm
23	2006	Haddad *et al*. proposed Honey Bee Mating Optimization
24	2007	Hamed Shah Hosseini offered Intelligent Water Drops
25	2007	Atashpaz *et al*. introduced Imperialist Competitive Algorithm
26	2008	Yang presented Firefly Algorithm
27	2008	Mucherino Seref suggested Monkey Search
28	2009	Husseinzadeh provided League Championship Algorithm
29	2009	Rashedi *et al*. introduced Gravitational Search Algorithm
30	2009	Yang and Deb offered Cuckoo Search
31	2010	Yang developed Bat Algorithm
32	2010	Kaveh proposed Charged Search System,
33	2011	Shah Hosseini introduced Galaxy based Search
34	2011	Tamura and Yasuda designed Spiral Optimization
35	2011	Rao *et al.* presented Teaching Learning based Optimization
36	2012	Gandomi proposed Krill Herd Algorithm
37	2012	Civicioglu introduced Differential Search Algorithm
38	2014	Kaveh Magnetic Search System
39	2016	Kaveh proposed Evaporation Algorithm
40	2016	Chandrasekhar proposed Aqua Search Algorithm for Continuum Structures

TERMINOLOGY

Move

A move is counted when one particle I moves towards the particle J with lower weight [8]. One move requires two FE computations. One iteration completes when all the individuals move towards the other individuals with lower weight. One run has several iterations. A finite element program developed in C++ is used for performing topology optimization [6].

Seed Element

Elements with supports or carrying the load will have material at all times during the optimization. The density of the elements is made equal to one.

Stress Based Proportioning [9]

The distribution of material is done based on the stress carried by the element. In other words, the element carrying more stress will be having a higher density value and the element having lower stress will have a lower density value. The density is computed as follows:

$$Relative\ Density = \frac{maximum\ principal\ stress\ carried\ by\ the\ element}{maximum\ principal\ stress\ carried\ by\ the\ structure}$$

The density value varies in the interval of [0 1]. This should ensure that the material distribution is done efficiently by identifying the elements which can carry material and the newer configuration of material distribution in the structure can be effectively used to safely transmit the loads.

Objective Function

The objective is to find the minimum weight of the structure subjected to the constraint on the amount of material used and the stresses in the structure [10].

$$f = \left(\sum_{i=1}^{n} \rho_i v_i\right) * \bar{\rho}$$

Where, ρ_i is the density parameter of the element, v_i is the volume of the element, and $\bar{\rho}$ is the density of the material subjected to:

$$M * v - \left(\sum_{i=1}^{n} \rho_i v_i\right) \geq 0$$

Where, M is the allowable material in percentage, and v is the volume of the structure subjected to:

Stress $\sigma_{ij} \leq \sigma_{allow} \quad i = 1, 2, 3 \;\; j = 1, 2, 3$

Subjected to
Principal stress $\sigma_i \leq \sigma_{allow} \quad i = 1,2,3$

Solid Isotropic Material with Penalization (SIMP)
The Youngs Modulus of the elements having the intermediate densities are penalized using the Bendsoe SIMP law [11].

Aqua Search (AS)
Inside the deep sea, it is completely dark and the diver has to search based on a set of criteria namely the interaction of the diver with the base above using a GPS device, his instinct and visibility as well. Alike other metaheuristic algorithms, this algorithm has quite a few parameters. A group of divers are performing the search operation. The diver takes into account the information from the base station, intuition and field conditions such as visibility [2].

Representation [12]
Coding/representation of structures has been an interesting topic over the last few decades. Coding plays a vital role in finding the optimal solution to the optimal structural configuration. Several theories have been proposed by many researchers, yet, this area remains unexplored. This area of study has enough room for innovative representation techniques for the optimization of truss structures. These coding schema along with evolutionary algorithms such as genetic algorithms have been widely used to solve topology optimization of structures.

OPTIMISATION PROCESS [12]

The optimization is done using Aqua search algorithm and two finite element analysis (FEA) approach. In the first FEA, the stress values are computed for each element at the centroid of each element. The stress values are checked with the permissible stresses, the principal stresses are computed as the eigen values of the stress matrix. Error component can be calculated if the stress values exceed the permissible stress.

This step should identify all the elements that can carry material during the second FEA. If the stresses are below the lower cut off, i.e., the minimum stress, these elements will be assigned the relative density value as 1e-5. The relative density for seed element is always made equal to 1, for these elements shall carry material at all times during the entire process of optimization. Connectivity check is done, after which the newer values of relative density are assigned for each element.

In case the connectivity analysis does not contain any output, then the original point is retained. During the second FEA, the elements having relative density higher than the minimum cut off value are assigned the value of 1, and all the other elements are assigned a value of 1e-5.

In reality, as there is no change in thickness of the element, the relative density of all the elements having the relative density above the minimum is taken as 1, to depict the reality. The second FEA is done to verify the stress of each element at all Gauss points and centroid to be below the permissible stress limits.

In order to analyze the response of the structure at a finer level, one way is to discretise the continuum into a finer mesh which means higher number of elements and finite element analysis could be prohibitively expensive, one other better way is to compute the stresses at different locations within the element. The objective function is the weight of the structure calculated using the weight density times volume of the structure. This process is iterative and until the minimum weight of the structure is reached satisfying all the constraints.

A CANTILEVER PLATE CARRYING A POINT LOAD AT THE CORNER

A cantilever plate of size 0.16x0.10 and 0.001 thick is fixed on the left edge and is free on the right side. It carries a load of 3000 at the bottom corner on the right side. The modulus of elasticity of the material is 200×10^9 and the Poisson ratio is 0.33. The maximum permissible stress is 200×10^6. The domain is discretized using four noded quadrilateral elements in plane stress condition. The number of elements is 640 and the number of nodes is 693. The objective is to find the distribution of material having minimum weight subject to the constraints. Aqua search optimization algorithm is used to optimize the distribution of the material in the design domain. Figure 1 shows the screen shot of the iteration wise minimum weight using one search engine. Figure 2 shows the screen shot of the iteration wise minimum weight using two search engines exploring the domain simultaneously. The results clearly show that multi population search can identify a better minimum in a narrow search space as well. Table 1 shows the comparison of results using one search

```
Reading the element table
Finished reading the element table
Reading the material table
Finished reading the material table
Reading the geometry table
Finished reading the geometry table
Reading the elements
Finished reading the elements
Reading the boundary conditions
Finished reading the boundary conditions
Reading the forces
Finished reading the forces
Reading the Stress data
Finished reading the Stress data
Reading the analysis options
Finished reading the analysis option
inside newEq
LinearStaticSkylineSym

 iGEn 1 count   247
0.0221084 0

 iGEn 2 count   250
0.0118788 0

 iGEn 3 count   315
0.0108055 0

 iGEn 4 count   400
0.00936542 0

 iGEn 5 count   417
0.00936542 0

 iGEn 6 count   438
0.00936542 0
```

Fig. 1: *One Engine with Aqua Search Optimization Algorithm.*

engine and two search engines. The number of computations required while using Aqua search with one engine is about 1212 compared with the number of computations required while using Aqua search with two search engines is 1730. The computational effort required for two engines is comparatively lower than the effort required when using one search engine. The pop size is taken as 30 for each engine.

Table 1: *The Comparison of Results with Single Engine and Two Engines.*

	AS with One Engine	AS with Two Engines
Minimum Weight	0.00936542	0.00908712
Number of FE Computations	1212	1730
Pop Size	30	30 each

```
Reading the element table
Finished reading the element table
Reading the material table
Finished reading the material table
Reading the geometry table
Finished reading the geometry table
Reading the elements
Finished reading the elements
Reading the boundary conditions
Finished reading the boundary conditions
Reading the forces
Finished reading the forces
Reading the Stress data
Finished reading the Stress data
Reading the analysis options
Finished reading the analysis option
inside newEq
LinearStaticSkylineSym

 iGEn 1 count   236

 iGEn 1 count   251
0.0237483 0
0.0197588 0

 iGEn 2 count   253

 iGEn 2 count   267
0.0128865 0
0.0134816 0

 iGEn 3 count   382

 iGEn 3 count   341
0.00910463 0
0.00908712 0
```

Fig. 2: *Two Engines with Aqua Search Optimization Algorithm.*

CONCLUSIONS

NP hard problems having complex domains require lot of computational effort to optimize and identify the optimal distribution of material with least weight. Topology sets the direction to the overall picture of the distribution of material. The entire process of optimization can be optimized by developing a better algorithm such as Aqua search (AS), improving the C++ programming language which can efficiently use the available computational resources, and finally access to high end performance computing servers which can be quite costly. This paper falls into the category of developing the program to efficiently make use of the available limited hardware resources. This paper presents the use of two search engines unlike the conventional way of using one search engine to perform optimization. The result shows that the computational effort required can be considerably reduced along with the weight of the final distribution.

FUTURE STUDY

Aqua search (AS) can be used along with two search engines to optimize the larger complex domains such as shell structures.

ACKNOWLEDGMENTS

I sincerely thank everyone who helped me complete the paper and review.

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Cite this Article
Chandrasekhar KNV, Sangu Swapna. Multi Population Search Engines for Topology Optimization of Continuum Structures. *Recent Trends in Civil Engineering & Technology*. 2017; 7(1): 17–23p.