Title:
Structural Optimization in Multilevel design

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Keywords:
Structural optimization, topology, multilevel, FBS

DOI: 10.14733/cadconfP.2017.90-94

Introduction:
This paper deals with a new methodology based on "multi-level design" approach that foresees the development and integration of computer aided tools to support designers' work. Multilevel design is not intended here as the relationship between product design, service, system and society but as the design of products taking into account a plurality of design perspectives at different detail levels, from macro to micro. In the following we introduce an overview of some research areas that involve a multilevel approach, such as biomimetic, problem solving and material science, that constituted the basis for the definition of the new design methodology.

Multilevel in biomimetic:

Living beings offer an endless collection of examples of how the stunning mechanical characteristics directly depend on the hierarchical organization of the organic material itself; such organization is defined at various dimensional scales, so that the properties at lower levels influence the behavior of the structures at higher levels.
An evidence of the fact that multilevel organization of organic structures is a competitive factor, we can observe that the "evolutionary trend" of living beings promote the creation of more and more complex organisms, so that we had an evolution from simple mono cellular bacteria to extremely complex animals, adding from time to time more and more levels of complexity.
As an example, Raabe and his colleagues in [9] describe the arthropod's exoskeleton starting from the hierarchical organization of its structures, decomposing it in many structural layers, each one with many different functions and, consequently, different (mechanical) behaviors. According to this complex theoretical model, the local stiffness of the material of each structure may be calculated by considering the structural compliance of a twisted plywood pattern: such compliance basically depends on the stiffness of its constituent chitin-protein honeycomb, which stands in another dimensional level of description.
Similarly, spider web is another remarkable example. It would be a mistake considers it only as a reticular structure; in fact, the only nature of its macroscopic design wouldn't explain its excellent mechanical (and not only mechanical) properties. Such features are the result of a very complex interaction between the organization of the organic material at various dimensional scales [14].
Anyway, in biomimetic, the multilevel approach has been used mostly for analysis purposes. Many models have been created in order to understand and simulate the behavior of the biological structures, but very few address the use of a multilevel approach in order to create a new paradigm for design. An effort has been presented in [10], trying to describe how natural structures overcome contradictions operating a different scale levels, and extend this concept as design strategy.

Multilevel in conceptual design and problem solving:

On the other hand, most of the design studies merely describe the system at a single level of detail, creating an alternative abstract level of description based on functions, and getting down to a lower technical level of detail only for choosing the material [8]. One of the most representative design models is FBS. According to it, all systems can be described analyzing at the same level of description how its structures, collaborates together in order to create a certain behavior that allows the system to fulfill a certain function [6].
Instead, more practical design approaches, such as TRIZ or psychological methods for problem solving [12] (e.g., lateral thinking), propose tools for changing point of view and face the problem at different scale of representation. For example, one of the 11 TRIZ Separation principles (namely macro-micro) is dedicated to solutions working at Macro-Micro levels. It suggests how to overcome a physical contradiction trying to solve conflicting requirements at different levels of detail. For example, if I want a protective wall very thick in order to be resistant, and very thin in order to be light, Macro-Micro separation suggests to think "a big layer at macro level, made of very thin layers at micro level, such as honeycomb, multilayers, porous materials, etc.

Dynamics laws of evolutions, always formulated by Altshuller in TRIZ theory, describes the Transition from macro to micro level: "The development of working organs proceeds towards a better exploitation of the resources at first on a macro and then a micro level. The transition from macro to micro level is one of the main (if not the main) tendency of the development of modern technical systems that use energy fields in order to achieve better performance and control".
Even if some TRIZ tools (e.g., Multiscreen, some inventive principles, the concept of operative zone,) or other methodologies (lateral thinking), can help to move to a multilevel approach, until now, rare examples of the adoption of a real multilevel design has been investigated both in problem-solving [11], or for slightly different purposes, such as forecasting [7].

Multilevel in computational materials:

One of the fields, which took most from the observation of the nature, is the study of materials, and, in the last years, many attempts have been done in order to characterize materials studying their own inner structures. Starting from a nano-metric dimensional scales, different properties of the materials derive from different structures, and a central topic is the relation between the different structures, and how difference parameters influence one another [5]. Anyway, beside the most recent researches, such approach has been adopted in various forms since long time. An example is the study of different micro structural materials [4], which investigate the relation between the lattice topology, and its mechanical characterization, underling the evidence that hierarchical design increase buckling strength
To the author's best knowledge, once again, all this research has the limitation of realizing an analysis of materials in order to describe (and eventually simulate) the behavior of the material (bottom up approach), but such considerations are not implemented in a methodology for supporting the conceptual design.

<u>Multilevel definition:</u>

From the previous analysis, there is the evidence that multilevel comes out naturally while facing a certain number of scientific and technical issues. The use of multilevel approach, so heterogeneous and in different and far disciplines is reflected in a lack of a shared definition. Before describing the proposed methodology, we introduce the main bricks for a future ontology for multilevel reported in Table 1.
In the presented schema, the two generic elements of the ontology are presented: the upper (relative) level, the lower (relative) level, the basic relation between levels, and the possibility of iterating the scheme itself.
For example, from a certain point of view, FEM analysis schema belongs to a bi-level framework; in fact, in this kind of analysis, the continuum spatial domain is decomposed in a certain number of discrete elements, so that we have a passage from a macroscopic level, to a lower scale domain.

MAIN LEVEL (MONO-LEVEL)	At a first step, multilevel approach states that a structure may be schematized by a set of constitutive elements, and the interaction among them, under certain external conditions, defines the behavior of the structure itself. The main level is the level of the first main structure, thought as one.
SUBLEVEL (BI-LEVEL)	The constitutive elements, thought as part of the structure, are elementary entities, which have their own (mechanical, but not only) properties, and should not be divided. At microscopic level, the elements may be represented as structures, which, in this new domain, are composed by a further set of elements. In this way, the characterization of the elements at a macro level, is the behavior of the same element thought as structure at micro level. The totality of the set of elements thought as separated entities represent the second level.
MULTI-LEVEL (RELATION BETWEEN LEVELS)	Depending on the way the main level and sub-levels are defined, the physical characterization of the elements at the upper level depends on the behavior of the structure at the lower level. Such framework can be iterated, so that the lower level of the first iteration step represents the upper level for the further iteration step.

Tab. 1: Elements for multilevel ontology.

<u>Aim of the research:</u>

The scope of the present work is to investigate the possibility of integrating a new optimization level in structural optimization software according to multilevel design. Therefore, the proposed design methodology foresees the use of structural optimization tools adopting a multilevel approach.
Under the name of "optimization of structures" there is a number of different approaches to solve the problem of identifying the best design for a structure. We took into account only topological optimization that is the research of the ideal distribution of material in a certain region of space, in order to fulfill a number of specific goals, usually regarding the stress configuration and compliance of the structure itself. The word "topological" refers to the idea that a certain procedure, in order to identify the "ideal layout" for the structure, changes the topological

class of the initial design space, generally adding or subtracting a certain quantity of material. According to multilevel design, topological optimization can be rethought adding a new optimization at a deeper level of detail.
Usually, in FEM, the "continuity" of mechanical (thermal, fluidic, etc.) parameters inside the elements is ensured by the use of the shape functions.
Using the multilevel approach, the elements themselves can be thought as structures, and their mechanical (thermal, fluidic, etc…) behavior may be set in a more accurately way. This offers the possibility to operate a topology optimization at many different dimensional levels, so that the way the elements at "lower" dimensional scales are "built" affects the global performance of the main design.

Main limits of software for topological optimization:

In literature, many techniques of structural optimization have been developed, depending on the formulation of the problem, regarding the domain (continuum or discrete structures), the optimization algorithm (gradient based or non-gradient based methods), and number of the objectives (single or multi objective). Anyway, a very first discriminating factor in topological optimization is the choice between macro-structural or micro-structural strategies [3]. Such initial setting is not secondary, because it may deeply affect the final result.
In fact, in different reviews regarding structural optimization, one of the first results obtained by analyzing a number of methodologies, is the evidence that it is necessary to use composite materials in order to improve the mechanical performance of the optimized structure, even if the desired solution was a well-defined macroscopic domain [3-1], which means that a microstructural approach may be taken in account. In other words it means the use of structures at a microscopic level.
Despite the evidence that the optimization of a structure means even an optimization at lower dimensional scales, at the moment, all the main commercial software providing topological optimization are based on variants of the SIMP density based method, and mostly aim to produce well defined results, where (isotropic) material and void are well separated at macroscopic level.
Another limitation is the so-called Pareto approach to multiple task optimizations: for the nature itself of the algorithms, after a certain level of optimization of the structure, it is impossible to optimize a certain goal, without worsen another objective.

Proposal:

According to the multilevel philosophy for the topological optimization, the main idea is to involve different optimization strategies at different dimensional levels, in order to take into account the evolutionary trend of the systems, which impose the reordering of material at different hierarchical levels. Figure 1 portrays the architecture od the proposed solution. The first step (optimization at macro level) is the topological optimization of the structure using a hard kill method, for example the BESO. The implementation of such method had already been discussed in literature [15], using the commercial FEA system Abaqus and a script realized in Python.

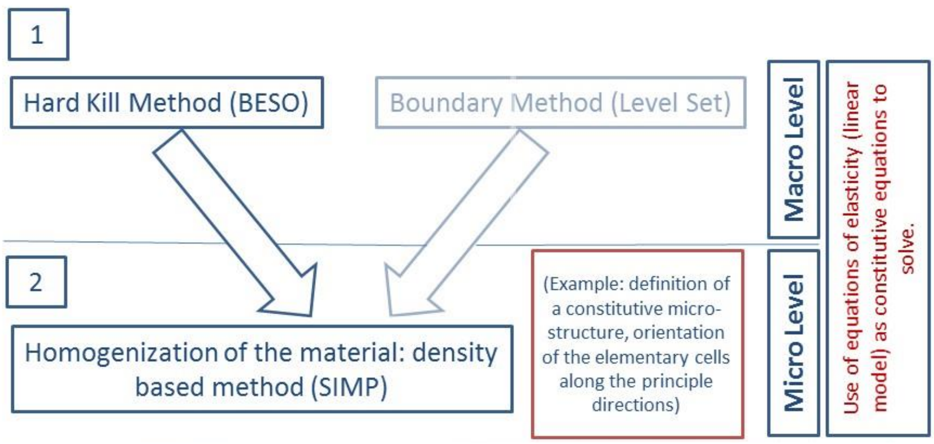

Fig. 1: Architecture of proposed solution.

Anyway, BESO is not the only feasible algorithm to carry out the first step of the optimization. Since we are considering a "global" optimization at macroscopic level, every method, which defines macro-zones of material-void are available, so that, for example, the Level Set method could be an alternative as well.
After a first distribution of material has been defined, the second step is applied using the SIMP (Solid Isotropic Microstructure with Penalization) method. As well known, the better performances for structural purposes are obtained realizing objects, which, at a microscopic level, are constituted by elements (or cells), which are not isotropic, so that the singular elementary unit may globally have, along the three principal directions, different values of Young and Poisson moduli [3-1]. Furthermore, the orientation of the single constitutive elements may lay along the principal direction for stress and strain, which have been obtained by the macroscopic analysis. Python

scripts, which allow mapping principle direction in a continuum, have already been developed [12][14], and the macroscopic and microscopic analysis may be carried out in the same environment.
Moreover, the purpose of this research work is to develop a method in order not only to characterize the direction and the mechanical characteristic of the constitute microstructures, but also their topology optimization. Once the mechanical parameters for an elementary cell have been defined, it is possible to apply various strategies defining the structure of the cells themselves. In some homogenization methods, the main topology of the elementary structures are already defined using square cells or more complex microstructures [2-13].
Our idea is to perform a further topological optimization (at micro level) to defined the best microstructure topology of the constitutive elements (Figure 2).

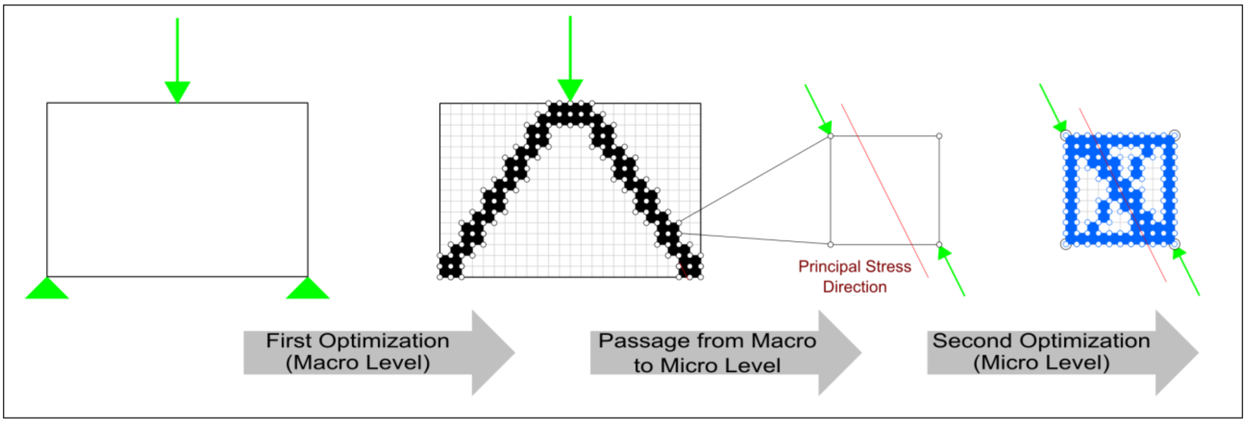

Fig. 2: Two-level Optimization.

In principle, the procedure can be extended to lower dimensional levels even if this requires further considerations. In fact, algorithms implemented in FEM software are based on constitutive equations (e.g., for linear analysis of structures they are the equations of elasticity), which are not valid at every dimensional level, because, at lower levels, for example, the hypothesis of isotropic elastic continuous material fails. This means that, moving from a level to a lower one, the mathematical model changes. This could be a limit of our iterative method, unless the new physical model is considered.
This approach can implement a strategy different from the Pareto one to fulfill multiple objectives optimization. In fact, it could be possible to assign the optimization of different parameters to different levels of details. For example, if the compliance optimization is obtained defining the macro-topology of the structure, an independent optimization of the frequency response may be obtained working at lower level of structural material.

At present, the methodology has been partially tested and its implementation will be one of the future developments. Various commercial systems for structural optimization have been tested and compared, in order to identify the compatibility with programming languages since one goal is to make available a software tool that implements the methodology.

Conclusions:
This paper analyses the multilevel concept and its use in different research fields. On this base, we extended this concept to topological optimization with the aim to develop a new design methodology integration both optimization and multilevel approaches. The underlying idea is to drive the designer to a more aware and efficient design activity and a choice of materials more suitable to her/his needs, also thanks to the possibility to realize products with complex structures using new production techniques, such as additive manufacturing.

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