2nd Int. Conf. on Structural Engineering and Construction
ISEC-02 – Rome, Italy, September 23-26, 2003

Multidimensional design and systemic vision in structural engineering

F. Biondini
Department of Structural Engineering, Technical University of Milan, Italy.

A. Marchiondelli
Consulting Engineer, Milan, Italy.

ABSTRACT: The progressively growing human sensibility towards the quality of engineering structures is changing the conception of the design process, which must search for solutions not only technically realisable, inexpensive and safe, but also complying with more general satisfaction criteria, like human comfort, aesthetics and ecological needs. In this paper, the complexity of a *multidimensional design* is handled by introducing a set of *quality indices*, which represent the multiple targets of design, and by a *systemic vision* of the structural model, which can be viewed either as a whole having its own emerging properties, or as composed by elementary parts with their own specific characteristics. Moreover, in order to overcome the limits of mathematical optimisation methods in solving design problems of high complexity and dimensionality, the optimal structural morphology is searched for through a two-levels heuristic approach based on biologically inspired evolutionary procedures. The application to the optimal design of a cable-stayed bridge is finally presented.

1 INTRODUCTION

In the 20th century, besides scientific and technological progresses of great importance, we have got the continuous development of a growing human sensibility towards the quality of engineering works. In fact, all fields of production have favoured the establishment of a quality design aimed to conceive objects not only technically realisable, inexpensive and safe, but also complying with more general satisfaction criteria, like human comfort, aesthetics, ecological needs, and so on.

In the context of structural engineering, this new trend has found its most effective synthesis in the term C*onceptual Design*, which try to combine together two different needs (Malerba 2002): (1) The conception of design solutions that are efficient from the structural point of view and able to achieve the required service life by preserving themselves from the inevitable damage sources; (2) The adaptation of the structural forms to the functional, aesthetic and ecological demands, so that the construction can suitably receive the humans and become a part of the environment in a discreet and respectful way.

This paper presents a tentative to handle the complexity inherent to a *multidimensional design*. To this aim, the concept of sustainable design is firstly recalled and the minimal targets that should be considered in designing a sustainable building are identified. These multiple targets are then quantitatively translated in a set of *quality indices* which allow a synthetic judgement about the goodness of a design solution and a direct comparison among different design alternatives. In particular, the definition of such indices takes advantage from a *systemic vision* of the structural model, which can be viewed either as a whole having its own emerging properties, or, at the same time, as composed by subsystems with their own specific characteristics. Moreover, in order to overcome the limits of classical mathematical-based optimisation methods in solving design problems of high complexity and dimensionality, the optimal structural morphology is searched for through a two-level heuristic approach based on biologically inspired evolutionary procedures which operate on the basis of some analogies with the growing and evolutionary processes of natural systems. The proposed approach is finally applied to the optimal design of the structural morphology of a cable-stayed bridge.

2 MULTIDIMENSIONAL DESIGN

2.1 *Analytical vs Synthetic design*

The awareness of the many factors influencing the quality of an object requires a radical change in the usual conception of the design process in the context of civil engineering too. In fact, in the past the designer, supported by his experience, intuition and cultural background, usually proceeded by discarding the solutions judged to be unfeasible and by choosing a structural scheme coherent with the basic technical and architectural requirements. The actual performance of such tentative scheme emerged from a series of analyses, which the designer exploited to make the adjustments eventually required to identify a definitive design.

This way of proceeding – that we may call *analytical design*, since it looks to a specific solution in the universe of design alternatives – does not give any guarantee that the adopted solution is actually the best possible. In fact, in this analytical process the designer usually refers to well-known schemes and to the results of analyses aimed to assess their performance, forgetting the actual role of the calculus in design, born as an aid to the general understanding of the problem and not as an alternative to the capability of making design choices and discovering new design solutions. For these reasons, the analytical design tends to produce repetitive structural schemes and, consequently, to limit the artistic sensibility of the designer which, on the contrary, is by nature daring and innovative.

Lately the designer has rediscovered his actual need: to achieve a synthesis, or to find, among all the possible configurations, the structure which better satisfies the desired requirements. In this relatively new design process – that we may call *synthetic design*, since it tends to explore the whole universe of design alternatives – the best solution is implicitly chosen through the preliminary definition of its target performances (Vincenti 1990). In this crucial phase, the designer must have a full vision of all the aspects influencing the quality of the final solution, not only from a structural point of view, but also with reference to other performances usually considered of secondary importance in the past, like the durability of the construction, the correct insertion in its context, the environmental impact, the aesthetic value, etc.

This approach clearly makes the design problem very complex and then less suitable to be formalised within the classical optimisation theory (Simon 1981). In fact, the typical mono-objective formulations looking for the most economical solution must leave place to more coherent multi-objectives formulations accounting for the actual complex nature of the problem. Moreover, the widening of the quality concept of constructions imposes a multidisciplinary design strategy, where the synergetic cooperation among several different fields (technical, economical, social, ecological, etc.) is required to effectively solve a *multidimensional design* problem.

2.2 *The challenge of the sustainable design*

The challenge of the designer of the future can be resumed in the management of the complexity inherent to the existing relationships among human society, natural environment and artificial built-up environment (Fig. 1). In fact, to safeguard the ecosystem of the planet and the human life quality, the new way of design must account for the global impact of any construction, during all its life cycle, on both the environment and society, not only with reference to the present generation, but with reference to the future one too.

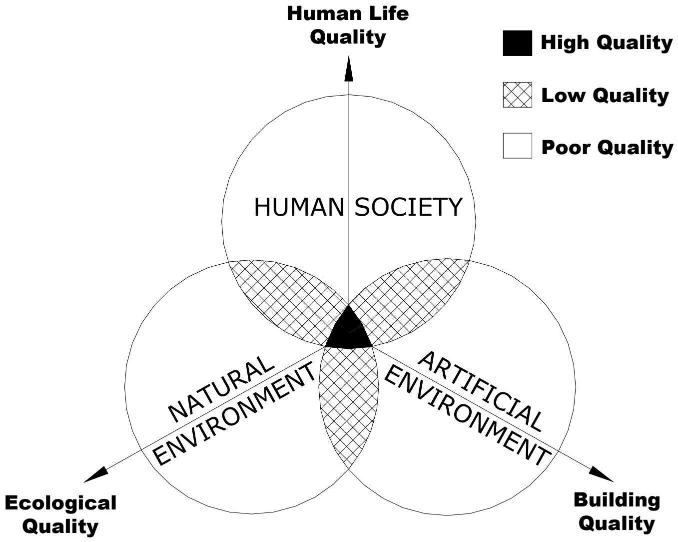

Figure 1. Design quality and relationships among human society, natural environment and artificial built-up environment.

These needs have been synthesised in the term *sustainability*, which in the years has assumed a wider and wider meaning aimed to sensitise a change of mentality and the adoption of a life style respectful of all the resources of the planet. Based on this concepts, the principle of sustainability invites to conceive a building not as something closed where to take shelter from the external agents, but to relate it to the surrounding environment and to make the construction contemporarily agreeable to humans and respectful of the loading capacity of the ecosystem.

A first step towards this new conception of design should clearly account for the mentioned multidimensionality of the problem. In particular, a minimal set of targets that should be considered as driving criteria in designing a sustainable building can be synthesised as follows:

- *Structural Efficiency*. The structure of a building must have sufficient strength and stability characteristics, with an overall stress distribution which allows a good exploitation of both the material properties and the structural volume.
- *Functionality*. A building must be able to comply in a satisfactory, ergonomic and comfortable way with the functions for which it has been designed. Since this capacity is needed over the whole service life, the building should be also characterised by sufficient flexibility and versatility to allow changes of destination.
- *Aesthetics*. This property synthesises the exterior pleasantness of a structure, its architectonic originality and artistic value. Furthermore, aesthetics represents the most immediate way to express the social value of a construction and to acquaint the community with it. For these reasons, it is essential to pay great attention to factors as geometrical order and regularity, structural simplicity and clearness, lightness and harmony of the proportions, either of the structure as a whole, or of its elementary parts, especially in relation to the characteristics of the surrounding environment (Leonhardt 1980).

- *Economy*. The cost of a building includes not only the cost of construction, but also the cost of management and maintenance during the whole service life, as well as the cost of final dismission at the end of this period. Another important aspect deals with the social cost of a building. In fact, the production and use of materials and services determines, on both environment and society, effects having a well defined economic impact (alterations of the ecosystems, pollution, injuries to the human health, loss of value of material goods, non-enjoyability of immaterial goods, etc.), with long term repercussions on the future generations too.
- *Durability*. A building must assure all the performance mentioned above during its whole service life. To this aim, it is necessary to provide a continuous monitoring of the building in order to plan proper maintenance processes and eventual restorations of its initial characteristics, inevitably altered because of the many potential sources of damage, coming for example from exceptional loading (fires, earthquakes, hurricanes, landslides) or from the ordinary interaction with aggressive environments (carbonation, corrosion, freezing and unfreezing cycles).

The first three targets mentioned above can be assimilated to the fundamental aspects already pointed out by Vitruvio as the essential characteristics of a construction: *firmitas, utilitas,* and *venustas*. In view of a multidimensional approach, we can imagine many of these targets, thought to be equally important, as located at the vertexes of a multidimensional solid completing the so-called *vitruvian triad* (Fig. 2).

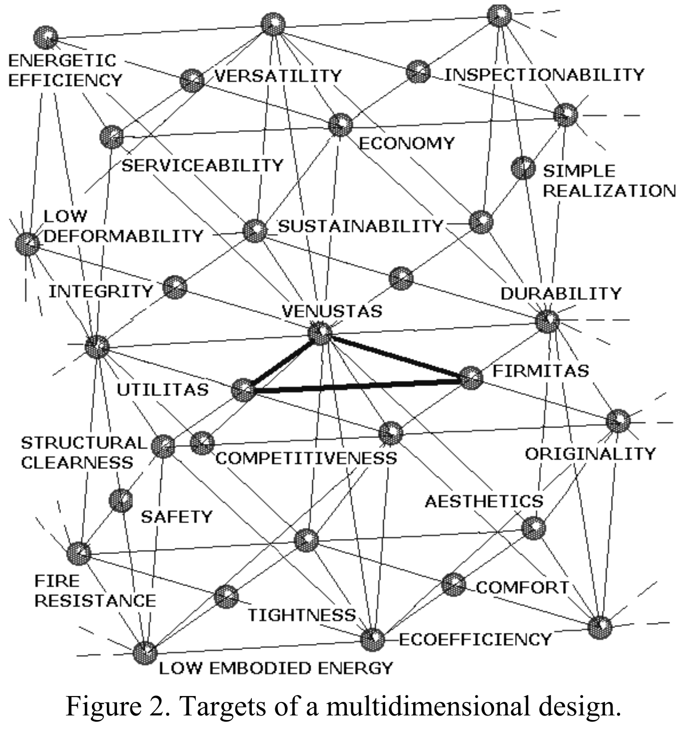

Figure 2. Targets of a multidimensional design.

3 SYSTEMIC VISION AND DESIGN QUALITY

3.1 *Holistic and Sectorial levels*

It can be observed that every *structural system* is an unitary whole composed by a plurality of elementary parts, having their own specificity, that have to be organised in an appropriate way to create an organic and durable system with its own emerging properties (Fig. 3). The systemic unity so defined is contemporarily structured and structuring, since its status derives from the status of the subsystems and, at the same time, influences it.

Based on this *systemic vision*, the design process can be set at two different levels. At the first one, that we call *holistic level*, a structure is conceived like a unity and the global quality of its emerging properties can be evaluated. At the second level, that we call *sectorial level*, the subsystems forming the whole are considered separately and the local design requirements, as well as the compatibility between the different parts of the system, can be verified. Clearly, the two levels are highly interacting since every decision about the whole unit influences the choices regarding the substructures and, on the other hand, each single subsystem may present local demands which require some modifications of the global properties. It is important to outline that this synergetic interaction leads to *feedback* phenomena with global effects different from those that can be obtained from the analysis of the subsystems taken separately (von Bertalanffy 1969).

3.2 *Quality indices and measure of design goodness*

In order to make possible a hierarchical classification of the explored design alternatives, a direct measure of all the emerging properties of the structural system is needed. To this aim, a tentative set of *quality indices* related to the main multiple targets of a sustainable design, such as structural efficiency, serviceability, durability, economy and aesthetics, are introduced (Biondini *et al.* 2002). They allow a synthetic judgement about the goodness of a design solution and a direct comparison among different design alternatives. In particular, the unitary value of these indices corresponds to the best solution, while a zero value denotes the worst alternative.

Structural Efficiency. This aspect depends on the stress distribution σ over the structure and it can be related to a good exploitation of the material properties (*mechanical efficiency*):

$$a_{ME}(t) = \sum_{k=1}^{m} \frac{\int_{V_k} |\sigma| \, dV}{\sigma_{adm,k} V_k(t)} = \sum_{k=1}^{m} \frac{V_{R,k}(t)}{V_k(t)} \qquad (1)$$

and of the structural volume (*volumetric efficiency*):

$$a_{VE}(t) = \sum_{k=1}^{m} \frac{\int_{V_k} |\sigma| \, dV}{\sigma_{k,\max} V_k(t)} = \sum_{k=1}^{m} \frac{V_{k,\max}(t)}{V_k(t)} \qquad (2)$$

where V_k, $\sigma_{\mathrm{adm},k}$ and $\sigma_{\max,k}$ are the material volume, the admissible stress and the maximum stress, respectively, of each subsystem $k=1,\dots,m$, while the time parameter t denotes a particular design solution.

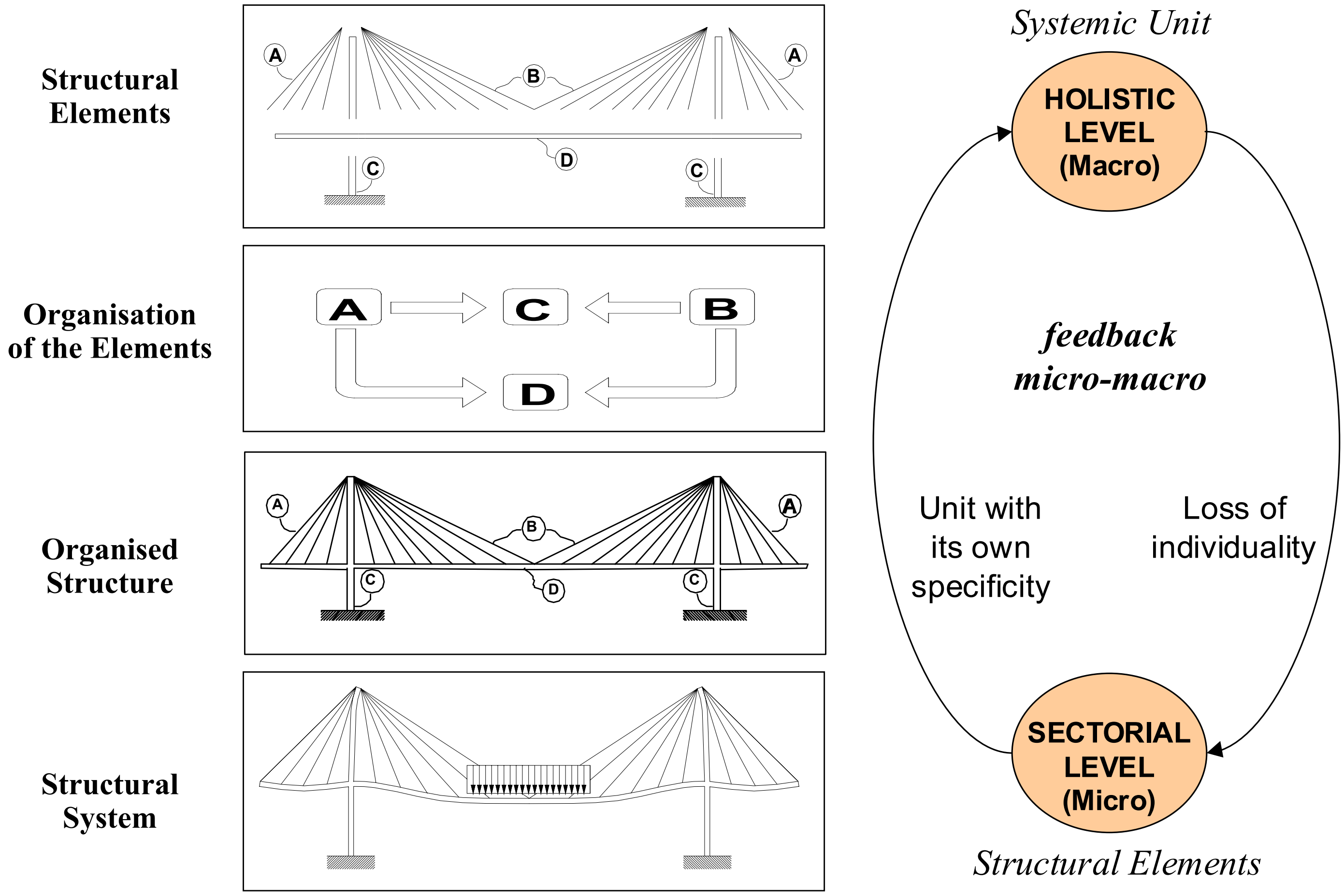

Figure 3. Systemic vision of a structure and feedback micro-macro between local and global emerging properties.

Serviceability. This requirement depends on the deformability of the structure and can be related to the maximum displacement s_{max} over the structure:

$$a_S(t)=e^{-\alpha_S\frac{s_{\max}(t)}{s_{0,\max}}} \tag{3}$$

where the subscript “0” refers to an initial design solution taken as reference.

Economy. At this stage the cost of management and maintenance is neglected. The initial cost of the structure mainly depends on the material volume V:

$$a_E(t)=e^{-\alpha_E\frac{V(t)}{V_0}} \tag{4}$$

Durability. This property depends on the capability of the structure to maintain its performance during the structural lifetime and it can be related to the area A of material exposed to the aggression of the environmental and chemical agents:

$$a_D(t)=e^{-\alpha_D\frac{A(t)}{A_0}} \tag{5}$$

Aesthetic value. The judgement of the beauty of a structure is clearly a matter of opinion and depends of a number of subjective factors. To simplify the complexity of the problem, only the *geometrical aspect* is here considered and the attention is focussed on properties like regularity, order, proportion and orientation of the structure. For framed structures composed by straight truss and beam elements, such properties can be measured as follows:

(a) Regularity and Order

$$a_{REG}(t)=e^{-\alpha_R\left(\frac{\Delta\bar{l}(t)}{\Delta\bar{l}_0}\right)} \qquad a_{ORD}(t)=e^{-\alpha_0\frac{\Delta\bar{\theta}(t)}{\Delta\bar{\theta}_0}} \tag{6}$$

(b)Proportion and Orientation

$$a_{PROP}(t)=e^{-\alpha_p\left(\frac{\Delta\hat{l}(t)}{\Delta\hat{l}_0}\right)} \qquad a_{ORIENT}(t)=e^{-\alpha_0\frac{\Delta\hat{\theta}(t)}{\Delta\hat{\theta}_0}} \tag{7}$$

with:

$$\bar{l}(t)=\frac{1}{m}\sum_{k=1}^{m}l_k \qquad \bar{\theta}(t)=\frac{1}{m}\sum_{k=1}^{m}\theta_k \tag{8}$$

$$\Delta\bar{l}(t)=\sqrt{\frac{1}{m}\sum_{k=1}^{m}\left(l_k-\bar{l}\right)^2} \qquad \Delta\bar{\theta}(t)=\sqrt{\frac{1}{m}\sum_{k=1}^{m}\left(\theta_k-\bar{\theta}\right)^2} \tag{9}$$

$$\Delta\hat{l}(t)=\sqrt{\frac{1}{m}\sum_{k=1}^{m}\left(l_k-\hat{l}\right)^2} \qquad \Delta\hat{\theta}(t)=\sqrt{\frac{1}{m}\sum_{k=1}^{m}\left(\theta_k-\hat{\theta}\right)^2} \tag{10}$$

where l_k and θ_k are the length and the inclination of an element with respect to a reference direction, respectively, and $\hat{l}$ and $\hat{\theta}$ are assigned optimal values.

The numerical constants α which appear in all the previous exponential terms are heuristically deduced. Proper values of such constants should be chosen in the range between 2.0 and 3.0.

4 BIOMIMETICS AND HEURISTIC DESIGN

4.1 *Heuristic vs Mathematical optimisation methods*

From a theoretical point of view, a multidimensional design problem can be formulated as a multi-objectives problem and can be treated with classical optimisation methods. Of course, in structural engineering mathematical optimisation appears to be a powerful explorative tool for a rational search strategy, especially in solving well defined mono-objective problems. However, due to the high complexity and dimensionality of the actual design problem, mathematical methods often are not effective in finding the harmonisation which resolves the contrast existing among the multiple design objectives. This goal can be reasonably achieved only by means of extreme simplifications of the design model, sometimes so large that the nature of the original problem itself is fully violated.

A possible way to overcome this drawback is the development of proper heuristic methods proven to be effective by the experience. These methods don't search for the optimal solution, but simply proceed by looking for some improvements of the solutions already known. For this reason, they are usually less efficient of the classical mathematical techniques in exploiting the actual "mathematical optimum", but the obtained design solutions can be considered *almost optimal*, and then good enough from the engineering point of view. In addition, due to their wide generality, heuristic methods allow to easily handle multidimensional design problems characterised by high levels of complexity. Consequently, heuristic *almost optimal* solutions of well-posed design problems are usually much better of the "mathematical optimums" provided by simpler and ill-posed models.

4.2 *Biologically inspired evolutionary procedures*

One of the most promising heuristic method which has been recently applied to the identification of optimal structural morphology deals with evolutionary procedures which operate on the basis of some analogies with the growing and evolutionary processes of natural systems. Such procedures belong to the field of *biomimetics* and are based on the simple concept that by slowly removing and/or reshaping regions of inefficient material, belonging to a given over-designed domain, the structure modifies its shape and topology evolving toward an optimal configuration (Baseggio *et al.* 2000).

Based on these methods, in the following the optimal structural morphology is found through a two-level evolutionary approach (Biondini *et al.* 2000, 2002). The *external* morphology, i.e. the geometrical dimensions and the topology of the structural type, is optimised at the first level (*macro-level*) by simulating the *Biological Growth* (BG) of natural structures like bones and trees. The *internal* morphology, regarding the geometry and the shape of the cross-sections, is instead selected at the second level (*micro-level*) by means of a classical *Fully Stressed Design* (FSD) combined with a process of *Evolutionary Structural Optimisation* (ESO) which removes elements at low stress level.

To this aim, the structure is conceived like a *systemic unity* composed of different parts, called *zones*. Each *zone*, considered singly, has its own specificity (*sectorial level*), while it looses its individuality within the unity (*holistic level*). This duality, already pointed out at the conceptual level (Fig. 3), is taken on again at the methodological level by means of a *macro-micro* approach mainly based on BG and ESO evolutionary procedures. BG procedure, in fact, having the aim to optimise the shape of the structure, acts at the *macro level*, while ESO strategy collaborates with FSD to search for the optimal internal morphology at the *micro level*. However, on the basis of the desired effect, it is possible to keep active only one of the two above mentioned levels and to optimise only particular details or zones of the structure.

In general, the synergetic interaction between macro and micro optimisation leads to better results than those obtained when the procedures work separately. Moreover, it is worth nothing that in the presented approach the internal morphology is modified by means of discrete design variables (commercial sections), while the external one is optimised in a continuous way (node locations). The effectiveness and versatility of the evolutionary strategies are pointed out also by this aspect.

The basic steps of the overall procedure should be repeated until optimal configurations appear. In particular, the best structural solutions emerging from the evolutionary process are identified on the basis of the quality indices previously introduced.

4.3 *Macro-optimisation of the external morphology*

At the macro level the structure is viewed like a systemic unity whose behaviour is obtained by the structural relationships existing among its zones. The aim of the macro-optimisation is the search for the optimal external morphology, that is, in the first place, the identification of the resistant scheme and, in the second place, the correct sizing of the global system and the search for its optimal shape and topology.

The BG procedure allows the structure to evolve by adapting itself to the applied loads according to the *axiom of uniform stress*, which states that, in the optimal configuration, the stress distribution tends to be fairly regular over the structure (Mattheck & Burkhardt 1990, Mattheck 1998). The structural shape and topology, therefore, are gradually modified by adding material in the zones with high stress concentrations and removing it from under-loaded zones (S*welling Step*). In this paper, the axiom of uniform stress is generalised by stating that, in the optimal configuration, the structure is characterised by uniform performance everywhere (*axiom of uniform performance*).

The main steps of the BG procedure can be briefly resumed as follows (Fig. 4):

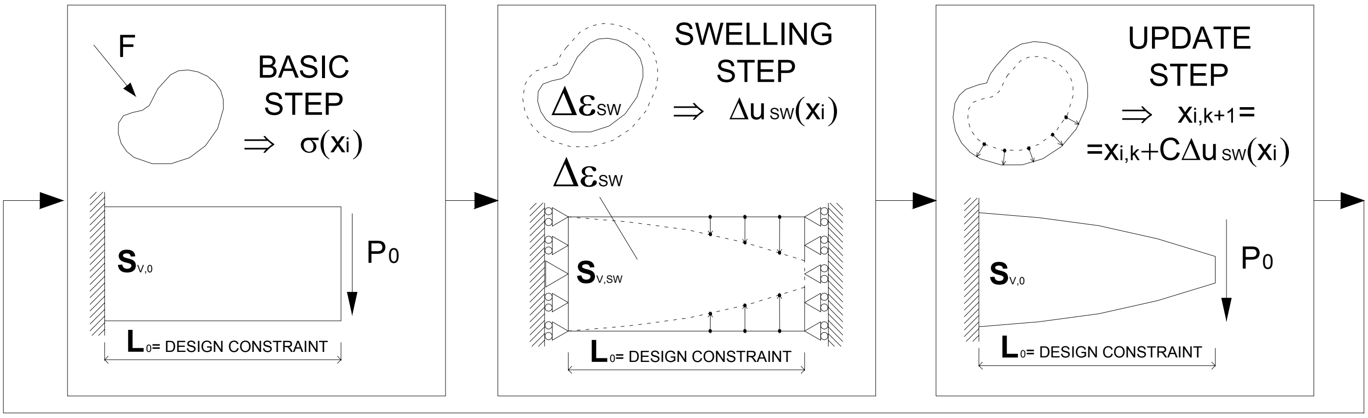

Figure 4. Fundamental steps of BG procedure.

(A) Basic Step: A finite element analysis is performed to obtain the stress distribution, as well as the other parameters which define the structural performance measured by the quality indices previously introduced.

(B) Swelling Step. In the original BG procedure, the evolutionary forces which drive the swelling of the structure are based only on the stress state. In the present formulation, the Driving Forces $DF=DF(t)$ of each zone are instead computed with reference to the quality indices a_i as follows:

$$DF(t) = A\sum_i w_i \beta_i(t)[a_i(t) - a_i^{ref}(t)] \qquad (11)$$

where A is a suitable constant, w_i is the *weight* of the i-th component of the driving force, $\beta_i = \pm 1$ is an *evolutionary index* that defines the direction of such component, and a_i^{ref} is the target value of the quality index a_i, usually assumed with the current mean value over the structure. The DF causes a constant swelling strain distribution $\Delta\mathbf{e}_{SW}$ in each zone. Based on such strain distribution, the load vector $\Delta\mathbf{f}_{SW}$ equivalent to *swelling* is derived and the corresponding incremental displacement vector $\Delta\mathbf{u}_{SW}$ is evaluated:

$$\Delta\mathbf{f}_{SW} = \int_V \mathbf{B}^T\mathbf{D}\Delta\mathbf{e}_{SW}\,dV \quad \Rightarrow \quad \Delta\mathbf{u}_{sw} = \mathbf{K}^{-1}\Delta\mathbf{f}_{SW} \qquad (12)$$

being $\mathbf{B}$ the compatibility matrix of the finite element, $\mathbf{D}$ the constitutive matrix of the material and $\mathbf{K}$ the stiffness matrix of the structure. It is worth noting that additional geometrical design constraints can be directly accounted for by replacing the actual boundary conditions of the *swelling model* so that swelling displacements which violate the constraints are not allowed. This concept is shown in Fig. 4, where the cantilever beam is forced to maintain its initial length during the evolution.

(C) Update Step. The location $\mathbf{x}_{i,k}$ of each node i of the finite element model at the current generation t is updated according to the swelling incremental displacements $\Delta\mathbf{u}_{SW}$ as follows:

$$\mathbf{x}_{i,t+1} = \mathbf{x}_{i,t} + C\Delta\mathbf{u}_{SW} \qquad (13)$$

being C a suitable extrapolation factor which implicitly contains the constant A. Such factor may be either considered as time-independent, or varied during the evolution. In any case, its value should be chosen to assure noticeable shape variations and progressively decreasing driving forces.

4.4 *Micro-optimisation of the internal morphology*

At the micro level the attention is focussed on the single structural element and the micro-optimisation aims to determine the optimal internal morphology, that is the best sizing, geometry and shape of the cross-sections. As mentioned above, this is obtained by means of an effective collaboration between a FSD criterion, which exploits the material of each structural element in an optimal way, and the ESO procedure, which removes inefficient elements. This synergetic action leads to a powerful search strategy here called *Evolutionary Fully Stressed Optimisation* (EFSO).

In particular, since in the optimal structure each element is subjected to its allowable stresses under at least one load condition (Gallagher & Zienkiewicz 1973), FSD chooses, among many available commercial profiles, the cross-section of each element so that the material is stressed at its allowable levels. Clearly, in this process the allowable stresses of the materials must be properly modified to account for both local and global instability effects. In any case, when an element has a low mechanical efficiency, FSD changes its geometrical properties choosing an always smaller section. When the smallest available section is no longer able to fully exploit the material, the ESO procedure checks the efficiency of the element and eventually removes it by degrading its constitutive properties, typically the Young modulus (Xie & Steven 1993). In this study, the efficiency of the element is evaluated on the basis of its *mechanical efficiency*: if the value of the corresponding index is less than a given lower limit, the element must be removed. In the basic formulation the minimum portion of removable material is then identified with a single finite element. However, a more general formulation can be achieved if the control of efficiency is performed on a *minimum elimination unit* formed by a *group* of elements.

4.5 *Evolutionary design of a cable-stayed bridge*

The presented evolutionary procedure is applied to the optimal design of the cable-stayed bridge shown in Fig. 5. The loading condition is given by the self-weight of deck and pylon, evaluated with a weight density $\gamma = 25$ kN/m^3, the prestressing of the stays $\sigma_{p0} = 1000$ MPa, and a uniform load $q = 100$ kN/m acting on the deck. To identify the optimal structural morphology, the following properties must be defined: the thickness of both the bottom and top pylon box cross-sections; the diameter of the stays; the inclination of the pylon and the height of its top part; the number of the stays and the location of their anchoring points along both the deck and pylon. The initial design domain is subdivided in 29 zones: the deck (1); the bottom and top parts of the pylon (2); the groups of stays located on the same side with respect to the pylon and having the same anchoring point along the pylon itself (26). The swelling model allows to move the anchoring points of the stays and enforces the pylon to maintain its straight profile.

Fig. 6 shows some steps of the evolutionary process driven by the index of mechanical efficiency, while Fig. 7 makes a comparison between the solutions obtained by using the other quality indices previously defined. The main results of these search processes are all resumed in Tab. 1.

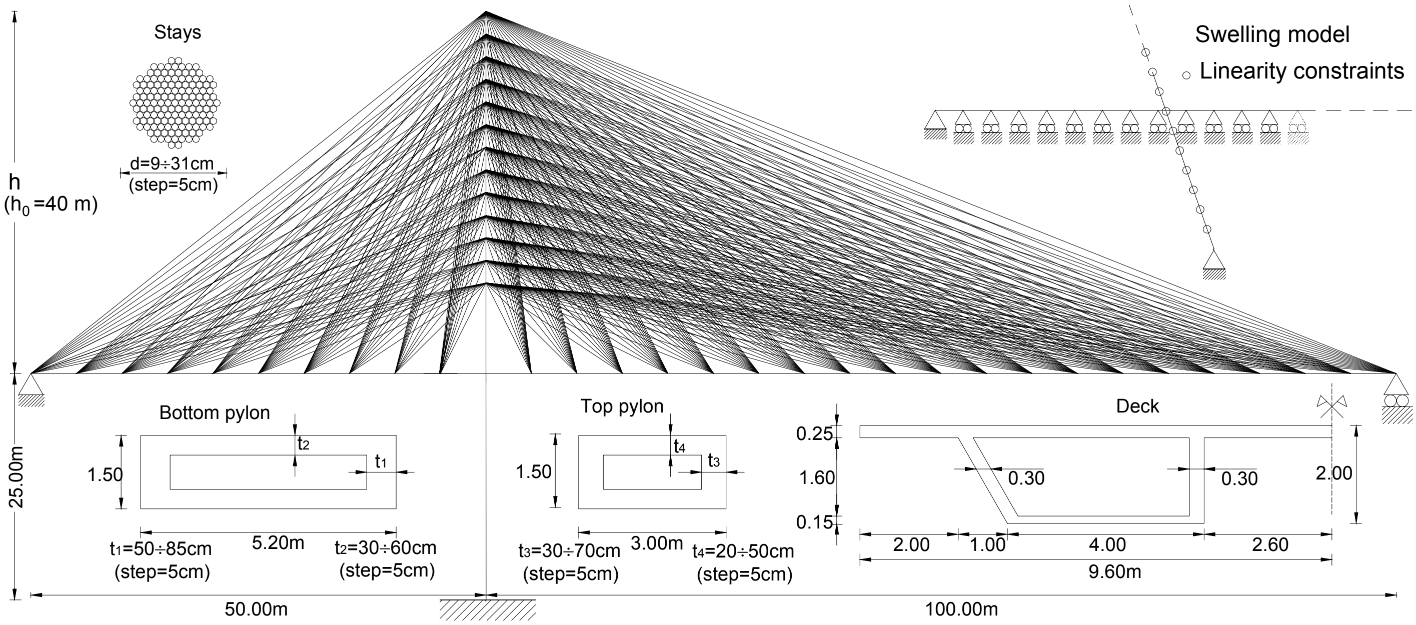

Figure 5. Cable-stayed bridge. Main dimensions of the initial design model and design variables.

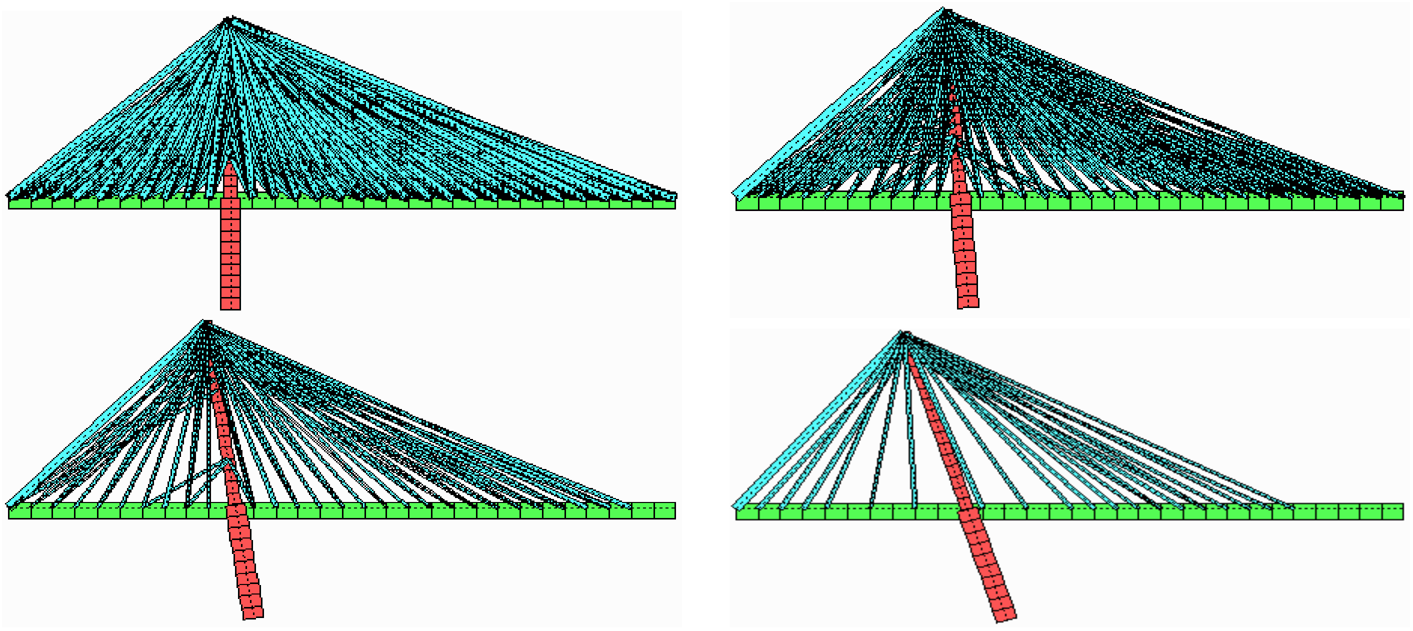

Figure 6. Some steps of the evolutionary process driven by the index of mechanical efficiency.

Driving Criterion (Quality Index)	t_1 [cm]	t_2 [cm]	t_3 [cm]	t_4 [cm]	d [cm]	h [m]
Mechanical Efficiency	75-80	50-60	65-70	40-45	13-21	35.63
Serviceability	80-80	60-60	70-75	50-55	17-25	48.62
Durability	80-85	60-65	65-70	40-45	19-27	36.32
Regularity	75-75	50-55	70-75	50-55	13-29	49.36
Order	75-75	50-55	70-75	50-55	9-31	47.08
Economy	75-80	55-60	65-70	40-45	13-27	32.48
Weighted Combination (w_i=1)	80-80	60-60	65-70	40-45	15-25	39.06

Table 1. Minimum and maximum values of the design variables for the optimal solutions.

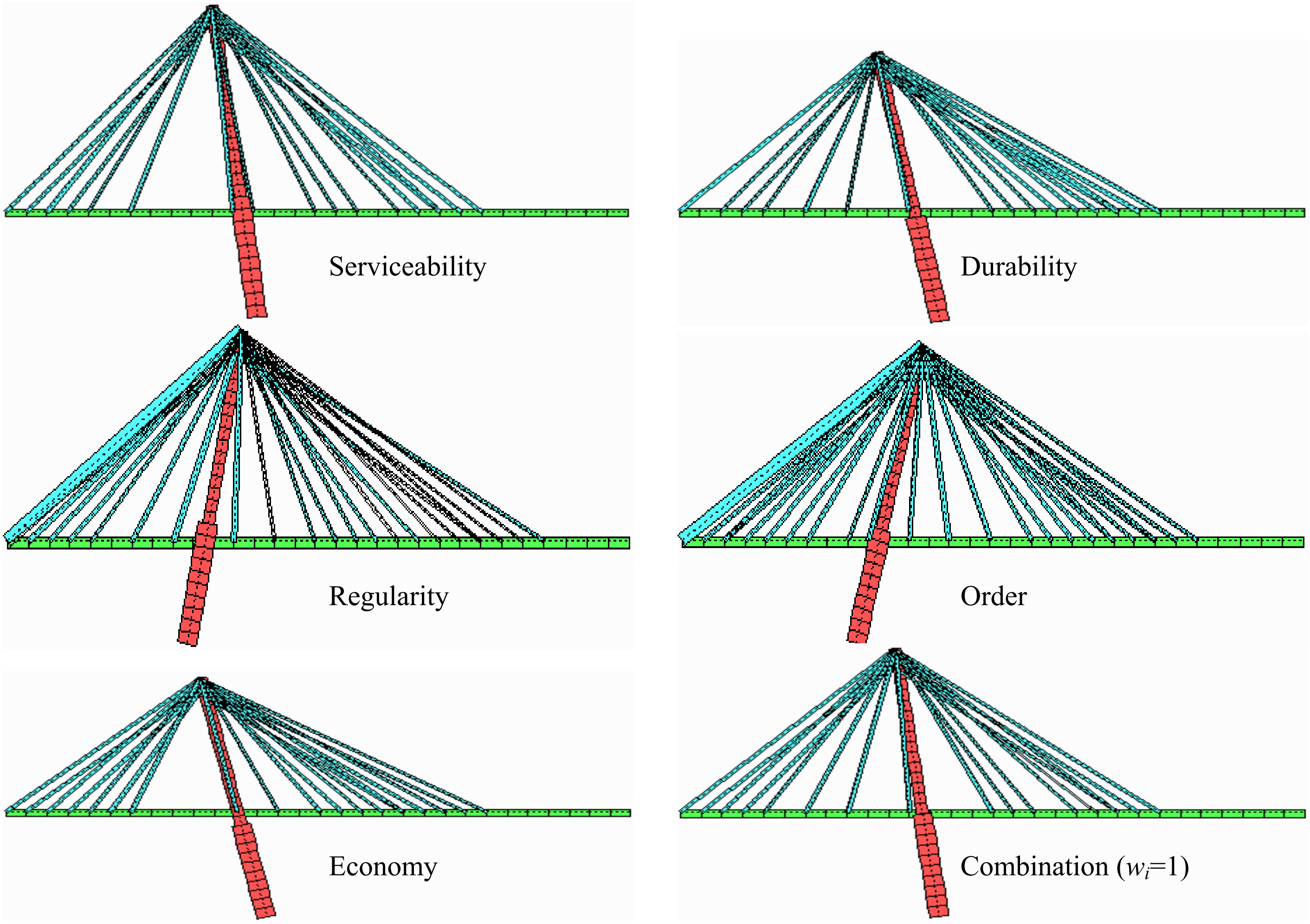

Figure 7. Some optimal configurations obtained by using different driving indices.

5 CONCLUSIONS

The main developments proposed in this paper can be resumed in the following points:

- *Multidimensional design*. The complexity inherent to the design process is taken into consideration by searching for feasible engineering solutions complying with several targets (*structural efficiency*, *serviceability*, *economy*, *durability*, *aesthetics*).
- *Quality indices*. The multiple targets are quantitatively translated in a set of indices which allow a measure of the goodness of a design solution and a direct comparison among different design alternatives (*hierarchical classification*).
- *Systemic vision*. In the design model, the structure is viewed either as a whole having its own emerging properties, or as composed by elementary parts with their own specific characteristics (*feedback*).
- *Heuristic methods*. The search process is based on design analogies which easily handle multidimensional and complex design problems, leading to heuristic *almost optimal* solutions usually much better of the “mathematical optimums” provided by simpler and ill-posed models (*biomimetics*).

The effectiveness of the proposed approach has been finally shown through the application to the optimal design of a cable stayed bridge. The analysis of the results shows how the evolutionary control of proper quality indices can effectively drive the *multidimensional design* process towards structural morphologies having desired performance.

6 REFERENCES

Baseggio, A., Biondini, F., Bontempi, F., Gambini, M., Malerba, P.G., Structural Morphology Optimization by Evolutionary Procedures. *Proc. of Structural Morphology Conf.*, 264-271, Delft, The Netherlands, August 17–19, 2000.

Biondini, F., Bontempi, F., Malerba, P.G., The Search for Structural Schemes by Optimality Criteria and Soft-Computing Techniques. *Proc. of Structural Morphology Conf.*, 179-187, Delft, The Netherlands, August 17–19, 2000.

Biondini, F., Boiocchi, S., Malerba, P.G., Marchiondelli, A., Biologically Inspired Evolutionary Procedures for Conceptual Design of the Structural Morphology. *Proc. of 2nd Int. Conf. on Advances in Structural Eng. and Mechanics (ASEM'02)*, Pusan, Korea, 21-23 August, 2002.

Gallagher, R.H., Zienkiewicz, O.C. (Eds.), *Optimum Structural Design*. John Wiley & Sons, 1973.

Leonhardt, F., Aesthetics in Structural Engineering. *Proc. of 11th IABSE Congress*, Vienna, August 31-September 5, 1980.

Malerba, P.G., Tools for Conceptual Design of Structures. *Proc. of 2nd Int. Conf. on Advances in Structural Eng. and Mechanics (ASEM'02)*, Pusan, Korea, 21-23 August, 2002.

Mattheck, C., Burkhardt, S., A New Method of Structural Shape Optimization based on Biological Growth. *Int. J. of Fatigue*, **12**(3), 185-190, 1990.

Mattheck, C., *Design in Nature. Learning from Trees.* Springer Verlag, 1998.

Simon, H., *The Sciences of the Artificial*. MIT Press, 1981.

Vincenti, W.G., *What Engineers Know and How They Know It*. The John Hopkins University Press, 1990.

von Bertalanffy, L., *General System Theory*. George Braziller, New York, 1969.

Xie, Y.M., Steven, G.P., A Simple Evolutionary Procedure for Structural Optimization. *Computers & Structures*, **49**(5), 885-896, 1993.