Proceedings of the 7th WSEAS International Conference on Evolutionary Computing, Cavtat, Croatia, June 12-14, 2006 (pp1-6)

Design Optimization with GA Fitness Functions based on Total Lifecycle Value or Cost

DAMIR VUČINA, ŽELJAN LOZINA
FESB, Faculty of Electrical Engineering, Mechanical
Engineering and Naval Architecture
University of Split,
R. Boskovica bb, 21000 Split,
CROATIA
Web page: www.fesb.hr

Abstract: The decision making process in multicriterial optimization problems is in many cases based on the a-priori articulation of the compromise integral criterion based on preferences which are frequently of rather intuitive nature. This reduces the comprehensive search for the Pareto front to simpler single-criterion optimization.
In this paper, this approach is followed in a specific manner. Instead of the rather arbitrary setting of weight factors in a weighted sum of partial objectives, or compromise selection using the min-max concept related to distance to utopia optima, a lifetime-cost-based integral criterion is used.
The GA fitness function is based on the total-lifespan-value aggregate optimality criterion. All nonrecurring investment costs (eg. production costs, mass of material) and recurring operational expenses (maintenance, labour) are discounted accordingly and aggregated into a combined best-compromise fitness metric based on the net present value (NPV) and/or internal rate of return (IRR), which construct the overall fitness function. This approach allows for coupled engineering & financial optimization which approximates real-world decision making.

Key- Words: GA design optimization, total lifespan cost, a-priori compromise formulation

1 Introduction

In many cases, design optimization is focused on physical criteria that minimize the investment cost, such as minimum mass or similar physical metrics. In other cases, design criteria may include technical performance criteria of the product.

On the other side, traditionally, project evaluation in the business environment [9] implies the integral estimation of the project performance over the respective lifecycle which includes both non-recurring investment-related and recurring operation-related elements. This is done by discounting and cumulating all elements in terms of their respective equivalent economic values into a single integral measure. An assessment based on the total net value approach or total cost of operation is usually pursued in the process of project feasibility analysis, more specifically the methodology of project appraisal.

In multiobjective optimization, excellence is measured by several criteria for which there is no simultaneous optimum in the design variables space. One of the approaches in such cases are compromise formulations that determine trade-offs that the decision makers assume to faithfully model the overall design excellence. Recently, there has been much attention in combining multiple criteria in compromise formulations. The total project appraisal framework is given in [9], while [8] provides a specific example of real value metrics in aircraft design and operation. References [2], [3], [4] provide insight into many of the approaches in decision making with multiple criteria, [6] discusses the robust design approach with variable operating points.

The goal here is to capture the total value or cost in fitness functions of the designs and to expand the MDO into coupled engineering and financial terms, bringing the (a-priori) decision making compromise closer to reality. The argument is here illustrated with very simple examples.

2 Problem formulation

In this paper, such an approach is applied in the context of optimum design. While the design optimization problem is modelled in standard technical terms, the objectives and the GA fitness functions are modelled in the 'expanded space' of equivalent economic terms. This approach inherently also allows for compromise single- objective formulations for problems with multicriterial definition of excellence, in cases where the individual criteria can be expressed in terms of respective equivalent value.

In fact, proper modelling of respective economic impact could allow that even complex and diverse terms be attributed equivalent economic values. For example, designing a vehicle based on individually contributing excellence criteria such as (1) low price, (2) high safety, (3) high reliability, (4) low operational and ownership costs, (5) high performance and (6) other criteria, could to a certain degree be formulated in such a life-span value-based fashion. While the quantitative values of some of the criteria (1)-(6) fully or partly depend directly on the technical design variables, some of the equivalent values additionally depend on intangible categories such as 'environment conditions external to the project (design)', market conditions, customer perception of the product, and similar elements. However, the latter values (partly, less directly, and in a less measureable way) also may be represented in (empirical) dependence on the design variables.

Full economic modelling of total lifetime value adds to the engineering nonlinearity of the optimization model in several ways: discounting of values, discontinuous stepwise taxation, amortization models, financing costs and interests, stepwise engagement of resources (equipment, labour, ..), definition of IRR, delays in business cycle, demand & pricing, etc.

In this paper, however, only very simple cases with non-recurring investment costs (1) and recurring operational costs (4) are considered. A corresponding fitness function is therefore constructed to encompass the integral lifecycle cost, which is numerically implemented by means of the net present value (NPV) and the internal rate of return (IRR) .

In such a capacity, the NPV- IRR fitness criterion depends both on the engineering design variables, but also on the parameters of the business environment and the product's interaction with the environment, such as product life-span, discounting rate and operational costs. Beyond the standard generic design parametrization as part of the process of modelling for optimization, several other elements need to be included if the objective (or fitness) function is to be constructed in line with the IRR definition.

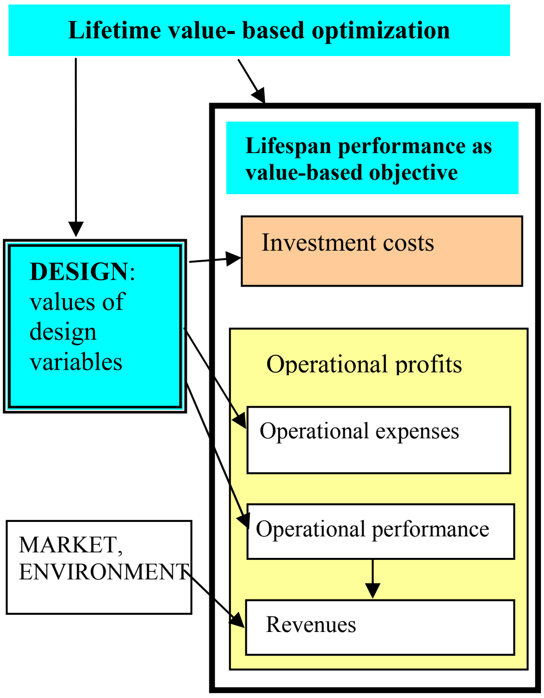


Fig.1, Lifetime value fitness composition

The above model obviously implies an expansion beyond the standard optimization models but consequently yields more realistic optima. Due to the impact of circumstances external to the project which define the project environment and the market conditions, empiricial and probabilistic modelling could also partly be employed to reflect uncertainty.

The 'investment cost' category includes mainly the non-recurring items such as expenditure of material, production cost, set-up costs, complete product development, etc. These elements depend on the design variables in the standard way.
The recurring 'operational profits' category measures the revenue-related performance of the project and

also depends on the current design characteristics captured in items such as corresponding maintenance costs, operations costs, indirect costs, cost of work, etc. In general, it also includes elements such as depreciation of equipment, cost of financing, etc, all of which is usually given in periodic terms. However, beyond the design variables, the operational profits also depend on the changing parameters of the project environment and the market.

All these elements are properly discounted and aggregated to give an integral value-based measure of optimality, which, in form of NPV and/or IRR formulates the fitness function in the given examples.

The internal rate of return is a scalar measure defined as the discount rate that drives the value of the net present value of the project to zero. The net present value is the equivalent cumulative economic potential of all project events discounted to the initial moment of the project lifecycle. The project events generally include investments, revenues, costs, etc. In the more general sense, it simultaneously accounts for the 'manufacturing' costs and 'operational' expenses, both depending on the design variables, hence the resulting total project value is measured. This is in line with the spirit of the optimization objectives.

The examples included are simplified with respect to the above more general model to merely illustrate the concept and some consequences on the optimal designs. The market impact is neglected and the revenue aspect disregarded. In the simplest form, only the total lifetime cost is formulated to include the discounted investment costs and operational (ownership) expenses only, which is then minimized. This makes it possible to optimize a technical problem based on economic criteria which is a realistic viewpoint.

The net present value [9] is defined based on net economic flows E_N and discounting rate d as

$$NPV = \sum_{i=0}^{n} \frac{E_N(i)}{(1+d)^i} \quad (1)$$

and the internal rate of return as the discounting rate d such that

$$NPV(d) = \sum_{i=0}^{n} \frac{E_N(i)}{(1+d)^i} = 0 \quad (2)$$

The NPV / IRR based integral fitness criterion can in some cases also be applied to multiobjective optimization problems, in particular those where the individual criteria can equivalently be expressed by corresponding value or cost terms by econo-metric modelling. In such cases the NPV / IRR based fitness formulation reduces the multicriterial problem to a lifetime-value best-compromise combined criterion which constructs the fitness function. In such capacity it acts similarly to a utility function or acceptability function. This can also be applied to some robust optimization problems where the NPV metrics can be evaluated on the given distribution of operating regimes in the total product lifespan.

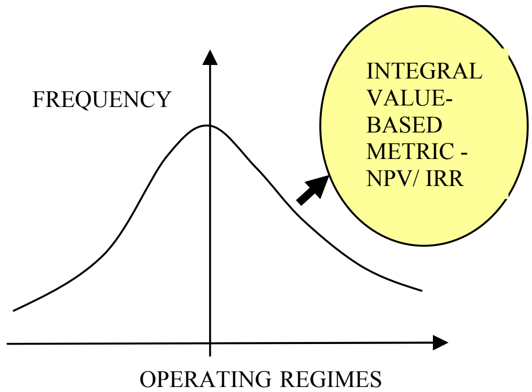


Fig.2, Variable operating conditions

Based on economic considerations (NPV), in the case in Fig.2, minimization of the respective aggregate economic impact during the entire lifespan provides the compromise fitness formulation.

3. Simple illustrative examples

As a simple example, one can consider the problem of the optimal design of a beam:

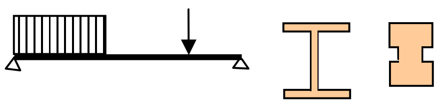


Fig.3, Designs of a beam optimized for different excellence criteria

under stress constraints

$$\max \{\sigma(M_y / W_y)\} \leq \sigma_{dop} \quad (3)$$

and dimensional constraints. If the cross-section shapes were to be optimized for minimum mass of material (minimum investment cost) then the cross-sectional area would be the fitness criterion. If the operational maintenance costs would have to be minimized, then the length of the contour would construct the fitness function.

With the equivalent lifespan value approach to fitness function construction, the best-compromise criterion would combine the investment costs and operating costs into a single fitness descriptor. In the simplified case with disregarded revenue-related items, the fitness is based on the total cost of operation based on the NPV / IRR metrics including cost elements only.

The beam is optimized for the criteria of minimum lifecycle costs based on the NPV / IRR measures in (1) and (2). The constraints of permissible stresses under bending and dimensional ratios are simply implemented by penalizing the corresponding terms. Standard GA optimization is performed in MATLAB with fitness functions constructed according to the above expressions.

Several variations of parameters in the NPV/ IRR based formulation of the GA fitness function were carried out for illustration. Firstly, the cost coefficient ratio of material cost versus maintenance cost was gradually decreased. In the NPV/ IRR fitness function this has led to a decrease of contour length (proportional to maintenance costs) and increase in cross-sectional area (material costs), as illustrated in Fig. 4.

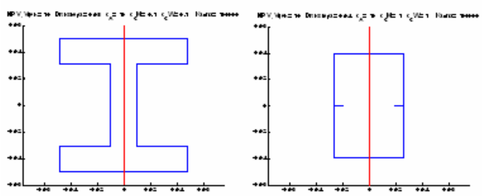


Fig. 4, Beam optimized for NPV / IRR total lifespan value, increasing operational costs

The second variation, shown in Fig.5, presents the impact of decreasing the value of the discounting rate in the NPV expression which increases the fitness of those GA population members which code beams with larger cross-sectional area and smaller contour length. This happens because the maintenance costs in later years in the lifetime become more significant due to weaker discounting.

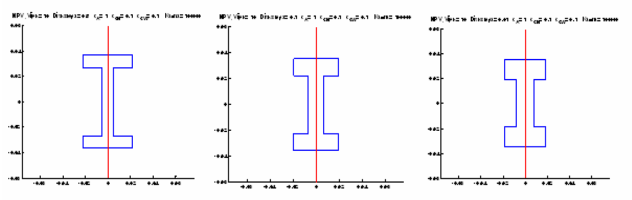


Fig. 5, Beam optimized for NPV / IRR total lifespan value, decreasing discounting rate

The third variation presented here is increasing the economic lifespan of the beams, and other parameters in overall fitness held fixed. This leads to increased impact of the maintenance terms (contour) in the overall fitness and increased GA selection of beams with shorter contours.

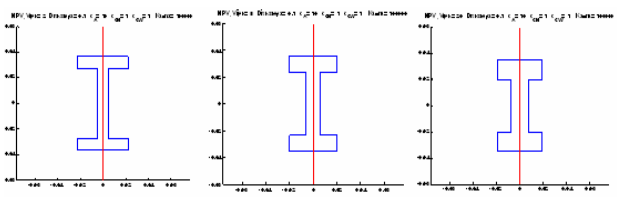


Fig. 6, Beam optimized for NPV / IRR total lifespan value, increasing lifetime

This simple example is presented in order to illustrate the impact of the change of some basic economic parameters on the optimal shape of the otherwise engineering problem.

Another simple example selected here for the illustration of the IRR-based optimality (fitness function) formulation is a rotating system consisting of a hollow shaft (design variables d_1 and d_2) and discrete rotating masses (Fig.7). The system is subject to penalized constraints related to allowable torsional stresses, dimensional ratios and resonance.

The shaft is subject to constraints of sufficient static torsional stiffness

$$\frac{M}{I_p}\cdot\frac{d_1}{2}\le\tau_{\max} \qquad (4)$$

and the requirement that none of the (design-dependent) eigenfrequencies may exist within the ± 20% band around the excitation frequency Ω .

Given values: masses and radii m_1=50 kg, r_1=0.2 m, m_2=75 kg, r_2=0.25 m, m_3=100 kg, r_3=0.3 m, length l=0.5 m, modulus G=80 GPa, permissible stress τ_{max}=50 MPa, moment M=212 Nm, rotational speed n=650 rev/min . Dimensional ratio: $d_1/d_2 \geq 1.5$

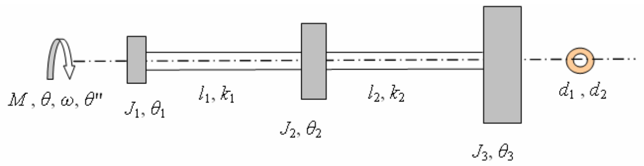


Fig.7, Simple rotating system

When the fitness function is constructed based on minimum mass of shaft only

$$f = d_1^2 - d_2^2 \qquad (5)$$

the following results are obtained:

$[\ d_1 \ \ d_2\ ] = [0.0327 \quad 0.0218]$

in the constrained domain as in Fig.8.

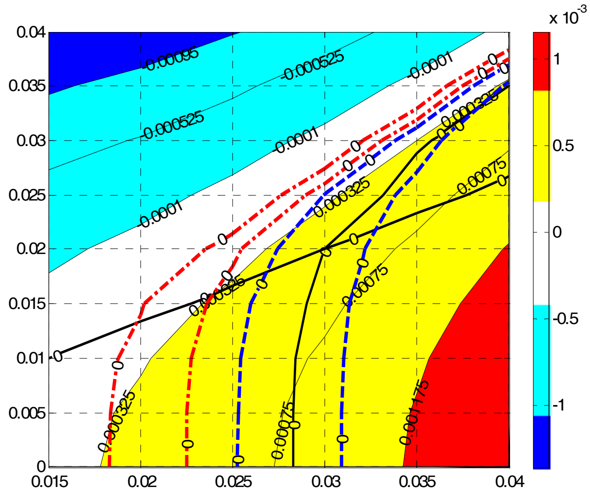


Fig.8, Constraints for problem in Fig.7

Alternatively, the fitness with superimposed penalties for the constraints can be visualized as:

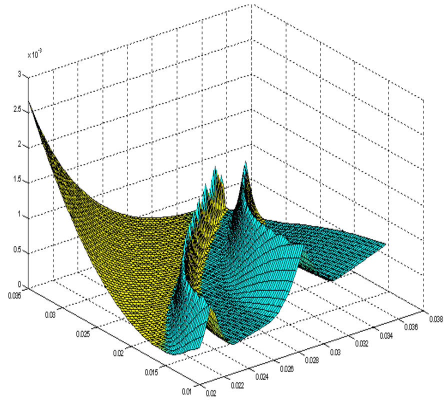


Fig.9, Penalized objective function (fitness) for problem in Fig.7

Variations of the optimization problem are now carried out in the sense that the minimum mass (investment term) is combined with the maintenance cost (operational term proportional to the outer surface) in the NPV / IRR based overall total cost fitness. The following change in the optimal dimensions is obtained:

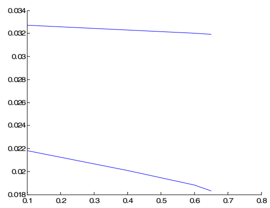


Fig.10, Change in optimal dimensions d_1 , d_2 of the shaft due to increased operational cost in NPV

Another example under consideration with the NPV / IRR total-cost based fitness definition is that of the optimum design of metal sandwich plates:

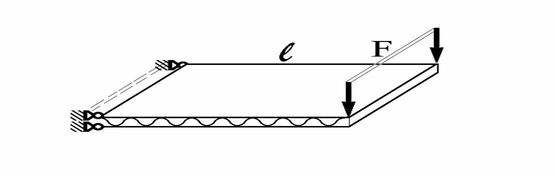
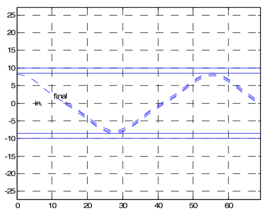


Fig.11, Optimum design problem of metal sandwich plate with shape parametrization

where the design freedom includes the thicknesses and variables in shape parametrization of the cores.
In this case, the total lifecycle cost as the compromise optimality criterion needs to include the investment costs such as material cost of metal sheets, glue (bonds), production costs, as well as the

recurring maintenance and periodic inspection costs. In the simplified case, only the nonrecurring material cost of the metal and recurring cost of maintenance & inspection proportional to total surface area are included for demonstration of the concept. The constraints include (1) structural strength and local buckling resistance of the outer plates, (2) structural strength and local buckling resistance of the corrugated plate, (3) sufficient strength under given loading of the glued bonds, (4) minimum possible radius of curvature of the corrugated core.
The numerical specimen is an aluminum cantilever beam with thickness of 10 mm, width of 20 mm, length of 100 mm, and with a 100 N loading. The lifespan of 5 years and discounting rate 0.1 results in the optimum shape:



d, t0, tk = 27.6438 1.4342 0.7082
mass, length = 304.8408 94.1524
f = 67.3893

Fig.12, Optimized metal sandwich shape

While many multiobjective methods [2], [3], [4], apply evolutionary algorithms and generate the Pareto front using a-posteriori decision making, the method presented here belongs to the group with a-priori articulation of the compromise decision based on the aggregate function approach. Compared with the standard aggregate function approach which is typically efficient but tends to be subjective in the choice of the weight factors, the NPV/ IRR based aggregating function shown here employs economic reasoning and financial valuation to formulate an economically viable and unbiased trade-off.

4. Conclusion

The fitness function construction based on the total value or total cost approach during the entire lifespan seems to be a reasonable compromise formulation and can be viewed as an integral utility function. The project appraisal metrics such as the net present value or internal rate of return present appropriate aggregate indicators, realistic in measuring the overall economic impact. In simpler cases, full NPV / IRR based appraisal can be reduced to total cost terms only.
Simple examples illustrate how optimum designs change their respective shapes when fitness is measured in total economic benefit which they generate in their respective lifetimes. Further work is under way to develop the concept to fit with more complex problems.

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