J Mater Sci (2020) 55:9436–9447

Computation & theory

Multi-material design: architecture and components simultaneous selection

P. Baracchini[1], F. X. Kromm[1,*], C. Guillebaud[1], and H. Wargnier[1]

[1] *University of Bordeaux, CNRS, Arts et Metiers Institute ofTechnology, Bordeaux INP, INRAE, I2M Bordeaux, 33400 Talence, France*

Received: 30 March 2020
Accepted: 2 May 2020
Published online: 11 May 2020

ABSTRACT

The design of multi-materials requires the determination of several variables: morphology, components and geometric parameters. Previously developed methods help designer making these choices separately because they always lie on a reduction in the number of design variables, as some of them are fixed at the beginning of the study. This paper proposes a method to carry out the simultaneous definition of all these variables in a preliminary design step. The beginning of this work consists in the formalisation of the multi-scale decomposition of the architecture materials. This outline is a guide for the use of databases of materials and architectures, whose combination enables the generation of multi-materials. Within the huge solution space resulting from this approach, a genetic algorithm allows to find optimised materials to fulfil a set of requirements with a limited number of calculations. An analytic example illustrates the efficiency of this method and shows it can provide designers with several propositions of materials.

Introduction

The optimisation of costs and performances has resulted in the multiplication of multi-materials applications in various domains like aeronautics, automobile or energy. Unlike monolithic materials whose properties are almost invariable, the properties of a multi-material depend on several attributes of very different nature: components, volume fractions, architecture (morphology of each component) and interface (bonded or sliding, for example). As a consequence, multi-material design is more complex than materials selection because it implies taking numerous decisions.

The contributions aiming at defining a design method for those materials always lie on a reduction in the number of design variables, as some of them are fixed at the beginning of the study [1]. It appears that in each case, a methodical approach can be defined to find solutions in a space previously narrowed by arbitrary assumptions. In most cases, the design is generally focused on either the geometric definition of the architecture or the choice of the components and leads to operate classic-shape optimisation or materials selection. With these methods, the effects of the coupling of architecture and components in the resulting properties are avoided, so

Address correspondence to E-mail: francois-xavier.kromm@u-bordeaux.fr

https://doi.org/10.1007/s10853-020-04778-1

that the design is facilitated, but the opportunities of creativity are limited.

The aim of this paper is to develop a method for the simultaneous definition of the architecture and components of a multi-material. In a first time, a review of the existing methods allows the identification of the most suitable approach and the tools that have to be used to put it into practice. Then, a definition of a multi-material is presented, on the basis of the different scales of combination. The resulting attributes are finally defined, with their related databases and homogenisation models. As the association of these different databases generates a huge space of multi-materials, a numerical method is chosen to find solutions to this combinatorial problem in a reasonable computation time. Then, in a final step, the method is applied to an elementary case study concerning electronic packaging for aeronautics.

Methodological approach

Review of existing methods

Designing a multi-material means defining all its attributes and consequently implies different tasks like defining geometric attributes (shape, dimensions) and selecting materials. Thus, designing such materials is much more difficult than a single material choice and forces the development of specific methods. However, some similarities can be pointed out between materials selection methods and multi-materials design.

The starting point of materials selection is the derivation of the requirements of the material from the specifications of the product. One reason for designing multi-materials is that no monolithic material can fulfil all these conditions. Therefore, this set of requirements, including binary constraints and ranking criteria, all expressed in terms of material properties, is a basis of multi-material design because these requests are considered as the homogenised properties to reach.

At this stage, an approach consists in drawing up a set of requirement for each component. A preliminary analysis of the specifications, thanks to principal component analysis, allows the identification of incompatible requirements [2]. Then, they can be split in several sets, allowing a material selection method to be applied to select each component.

Materials selection methods are presented in three categories: free search, analogy or questionnaire methods [3]. The first type of method consists in searching a solution in a material database following criteria on their properties (whether they are numerical or qualitative). The second type does not use databases but knowledge bases. The difference is explained in Sapuan's works [4], where a knowledge is defined by a link between data or sets of data. In the last type of methods, a questionnaire guides the designer, reducing the set of solutions after each given answer [5].

Whatever the chosen way, the main steps of the process are the same and are representative of the growing precision of the choices [6]. The identified steps aim at defining the selection criteria, forming sets of potential candidates, and determining a solution. Unlike the derivation of the criteria who is the same for a multi-material, the next stages differ and give rise to various approaches. Among previous studies developing tools aiding this decision stage, it appears that each one is focused on a part of the process, often in a narrowed application where only few attributes are concerned and the other are fixed.

Some studies deal with multi-materials selection by handling them like monolithic ones. For the selection of sandwich materials, Pflug uses Ashby charts to compare the equivalent sandwich properties with monolithic materials ones, for different values of thicknesses in a case where the sandwich's components are fixed [7]. Following a similar approach, it is possible to calculate the homogenised properties of multi-materials for several architectures, components and volume fraction and to integrate them as additional materials in a database [8]. However, including all the possible combinations of materials with their properties in a single database can be useful if the solution space is small, but it may become tedious if too many combinations are considered.

The properties of a multi-material depend on the architecture and the components properties, and it is generally impossible to separate these variables in the expression of an homogenisation model. However, the selection of the components can be handled independently from the architecture. For example, Voigt and Reuss models can bound the properties of the association of two materials. Thus, in the case where the number of potential components is small, they can be considered by pairs, and the envelope of the properties of the resulting multi-material can be represented on a selection chart [9]. If the number of possible components is high, a filtration step can be processed before ranking solutions. Indeed, binary criteria for the elimination of candidates can be defined thanks to the analysis of the antagonist constraints of the set of requirements [10].

In addition to this component choice, multi-material design includes the selection of an architecture. In the case where only one material is used, some analytical methods allow the choice of a morphology to increase the performance of a part. With slightly different formulations, the authors characterise, thanks to an adimensional property called shape factor, the influence of the geometry of a cross section on the performance of a beam with respect to a reference shape [11, 12]. Thus, following the same principle as for the materials, an optimal cross-sectional shape can be chosen in a list of possible candidates.

A more recent work develops a method for the design of composite structures considering the geometry of the part, the architecture of the composite and the manufacturing process [13]. The authors assume that more design options are offered by taking into account geometrical constraints first. Various architectures and processes can then be generated thanks to compatibility tables linking geometries to processes, and processes to architectures.

The problem of designing an architecture involving several components is generally not analytically solved. For example, some works on sandwich materials propose different approaches. In the first one, shape optimisation methods like level set are used to design a representative volume of the material, on which a numerical homogenisation is processed [14]. Then, in another one, the use of Pareto front and genetic algorithm allows the multi-objective optimisation of the skin and core materials and thicknesses [15].

This list of publications gives an overview of the variety of existing methods, but it is necessary to see if they are suitable for multi-materials design in preliminary design.

Analysis

The searched design method has to fulfil several criteria. Indeed, it must be able to make a selection of architecture and components, allowing the comparison of very different solutions and using relatively simple and preferably analytical models.

In this context, assigning a shape factor to a morphology is an interesting approach. However, the applied method in Weaver et al. and Pasini's works [11, 12] is possible when only one component is involved. Indeed, the determination of this analytical expression is based on the separation of geometric parameters and material properties, which is generally impossible to manage for a multi-material.

On the contrary, numerical-shape optimisation methods allow choosing a morphology, but the solution at the end of the iterative process depends strongly on the initial shape that is imposed at the beginning, so they cannot give a quick comparison of candidates with very different architectures, and the final morphology keeps close to the starting one.

The GAP methodology (Geometry, Architecture, Process) allows a choice of numerous parameters in preliminary design [13], but only includes the definition of the architecture, and considers that materials selection has to be treated separately. Therefore, in this sequential method, the choice of the architecture depends only on the geometry and manufacturing constraints, so the effect of the coupling between the architecture and the components on the final properties is not taken into account.

Designing a multi-material, either for an innovative application or to replace a less performant material, necessitates a method compatible with the generation of new solutions. Therefore, free search approach is more suitable than methods based on knowledge or analogy who lead to existing solutions. Moreover, questionnaire are generally considered as complementary tools to other design methods [5], as they focus the designer's attention on crucial points in the domain of the concerned application.

Thanks to the analysis of the suitability of the different approaches for the multi-materials selection, the choice of a method can be made.

Definition of the approach

The main characteristic of the developed method is to be able to investigate a huge solution space. The efficiency of this exploration is based on the ability to proceed to a quick calculation of the candidates performance (thanks to analytical models) and to find an optimal solution after a reduced number evaluations.

Therefore, selecting elements in two different databases, as shown in Fig. 1, is the most appropriate way for components and architecture simultaneous optimisation. Following this method, illustrated in Fig. 1, the selection in multiple databases allows a quick comparison of very different morphologies. Then, when a first ranking of the candidates is made, the chosen architecture can be optimised, thanks to topology optimisation methods in a final step.

The main difficulty in this method is to develop an architecture database because unlike material database, no one is available in the literature. Thus, an important part of this work consists in collecting and structuring data about morphologies. Then, as the components and architectures databases have to offer a wide range of choice, the number of possible combinations is huge, so the choice of the numerical method is important in order to find solutions in short times.

Numerical method for selection

Considering the previously described association of an architecture database with a material one, the number of elements composing the resulting space is infinite if the geometric parameters are considered as continuous (which is theoretically the case for most of them). The choice of a numerical method to find a solution in this problem has to meet different criteria. First, a solution must be obtained in a reasonable calculation time. Indeed, the combination of material and architecture databases results in a huge number of potential solutions. As a consequence, a complete screening of the solution space is not worth considering. Indeed, if the performance of every possible multi-materials was evaluated, the calculation time would be too high. So, an important criterion for the choice of the numerical method is to be able to converge with few calculations, avoiding the screening of the complete solution space for the determination of optimised multi-materials.

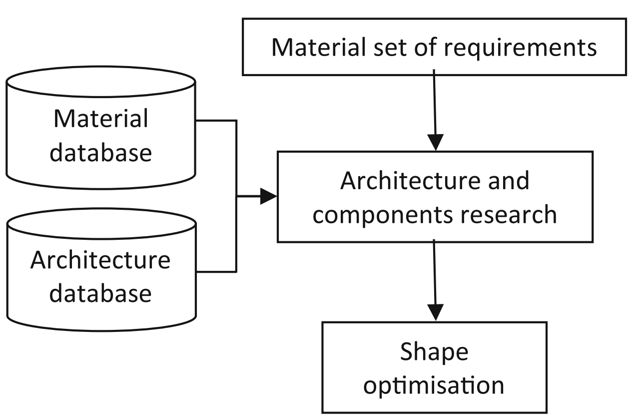

Figure 1 General method for architecture selection.

The next characteristic of the numerical method is to deal simultaneously with numerical variables (geometric parameters) and qualitative ones (morphology, materials). What's more, the set of solutions that can be generated by the combination of the different databases is multimodal, so the algorithm must be able to avoid being trapped in a local optimum.

To fulfil all these conditions, stochastic methods are the most suitable. Some comparisons have been made between the different approaches [16, 17], but notice that no universal ranking can be made for these metaheuristics. As a consequence, the choice has been guided by the specifications of multi-materials design. In this domain, genetic algorithms have previously been used, for example, for skin and core materials selection for sandwich panels [15], choice of components and type of reinforcement for composites [18], or optimisation of stacking sequence of laminated composites [19]. Thus, this numerical method is chosen to find a solution to the combinatorial problem of architecture and components selection.

Then, the data involved in this choice have to be defined. Unlike material database, the architecture database is not easily available and has to be defined in the next paragraph.

Structuration of an architecture database

The choice of the method implies building an architecture database that can be representative of the multi-materials diversity. This important step needs first to get a clear definition of a multi-material that will help structuring the database.

General definition

Using a material database is usual, architecture databases are far more uncommon so, although a rough outline has been given in the literature [20], a more complete one has to be defined. This database is built according to a structured definition of a multi-material. Indeed, the definitions of a multi-material that have been given previously [20–22] are conceptual, so they aim at being as general as possible. In order to be exploitable in this study, the definition has to be formalised more precisely, especially about the structuration of the architecture.

The first point of this definition is that, as a multi-material must always have a representative volume with at least one very small dimension in comparison with those of the part, it composes [21, 22]. The whole material is then generated by the repetition of this elementary pattern. The second assumption is that within this representative volume, several scales of combination of materials can exist. Indeed, the representative volume can be split in several parts with different morphologies. Then, each of these phases can be multi-materials too, with their own architecture and components, so that the global architecture of the material can be made of the combination at different scales of several architectures. As a consequence, the multi-material can be discretised according to the scales of combination, making a hierarchy between principal architecture and secondary ones.

This kind of multi-scale decomposition can be observed in the description of natural fibres [23–25]. Indeed, vegetal fibre can be represented by cellulosic fibril embedded in lignin matrix. At lower scale, the study of each part shows that it can be divided into different components following the same fibrous composite pattern. This example of description gives a base to define a structuration of the architecture of a multi-material. These observations can be generalised in order to give structured frame to the definition of the architecture of a multi-material.

Let us consider a macroscopic domain of interest (DOI) $\Omega \subset \mathbb{R}^d$, where $d = 1$, 2 or 3 represents the number of spatial directions. This domain is built by the repetition of an heterogeneous characteristic volume called representative volume (RV), so the description of the domain Ω comes down to investigating the heterogeneity of the RV. This volume is considered as an assembly of sub-structures at different scales. The first rank sub-structures are noted D_i ($i \in \mathbb{N}$), so that $\sum_i D_i = \mathrm{RV}$. The second rank sub-structures are noted with a supplementary index j so that $\sum_j D_{ij} = D_i$. Then, for all the following sub-structures, an index is added each time the rank of division is increased, until the different parts of each sub-structure are made with homogeneous materials (see Fig. 2).

In this illustration, the last rank elements are D_{11}, D_{121}, D_{122}, D_{21}, D_{22}, D_{31} and D_{32}. They are made of an elementary pattern in which each phase is supposed to be homogeneous. Thus, the proposed notation allows a clear identification of the different parts, including information about the division scale of the considered phase.

Examples of structuration for different types of geometry

Section type geometry

The first example of that type of structure, that is invariant or periodic following one direction, is a multi-material cable or a segmented beam (Fig. 3).

The homogeneous RV can be divided into rank 1 sub-structures made either of material A or material B. The length of the RV can be chosen arbitrarily because the cross section is unchanged all along the cable. In the case of a twisted yarn, the RV is defined by a segment of yarn whose length is determined by the periodicity of torsion.

Plate or shell geometry

This kind of structure is obtained by invariance or periodicity in two directions. One recent example of these materials is a specific sandwich panel developed to combine great flexural stiffness and high electromagnetic protection [26]. The panel looks like a

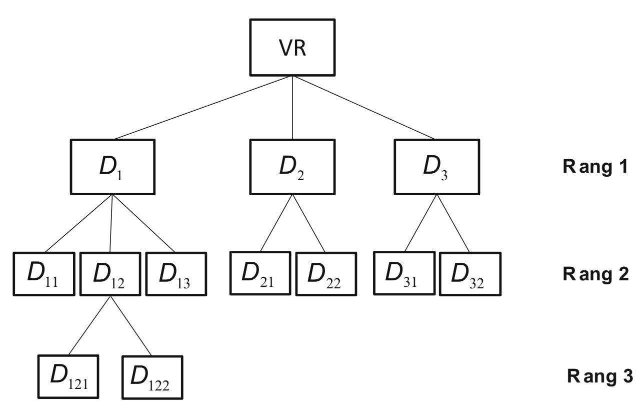

Figure 2 Structuration principle of the RV.

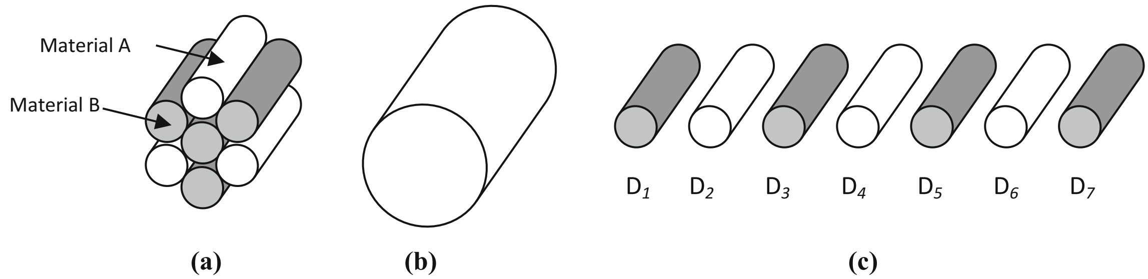

Figure 3 **a** Representation of the cable, **b** its RV and **c** decomposition of the RV.

classic sandwich structure with composite skins, but in this application, honeycomb cells are filled with a polymeric foam reinforced by carbon nano-tubes.

The RV of this material is made of a multi-layer architecture, composed of higher-rank structures like fibrous materials, honeycomb or foam (Fig. 4).

Volume type geometry

Example of materials exhibiting 3D periodicity can be found in different kinds of developments, like lattice materials [27] that can be built with the repetition of a representative volume made of truss in three different directions. Another example concerns bi-continuous material for simultaneous transfer of heat and electricity [28]. In this study, one component is a good thermal conductor and poor electrical conductor (phase 1), while the other is a good electrical conductor and poor thermal conductor (phase 2). The material offering the best compromise between these two conductivities is like a 3D composite structure in which the fibrous parts are connected across the sample in the three directions. A representative volume of this material is shown in Fig. 5.

Application

Description of the case study

The case study for the application of the developed method concerns a material design for lightweight electronic packaging in aeronautics. The functions of such parts generally deal with thermal problems

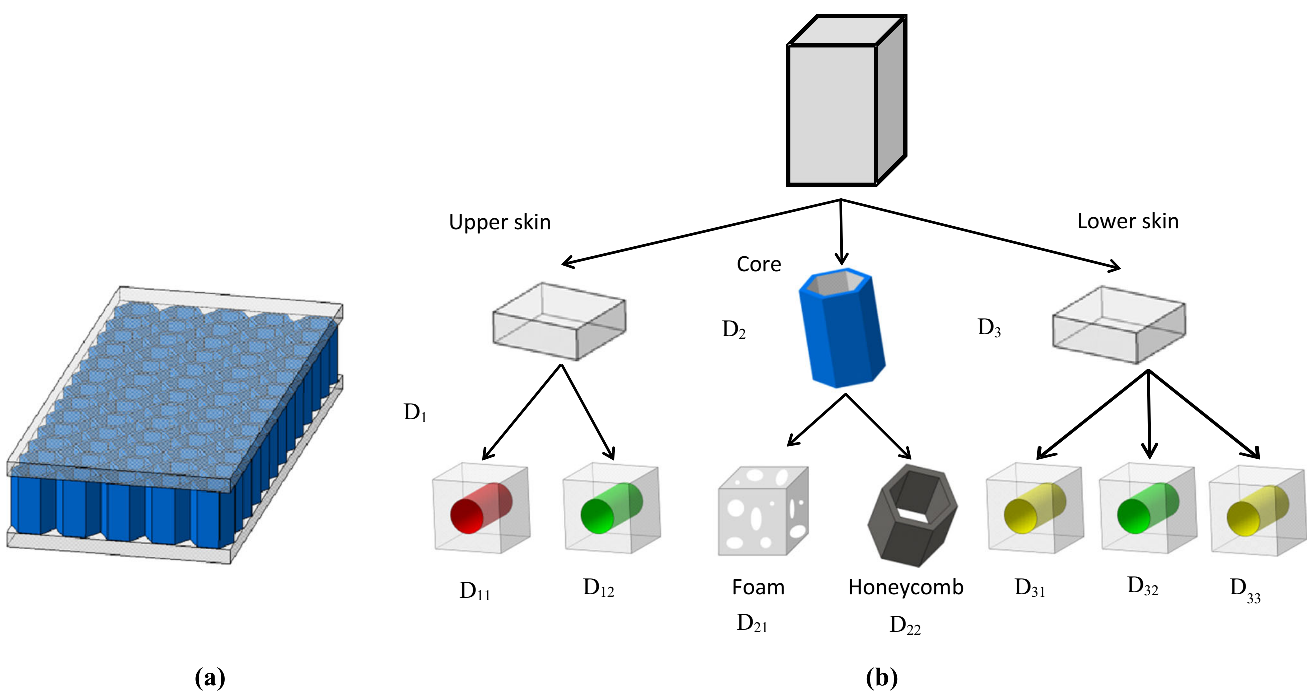

Figure 4 **a** Representation of the sandwich, **b** its RV and the decomposition.

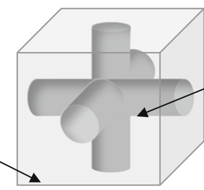

Figure 5 Representation of the bi-continuous 3D material for heat and electricity transportation.

(prevent the electronic components from reaching their maximum service temperature), mechanical constraints (no resonance frequency in a given range) and electromagnetic protection of the devices.

In order to be analytically modelled, this set of requirements is simplified as detailed in Table 1 and schematised in Fig. 6. Thus, the mechanical constraint is taken into account through an imposed in plane tensile stiffness, and the electromagnetic field shielding and the chassis grounding are reduced to a maximum electrical resistance of 2 mΩ along the length of the packaging. The rectangular plate representing the packaging is insulated along its four edges, the heat flow generated by the electronic components is supposed to be uniform on the lower surface, and natural convection is considered on the upper one.

Creation of an architecture database

The general approach given at 3.1 describes the multi-material as a combination of architectures at different scales. In order to apply it for the creation of various materials, an architecture database has to be built. This database contains not only common patterns (multilayer and fibrous), but also specific functional architectures related to the application domain. Thus, in this study, the developed database is partly related to the electronic packaging problem.

A limitation is imposed in this study because the first rank partition of the RV is supposed to be multilayer, and the interface between the layers is perfectly bonded. This type of association is used in a lot of products and will avoid the creation of too complex architectures. Indeed, a random combination of patterns and components can lead to completely unrealistic materials, so the first rank combination is made of two separated layers. Then, at lower scale, each layer is filled with an elementary pattern or with monolithic material. Thus, although the method is illustrated with a multi-layer architecture, it still deals with very general aspects and can be applied the same way to any architecture.

The second rank patterns, used to fill each layer of the multi-material, are listed to offer a great diversity. A first geometric pattern database was outlined in previous works [20], but it has to be completed to be more representative of the diversity of multi-materials. Thus, it is divided into four groups:

- Cellular patterns: foams, honeycombs, lattices, stacking of hollow spheres;
- Composite patterns: continuous fibres, short fibres, particular, laminated, woven;
- Monolithic materials: bulk materials from database;
- Specific patterns: architecture allowing convective heat dissipation.

The organisation of the architecture database is illustrated in Fig. 7. Each pattern is defined by a variable number of discretised geometric parameters and is provided with its components picked in the material database. Thus, considering only a two layer material results in a space composed of 1.72 10^{48} multi-materials.

The evaluation of the homogenised properties of such a material has to be made at different scales successively using suitable models who will not need

Table 1 Set of requirements

Geometry	Rectangular plate, 113*247 mm^2, free thickness
Objective	Minimise mass, ensuring at least 20% decrease with respect to reference mass of 155 g
Constraints	
Thermal	Maximum temperature on the lower face must not exceed 90 °C
Mechanical	Imposed in plane tensile stiffness
Electromagnetic	Electrical resistance of the plate along the length under 2 mΩ

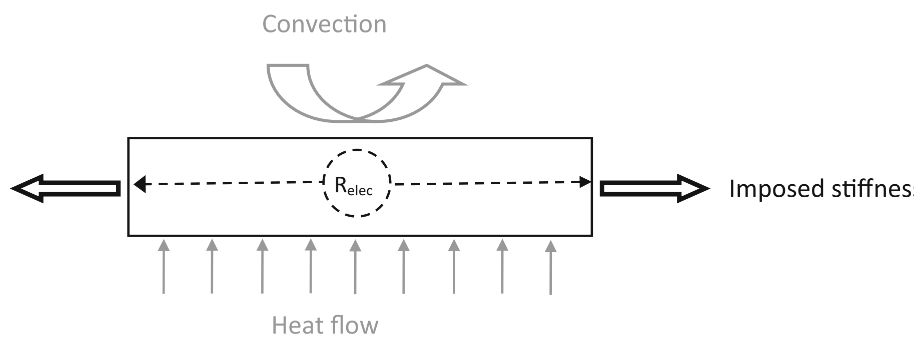

Figure 6 Requirements for electronic packaging.

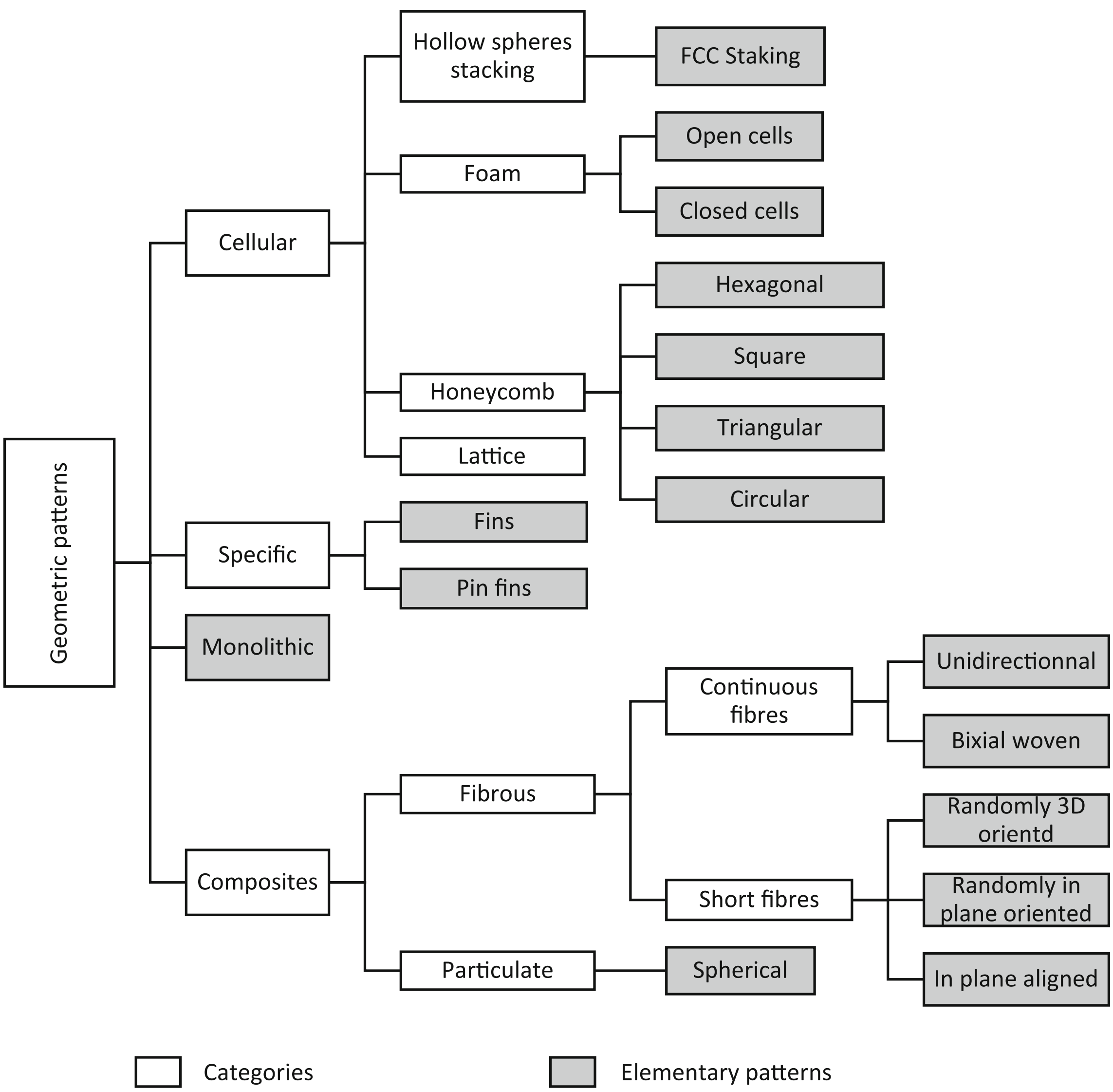

Figure 7 Organisation of the architecture database.

too many parameters for a preliminary design step [29]. Thus, in this study, order 2 models are associated with each pattern, in order to take into account the reinforcement morphology without having too sophisticated laws.

At macroscopic scale, a second homogenisation can be operated if necessary, in order to calculate the properties of the multi-layer.

Solution research

Genetic algorithm

The basic principle of a genetic algorithm is to consider a solution as an individual. It consists in creating an initial population and controlling its evolution following the rules of reproduction and natural selection. To apply this method, the individuals have to comply with the structuration of the multi-material that was proposed at paragraph 3.2 and with the formulation of the genetic algorithm. Therefore, as illustrated in Fig. 8, they will be made of two chromosomes (layers), each composed of twenty six genes picked in the suitable database:

- Secondary architecture from the architecture database,
- Components from the material database,
- Geometric parameters from sets of predefined values for each parameter.

The algorithm efficiency depends on the regulation parameters that define the way it operates (population size and crossing probability). The used genetic algorithm, BIANCA [30], has the classic parameters for this kind of software (number of populations, population size, crossover and mutation operators) but has one more specific factor called isolation time, defined by the number of generations of independent evolution of the populations before exchanging their best individual. Most frequently, these parameters are defined from an empirical approach [31] but in this study, a statistical analysis has been performed in order to determine their optimal values [32]:

This study results on the following values for the parameters:

- Number of populations: $N_{pop} = 2$;
- Number of generations: $N_{gen} = 150$;
- Number of individuals: $N_{ind} = 80$;
- Crossover probability: $p_{crossover} = 0.85$;
- Mutation probability: $p_{mutation} = 1/\ N_{ind}$;
- Isolation time: $I_{time} = 25$.

The obtained solution is made of magnesium matrix composite reinforced by UHM carbon fibres in the bottom layer, with magnesium-staggered pin fins in the top layer. As explained before, the algorithm creates associations of materials following specific architectures by picking each element in a database without consideration for the manufacturing process or the incompatibilities between materials. For this reason, the relevance of the proposed solution can sometimes be discussed, so it is interesting to analyse more precisely the materials the algorithm proposes.

Results analysis

At the end of the calculation, the genetic algorithm proposes an optimised solution to the problem. In order to have a more complete outlook on the results and provide the designer with a greater variety of solutions, two methods have been compared:

(1) Exploring all the solutions that the algorithm has considered during the computation,
(2) Repeating the calculation 100 times and store only the optimal solution of each one.

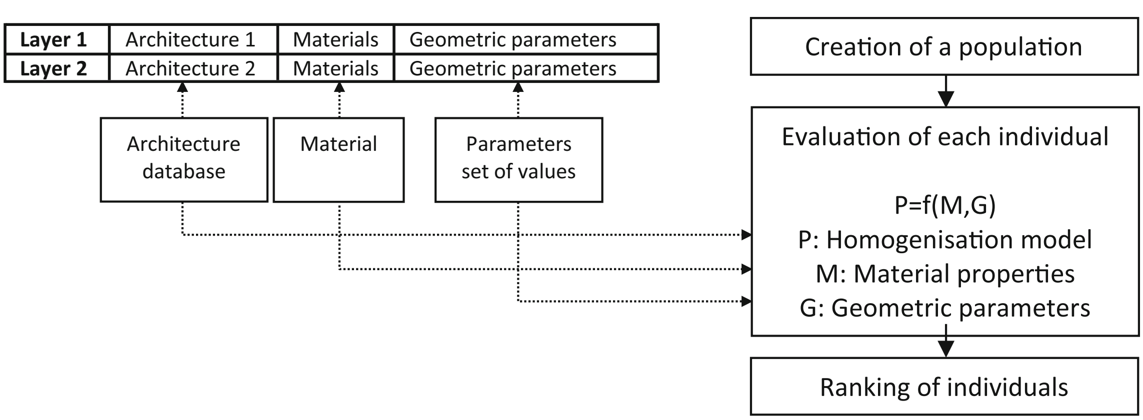

Figure 8 Creation and evaluation of solutions.

During the processing of the genetic algorithm, 24,000 individuals have been created and evaluated. Among these multi-materials, only 5930 allow a 20% mass decrease respecting all the constraints. As some of these solutions only differ by geometric parameters (thickness and volume fractions), they can be considered as identical, so in this set of solutions only 75 different associations of architecture and components remain.

These 75 multi-materials have been compared to the variety obtained taking only the optimal solution of 100 consecutive executions of the genetic algorithm. This time, 78 kinds of associations were found, and as shown in Fig. 9, they are very similar to the results of only one computation. Indeed, in both cases, as the thermal problem seems to be the most constraining, the upper layer is always composed of fins or pin fins, generally made with metallic light alloys, or, more rarely, ceramics or polymers. Composites found in the bottom layer are in every case, either with short fibres or particles. Once again, light alloys are often used as a matrix, and it can be noticed that more diversity is observed in the selection of the reinforcing material.

As a conclusion, the combination of the material and architecture databases allows the proposition of several multi-materials for the minimisation of the mass of the packaging while fulfilling all the constraints. Two different ways of searching solutions in these databases have been tried. The comparison of the results shows that the most represented solutions are the same in both cases, so, although the random initial populations influence the parts of the solution space that are explored, the genetic algorithm ensures the great representativeness of the provided solutions even with only one computation.

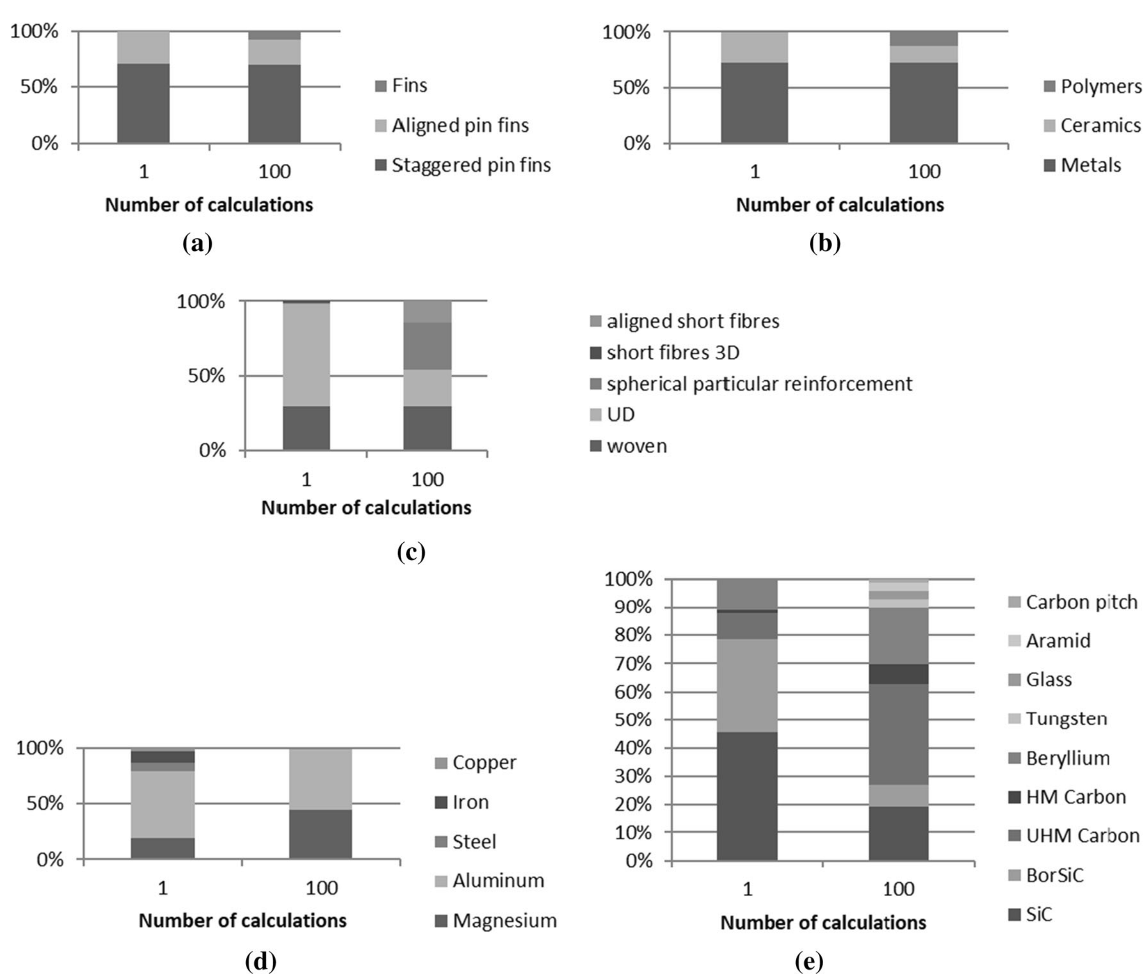

Figure 9 Comparison of the results between 1 and 100 calculations. **a** Upper layer architecture, **b** upper layer material, **c** bottom layer architecture, **d** bottom layer matrix, **e** bottom layer fibre.

Conclusions

The difficulty of the choice of a multi-material for an application comes from the high number of parameters that must be determined. As all these parameters influence the properties of the material and cannot be separated in the homogenisation models, they necessarily have to be considered simultaneously.

In order to be able to generate new associations of materials, a method, based on the selection of attributes in databases, has been developed. Prior to this task, as the architecture of a multi-material can have various configurations, a general frame has been given to its definition, allowing the hierarchisation between the different scales composing the multi-material.

The association of an architecture database and material databases resulted in a huge number of combinations so, as a systematic screening of this space was impossible, a genetic algorithm has been chosen to find optimal solutions with few calculations.

This method has been applied to a case study concerning an electronic packaging for aeronautics. According to the proposed formalism, a primary multilayer architecture was imposed to the multi-material, and a database was built to propose various secondary architectures for each layer.

A statistical study of the results, comparing the solutions of 100 executions of the algorithm and a deeper analysis of only one, has enhanced the excellent representativeness of the obtained solution.

This first approach allows the proposition of new materials to improve the performances of products, but some improvements could be made. Indeed, the pure free search of materials combination can sometimes lead to the proposition of incompatible components for processing, chemical or physical reasons. The implementation of these incompatibilities in the generation of the individuals of the genetic algorithm would avoid the unrealistic solutions. Moreover, the definition of the associated manufacturing process would be an interesting improvement because although it is not really a problem in the early stages of innovative design, it could, however, be a limit in the industrialisation of a product.

Compliance with ethical standards

Conflict of interest The authors certify that there is no conflict of interest in relation to this article.

References

[1] Wargnier H, Kromm FX, Danis M, Brechet Y (2014) Proposal for a multi-material design procedure. Mater Des 56:44–49

[2] Wargnier H, Castillo G, Danis M, Brechet Y (2010) Study of the compatibility between criteria in a set of materials requirements: application to a machine tool frame. Mater Des 31:732–740

[3] Ashby MF, Brechet Y, Cebon D, Salvo L (2004) Selection strategies for materials and processes. Mater Des 25(1):51–67

[4] Sapuan SM (2001) A knowledge-based system for materials selection in mechanical engineering design. Mater Des 22:687–695

[5] Edwards KL (2005) Selecting materials for optimum use in engineering components. Mater Des 26:469–473

[6] Jahan A, Ismail MY, Sapuan SM, Mustapha F (2010) Material screening and choosing methods: a review. Mater Des 31:696–705

[7] Pflug J, Verpoest I (2006) Sandwich materials selection charts. J Sandw Struct Mater 8:407–421

[8] Aceves CM, Skordos AA, Sutcliffe MPF (2008) Design selection methodology for composite structures. Mater Des 29(2):418–426. https://doi.org/10.1016/j.matdes.2007.01.014

[9] Ashby MF (1993) Criteria for selecting the components of composites. Acta Metal Mater 41(5):1313–1335

[10] Giaccobi S, Kromm FX, Wargnier H, Danis M (2010) Filtration in materials selection and multi-materials design. Mater Des 31(4):1842–1847

[11] Weaver PM, Ashby MF (1996) The optimal selection of material and section-shape. J Eng Des 7(2):129–150

[12] Pasini D (2007) Shape transformers for material and shape selection of lightweight beams. Mater Des 28(7):2071–2079

[13] Neveu F, Castanié B, Olivier P (2019) The GAP methodology: a new way to design composites structures. Mater Des 172:107755

[14] Laszczyk L. (2011) Ph.D. Thesis, Grenoble University, T: 2011GRENI088, tel-00721807

[15] Leite P, Thomas M, Simon F, Brechet Y (2015) Optimal design of a multifunctional sandwich panel with foam core: lightweight design for flexural stiffness and acoustical transmission loss. Adv Eng Mater 17(3):311–318

[16] Hao JK, Galinier P, Habib M (1999) Métaheuristiques pour l'optimisation combinatoire et l'affectation sous contraintes. Revue d'intelligence artificielle 13(2):283–324

[17] Wolpert DH, Macready WG (1997) No free lunch theorems for optimization. IEEE Trans Evol Comput 1(1):67–82. https://doi.org/10.1109/4235.585893

[18] Duratti L, Salvo L, Landru D, Bréchet Y (2002) Selecting the components of polymeric composites. Adv Eng Mater 4(6):367–371. https://doi.org/10.1002/1527-2648(20020605)4:6%3c367:AID-ADEM367%3e3.0.CO;2-7

[19] Montemurro M, Koutsawa Y, Belouettar S, Vincenti A, Vannucci P (2012) Design of damping properties of hybrid laminates through a global optimisation strategy. Compos Struct 94(11):3309–3320. https://doi.org/10.1016/j.compstruct.2012.05.003

[20] Ashby MF, Bréchet Y (2003) Designing hybrid materials. Acta Mater 51(19):5801–5821

[21] Brechet Y, Embury JD (2013) Architectured materials: expanding materials space. Scripta Mater 68:1–3

[22] Kromm FX, Quenisset JM, Lorriot T, Harry R, Wargnier H (2007) Definition of a multi-materials design method. Mater Des 28:2641–2646

[23] Gourier C. (2016) Contribution à l'étude de matériaux biocomposites à matrice thermoplastique polyamide-11 et renforcés par des fibres de lin. Ph.D. Thesis, Université de Bretagne Sud, NNT: 2016LORIS415, tel-01445578

[24] Bergander A, Salmén L (2002) Cell wall properties and their effects on the mechanical properties of fibers. J Mater Sci 37(1):151–156. https://doi.org/10.1023/A:1013115925679

[25] Dunlop JWC, Fratzl P (2013) Multilevel architectures in natural materials. Scripta Mater 68(1):8–12. https://doi.org/10.1016/j.scriptamat.2012.05.045

[26] Bollen P, Quiévy N, Huynen I, Bailly C, Detrembleur C, Thomassin JM, Pardoen T (2013) Multifunctional architectured materials for electromagnetic absorption. Scripta Mater 68(1):50–54. https://doi.org/10.1016/j.scriptamat.2012.05.011

[27] Deshpande VS, Fleck NA, Ashby MF (2001) Effective properties of the octet-truss lattice material. J Mech Phys Solids 49:1747–1769

[28] Torquato S, Hyun S, Donev A (2002) Multifunctional composites: optimizing microstructures for simultaneous transport of heat and electricity. Phys Rev Lett 89:266601

[29] Mottram J, Taylor R (1991) Thermal transport properties. In: Lee SM (ed) International encyclopedia of composites, vol 5. VCH Publisher, New York, pp 476–496

[30] Vincenti A, Reza AM, Vannucci P (2009) BIANCA: a genetic algorithm to solve hard combinatorial optimisation problems in engineering. J Glob Optim 48:399–421

[31] Irisarri F.X. (2009) Stratégie de calcul pour l'optimisation multiobjectif des structures composites, Ph.D. Thesis Université Paul Sabatier – Toulouse III, tel-00514120

[32] Baracchini P, Guillebaud C, Kromm FX, Wargnier H (2019) Multi-material design in the case of a coupled selection of architectures and materials: application to an embedded electronic packaging. J Mater Eng Perform 28(12):7248–7258