Back-tracing Technical Progress with Evolutionary Algorithms

Tino Stanković, Kalman Žiha, Neven Pavković
Faculty of Mechanical Engineering and Naval Architecture, University of Zagreb
Ivana Lučića 5, 10000 Zagreb, Croatia
tino.stankovic@fsb.hr kziha@fsb.hr neven.pavkovic@fsb.hr

Abstract. *This paper investigates the engineering development as an evolutionary process. Therefore it first reveals the benefits of evolutionary algorithms in engineering and considers the evolutionary design. Next it brings a simple analytical model of a common ship hull subjected to service conditions. Finally the optimization in the ship structural design is considered as an evolutionary process tackled by NSGA-II algorithm that is applied in back-tracing of the ship scantling development. The conclusion is that the history of technical development can support comprehension of the role of environment, knowledge, material properties and workmanship in engineering regarding safety, efficiency and manufacturing.*

Keywords. Evolutionary algorithms, genetic algorithms, stiffened panels, ship, aerospace, engineering, evolutionary design, robustness.

1. Introduction

The mankind achieved an astonishing technological development through centuries of innovation, creation and continuous improvement. The history of engineering is the inherent component of the civilization. Moreover, outstandingly important lessons for further development can be studied in the history of engineering. The investigation presented in this paper attempts to find out how the now days complex engineering knowledge, experience, analytical and computational tools may serve to explain the technical progress. For this purpose evolutionary algorithms are tested in order to simulate the developing complexity of engineering reasoning that in reverse direction might back-trace the primitive origins of modern products. The case study in the paper illustrate the back-tracing of the development of the stiffened shells in aerospace and shipbuilding industry to their primitive origins in boats originally made of carved-out log.

2. Evolutionary algorithms

Evolutionary algorithms own their properties and behavior to the process that they are trying to mimic in order to find solution - the natural evolution of living organisms. The solution or the set of solutions to the given problem evolves in time from the feasible solution population by the principle of the survival of the fittest – selection operator, with the fitness function acting as the evolutionary guide. The discreteness of algorithm is devised from its crossover operators, which when generating new solutions, are reusing and mixing together pieces of the past solutions making it very useful when dealing with non continuous problems. Such usage of the past knowledge described by Goldberg in the *Building Block Hypothesis* [1] gives to the algorithm property to converge to desired better solution to a given problem, which ultimately distinguish it from the plain random walk algorithms. More so when adding to the whole process the touch of randomness introduced in the form of mutation operator, the algorithm gains the property to avoid the pitfalls of local optima. Both of these processes, crossover and mutation, have been present in the natural evolution for eons of time. From an algorithms perspective crossover and mutation enable adaptation of the population of feasible solutions to the imposed environment conditions of the search spaces. The recent 15 years have presented a significant number of methods and tools [2] for application in engineering.

The general multi-objective optimization problem in the paper is tackled by the NSGA-II algorithm [3] that is implemented as a dynamic-link library in C# within Microsoft .NET Framework 2.0. to provide a generic multi-objective solver for various optimization models in engineering. NSGA-II for the purposes of this paper generates populations of optimal solutions distributed along the Pareto frontier, using constraint domination condition and constrained tournament selection operator [3].

Normally the design process is structured as a set of cyclic activities put in a logical order to control and guide the procedure until the desired aim is reached [4].

3. Evolutionary design

The design process in this paper is viewed as a shortcut to a satisfying product using knowledge and experience of design modeling in order to accelerate the technical development which naturally should occur evolutionary.

The design process is in clear correlation with the formulation of an algorithm as an iterative problem solving procedure involving a finite number of steps. One could define such a procedure as a search algorithm where the search space itself is built on lists of requirements or design variables and constraints – the problem or design task formulation, and the search for the feasible solution is being conducted by iteration, abstraction, concretization and improvement [4]. All of these four processes are built in core of an evolutionary algorithm. They are iterative – searching for solution during each new generation, abstracting – a common practice in multi-objective optimization where the objectives are put in order by degree of importance and evaluated respectively [8], concretizing – in order not to hinder the process the objectives can be introduced at a desired point in evolution when solutions are evolved enough, improving – by evolving solutions in every generation using selection, crossover and mutation operators. The evolutionary methods may provide enhancement of design process or findings about process itself. Properties of search spaces will depend on complexity of the design aim and could be constrained, multimodal and full of discontinuities. Many applications of evolutionary algorithms in search spaces have been recognized [1], [3], [5], [6].

Various methods enhance design innovation and creativity such as Delphi method, 635 method and synectics [7], [8], or brainstorming that support an unbiased human search for technical solutions. The evolutionary algorithms for this purpose use the form of mutation operator [1], [5] which stochastically alters feasible solutions. Until proved otherwise the evolutionary algorithms are as the natural evolution is still unbiased systems. By using evolutionary design the designer is shaping and adjusting his designs enabling their existence in constraint bounded design space by same principles recurring in natural evolution.

4. The engineering model

The simplified ship hull structure in this case study, see for example a traditional boat in Fig. 1, is modeled as a transversely framed shell of isotropic material under lateral outer pressure p, and longitudinal in-plane stress σ_L [9], Fig. 2, also considering the rules and regulations of classification societies in shipbuilding [10] [11]. The material properties are the elastic modulus E, the Poisson's ratio ν, the allowable normal σ_a and shear τ_a stresses in shell and in framing [10].

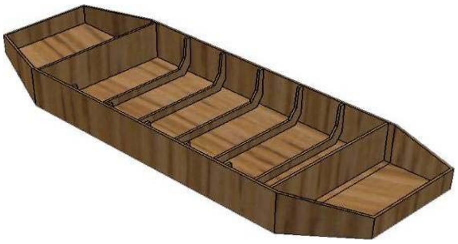

Figure 1. Boat hull structure

The small deflection elastic plate bending theory [9] defines the maximal local stress under lateral pressure p in the middle of the longer edge ℓ in the direction of the shorter edge s in the plating of thickness t clamped at stiffeners, Fig. 2. Using the semi-empirical plate side aspect ratio [9] $k_s = 1 - 0,4\left(\frac{s}{\ell}\right)^2$, the stress in the shell under lateral load p [10], [11] can be assessed as:

$$\sigma_p = 0,5 \cdot p \cdot k_s \cdot \left(\frac{s}{t}\right)^2 \tag{1}$$

The simple elastic beam bending theory [9] defines the normal stresses in frames [11], Fig. 2:

$$\sigma_f = p \cdot k_m \cdot \frac{s\ell^2}{W_{f,e}} \tag{2}$$

The end connection factor for clamped frame ends is k_m=1/12. The elastic section modulus $W_{f,e}$ of a single frame accounts for the width of the effective plate flange. The shear stress at supporting ends of the frame web [9], taking the correction factor c_w=3/2 for rectangular cross sectional area A_f of a flat bar [10] [11] is as shown:

$$\tau_f = \frac{c_w \cdot p \cdot s \cdot \ell}{2A_f} \tag{3}$$

The orthotropic plate elastic bending theory [9] defines the stresses in the edges of the longer side in the direction of the shorter edge, Fig. 1, of the whole transversely stiffened plate as:

$$\sigma_s = K \cdot p \cdot \frac{s \cdot \ell^2 \cdot e}{I_f} \tag{4}$$

In (4), I_f is the frame moment of inertia including effective plating width and e is the distance from the neutral axes to the plating. From Schade's diagrams [9] is K=0.0916 for the edges of the longer side in the direction of the shorter edge and K=0.0627 for the edges of the shorter side.

The critical buckling stress of plating under in-plane compression of plates between frames [9][10][11] using the term $\sigma_{p,e} = \frac{\pi^2 E}{12(1-\nu^2)}$ is:

$$\sigma_{p,c} = \sigma_{p,e} \cdot \left(\frac{t_p}{s}\right)^2 \cdot k_p \cdot k_\sigma \tag{5}$$

For transversely stiffened panels is $k_p = \left[1 + \left(\frac{s}{\ell}\right)^2\right]^2$ and for longitudinally stiffened panels is $k_p = 4$. For elastic buckling is $k_\sigma = 1$ and for plastic buckling is $k_\sigma = 1 - \left(\frac{\sigma_{c,e} - \sigma_y/2}{\sigma_{c,e}}\right)^2$ when $\sigma_{c,e} \geq \sigma_y/2$.

The torsional buckling of flat bar stiffeners prevents the empirical ratio of height to thickness [11] that is normally < 20.

The ultimate bending strength with respect to multimodal plastic failure modes of plates at the mid of the longer edge of unit plate plastic section modulus $W_{p,p} = \frac{t^2}{4}$ between frames under bending moment $M = k_m \cdot p \cdot s^2$ acting due to lateral pressures p combined with in-plane load σ_L, may be expressed by the following interaction formula [11] $\frac{M}{\sigma_y \cdot W_{p,p}} + \frac{1}{\beta}\left(\frac{\sigma_L}{\sigma_y}\right)^2 = \beta$. The usage factor β relates the maximal permissible load to the collapse load. Using the factor $k_{L,p} = \left[\beta - \frac{1}{\beta}\left(\frac{\sigma_L}{\sigma_y}\right)^2\right]$ to represent the influence of the in-plane stress, the ultimate lateral pressure on plating accounting for the yield stress σ_y [11] is as shown:

$$p_{u,p,\sigma} = 3 \cdot \left(\frac{t}{s}\right)^2 \cdot \frac{k_{L,p}}{k_s} \cdot \sigma_y \tag{6}$$

The ultimate bending strength of frames under lateral pressure and axial stress is the capability to prevent the plastic failure defined as a three-hinged mechanism [11]. For frames with plastic section modulus $W_{f,p}$ including the effective plate flange under bending moment $M = k_m \cdot p \cdot s \cdot \ell^2$ due to lateral pressure p and for small axial stresses σ_x (the shear is usually small) the relation derived from (2) holds [11]:

$$p_{f,u,\sigma} = 12 \cdot \frac{W_{f,p}}{s\ell^2} \cdot \varepsilon \cdot \sigma_y \tag{7}$$

where ε is the permissible usage factor [3].

The ultimate lateral pressure on the whole panel viewed as the orthotropic plate (4), is as shown:

$$p_{b,p,\sigma} = \frac{\sigma_y}{K} \cdot \frac{I_f}{s \cdot \ell^2 \cdot e} \tag{8}$$

Since the transverse in-plane compression of bottom plating is normally small, Fig. 1, it is not likely that buckling of plating occurs at all [11].

5. The optimization model

The model is a ship hull panel of thickness t, length ℓ, width b which is transversely stiffened by n flat bars of thickness t_w and height h_w at spacing s, Fig. 2. The plate is laterally loaded by pressure p and with in-plane stress σ_L.

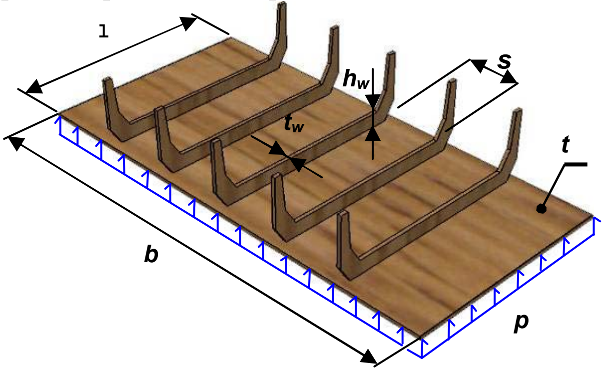

Figure 2. Panel structural model

The evolutionary design in the paper uses the engineering model from section 4 in order to demonstrate the technical development by employing genetic algorithms aspired with achievement of appropriate safety level as well as with reduction of weight, expenses and production efforts using different materials.

Therefore the stiffened panel design of the case study is defined as a general non-linear mathematical programming model of the appropriate ship structure built of the material characterized by material coefficient k and 1 density ρ following section 4 as follows:

- parameters: $p, \ell, b, k, \rho, \sigma_y, \sigma_f, \sigma_s, \tau_s$
- variables: n, t, t_w, h_w

Design goals are the minimization of panel mass m, the minimization of number of transversely stiffening flat bars n which expresses in a simple way the complexity of design or workmanship expenses and finally the minimization of standard deviation of ultimate load carrying capacity taken as a measures of robustness [12] st.dev.($p_{u,p,\sigma}$, $p_{f,p,\sigma}$, $p_{b,p,\sigma}$).

The later encapsulates the robustness of design by leveling out the safety apprehended as the maximum lateral pressure that the whole panel and its structural members – plate and stiffeners can withstand [12].

Finally the design problem is formulated as:

$$\left.\begin{array}{l}
\min\left[m(n,k,t,t_w,h_w,\ell,\rho)\right],\\
\min\left[n\right],\\
\min\left[st.dev.(p_{u,p,\sigma},p_{f,p,\sigma},p_{b,p,\sigma})\right],\\
\text{subject to:}\\
\quad W \geq W_{\min}(p,k_m,n,\ell,b,\sigma_{f,a}),\\
\quad t \geq t_{\min}(p,k_u,n,p_{u,p,\sigma},k,\sigma_{p,a}),\\
\quad t \geq 2\ mm,\\
\quad \sigma \leq \dfrac{\sigma_y}{k} \equiv \dfrac{235}{k},\\
\quad t_w \cdot h_w \geq A_f(p,n,k,\tau_{f,a}),\\
\quad \min\left[p_{u,p,\sigma},p_{f,p,\sigma},p_{b,p,\sigma}\right] \geq p,\\
\quad t_w / h_w \leq 20,\\
\quad t_w / h_w \geq 10.
\end{array}\right\} \qquad (11)$$

At the beginning hard constraints can hinder the evolutionary process since the majority of the early solutions are infeasible. Consequently, by measuring constraint violations one can rank infeasible solutions. Later that ranking is added to Pareto frontier of feasible population [3]. Constraint violation measure $\Omega(x^{(i)})$ of $i-th$ solution $x^{(i)}$ is derived as summation of normalized violations $\omega_j(x^{(i)})$ (12) [3]:

$$\Omega(x^{(i)}) = \sum_{j=1}^{8} R_j \omega_j (x^{(i)}) \qquad (12)$$

No violations were favored so the weighting factor used is $R = 1$ for all j.

For encoding of chromosomes binary strings were used. Every chromosome consists of four genes which comprise four design variables of the ship hull panel. In addition for the refinement of search the Gray coding was applied [7].

Table 1. The chromosome structure

Design variable	t	n	h_w	t_w
The gene number	*1*	*2*	*3*	*4*
Available strings per gene	*10*	*10*	*10*	*10*
Maximum value attainable after mapping [mm]	*130*	*200*	*430*	*20*

The emergence of new genes 2, 3, and 4, Table 1, for number of frames, thickness and height of the frame web opens potentials for development of plates stiffened by flat bars. These four characteristics together with the problem parameters define all the other panel properties.

Since the evolution was carried through fixed length chromosomes then the length of the individual genes is also a limitation - constraint put upon the search space, that guide evolution towards reasonable solutions and hopefully speed up the overall search process, Table 1.

Control parameters of the applied NSGA-II algorithm [3] were as follows:

- population size $\lambda = 60$,
- offspring population $\mu = \lambda$,
- uniform crossover [6] - probability $p_c = 1$.
- bit flip mutation probability $p_m = 1/l \cong 0.026$[6].

6. The results of evolutionary algorithms

The genetic algorithm tackles the design of the stiffened plate of a contemporary steel ship transversely stiffened panel structure, Fig. 3, of breadth b=28,8 m, length ℓ =5,17 m under lateral pressure of p=0.1 N/m^2 according to design loads defined by classification rules [10] using potentials of all the genes, Table 1.

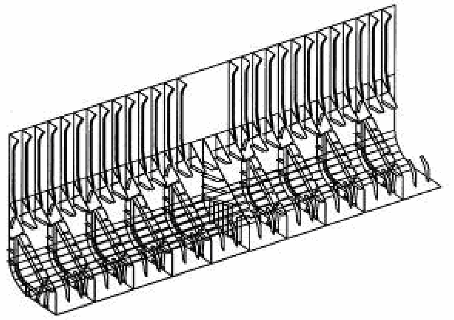

Fig. 3. The modern ship hull side structure

The computation results of one out of many iterative trials with repeatable outcomes on standard personal computers are presented as the 3-D Pareto frontier plot *n-m-st.dev.*, Fig. 4.

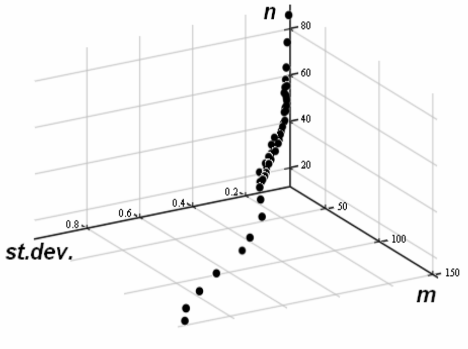

Figure 4. 3-D Pareto frontier plot

After the full gene potential of chromosome, Table 1, is being unleashed more up to date solutions evolved. The obtained results after 8000 iterations are plotted on Figs. 4. – 7.

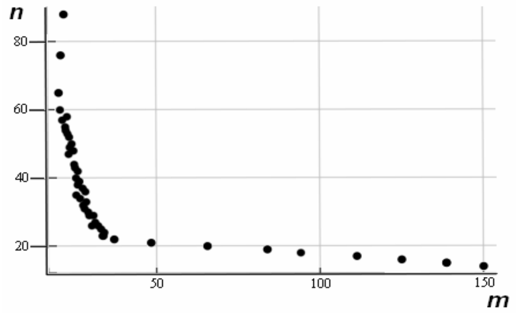

Figure 5. *n-m* plot

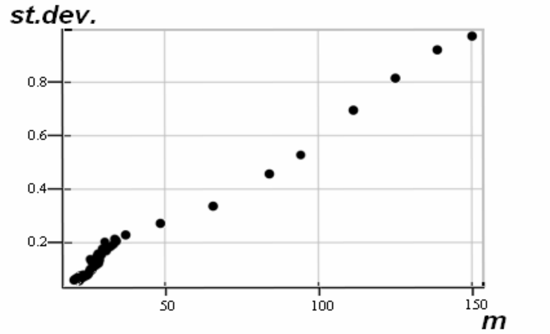

Figure 6. *st.dev.-m* plot

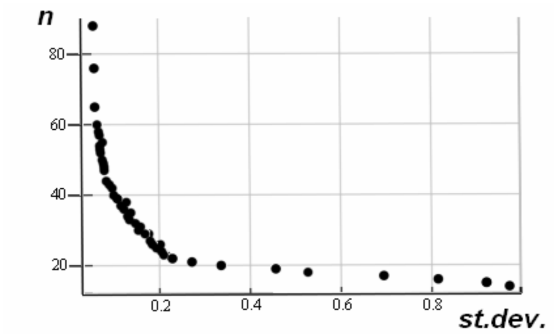

Figure 7. *st.dev.-n* plot

7. The result interpretations

The aim of the illustrative example is to interpret the optimization results obtained by evolutionary algorithm as the effects of social and environmental conditions on the development of technical structures. It is comprehensible on one hand, Fig. 5, how the expensive workmanship related to the number of stiffeners irrespective to the material expenses and other technical requirements may yield to preferable solutions of thicker plates with smaller number of stiffeners, even simple plates without stiffeners, regardless of the overall mass of the panel. On the other hand, the socio-environmental condition of expensive material or technical request for light structures irrespective to the workmanship expenses leads to solution of thinner plates with greater number of stiffeners. For highly efficient light-weight structures when the material and workmanship expenses are irrelevant, just the minimal mass, thinner plates with a greater number of stiffeners of higher class material are preferable.

The mathematical model in the paper incorporates the assumption of the importance of robustness when the environmental conditions imply uncertainties. The robustness is considered as the minimal variation among safety measures of different failure modes [12] (inter frame plate bending (6), frame bending (7), overall panel yield (8) and effect of shear stresses (3)). In Fig. 6 it is shown how the request for maximum robustness (minimal standard deviation of safety measures) in this example leads to solution of minimal mass panel that satisfies the prescribed safety level. Moreover the increase of robustness followed by diminution of mass is affordable only by significant increase in workmanship efforts due to large number of built-in stiffeners, Fig. 7.

Implementing the ancient conditions of expensive (unavailable) material (except for example wood) and tough workmanship (no experience and tools available) into the mathematical model the solutions points to least expensive plane plate, Fig. 5, without stiffening as the primitive carved-out logs, Fig. 8.

Fig. 8. The primitive boat structure

Finally, the contemporary engineering model in section 4 resulting in four genes, Table 1, in the last run degenerates to the one single primitive gene number 1, having the plate thickness for the only property. The design model is used in its most degenerative form appropriate to early days of shipbuilding and lack of engineering knowledge and experience. As a final consequence, the mathematical model points to un-stiffened 125 millimeter thick plating, Fig. 8, as the least workmanship demanding solution although inappropriate for now days practice.

The only affordable outcome of one primitive gene is the simple un-stiffened plate of minimal thickness appropriate to ancient conditions for carved-out logs that satisfies the past and modern safety requirements, Fig 9**.**

Figure 9. Carved-out log

8. Conclusion

The evolutionary design supports normally the contemporary progressive engineering reasoning aspired with achievement of highly efficient products providing socially acceptable safety levels and appropriately lower costs by employing genetic algorithms. However, it is investigated in the paper how the reverse process to the technical progress can reconstruct the origins of contemporary products using evolutionary algorithms on engineering models in two manners. The simplest way is the replication of primitive conditions, such as for example lack of experience, unavailability of appropriate material and technology. Introduction of past conditions into up to date mathematical models corroborates early solutions based on past engineering practice. Reconstruction of past social and environmental conditions may lead to primitive solutions appropriate to early human's engineering but it does not characterize only the evolutionary algorithms. Another way is the simplification or degeneration of the design model that is in terms of genetic algorithms, deactivating or removing more complex genes from the chromosomes that might be viewed as a particular feature of evolutionary algorithms.

Evolutionary design approach upholds that the technical progress goes on if the existing gene potentials are activated or the new evolutionary potentials based on additional knowledge are introduced.

However, the optimization search by genetic algorithms may be viewed as time-condensed best-practice that in reverse order can back-trace the engineering development either by replicating past condition or by omission of chromosomes introduced into evolutionary models by growth of engineering experience.

References

[1] Goldberg, D. E. Genetic Algorithms in Search Optimization and Machine Learning, Addison Wesley Longman Inc, 1989.

[2] Tan K.C., Lee T.H. and Khor E.F. Evolutionary Algorithms for Multi-Objective Optimization: Performance Assessments and Comparisons, Artificial Intelligence Review 2002; 17: 253–290, Kluwer Academic Publishers,.

[3] Deb, K. Multi-Objective Optimization using Evolutionary Algorithms, John Wiley & Sons Ltd, England; 2001.

[4] Hubka, V., Eder, W. E. Engineering Design: General Procedural Model of engineering Design, Springer-Verlag Berlin Heidelberg; 1992.

[5] Bentley, P. Evolutionary Design by Computers, Morgan Kaufmann; 1999.

[6] Bäck T., Fogel D. B., Michalewicz Z. Evolutionary Computation, Advanced Algorithms and Operators, Institute of Physics Publishing, Bristol and Philadelphia; 2000.

[7] Pahl, G. and Beitz, W. Engineering Design – A Systematic Approach, Springer Verlag; 1988.

[8] Wood, K.L. and Otto, K.N. Product Design Techniques in Reverse Engineering, Systematic design, and New Product Development, Pren-tice-Hall, NY; 1999.

[9] Hughes, O. Rational Ship Structural Design, SNAME, New Jersey; 1972.

[10] CRS: Rules for the Classification of Sea-Going Ships-Part 2 Hull, Croatian Register of Shipping, Split; 2006.

[11] DNV: Ship' Load and Strength Manual, Det Norske Veritas, Hovik; 1978.

[12] Žiha, K.: Redundancy and Robustness of Systems of Events, Probabilistic Eng. Mechanics, Vol. 15, 2000, pp. 347-357.