



# Investigating the multilevel logic in design solutions: a Function Behaviour Structure (FBS) analysis

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## Abstract

One of the reasons why Function Behaviour Structure (FBS) model did not become a pragmatic tool in industrial practice is its inability to push the designer to develop solutions beyond the dimensional scale where components, materials, and their relationships, of an artifact are defined. This paper introduces the concept of “topology” into the FBS model to support design in a multidimensional way. Though the proposed method, instead of describing a technical system with a unique FBS model, as many models as there are levels of detail in which it can be decomposed, can be exploited. Topology is crucial for linking them together in a hierarchical organization from macro to micro, so as to use the FBS ontology both to interpret and exploit physical phenomena in the design phase. Test results about the application of the proposed FBS multilevel method on a real industrial case study with engineering students showed its ability to modify their design attitude to generate solutions from an early expansion of concepts (breadth-first strategy) to the reformulation and refinement of the same (to depth-first strategy). More in detail, through the method, the students deeper analyse of the system, individuate a greater number of parameters on which to work and provide solutions exploiting the available resources more rationally.

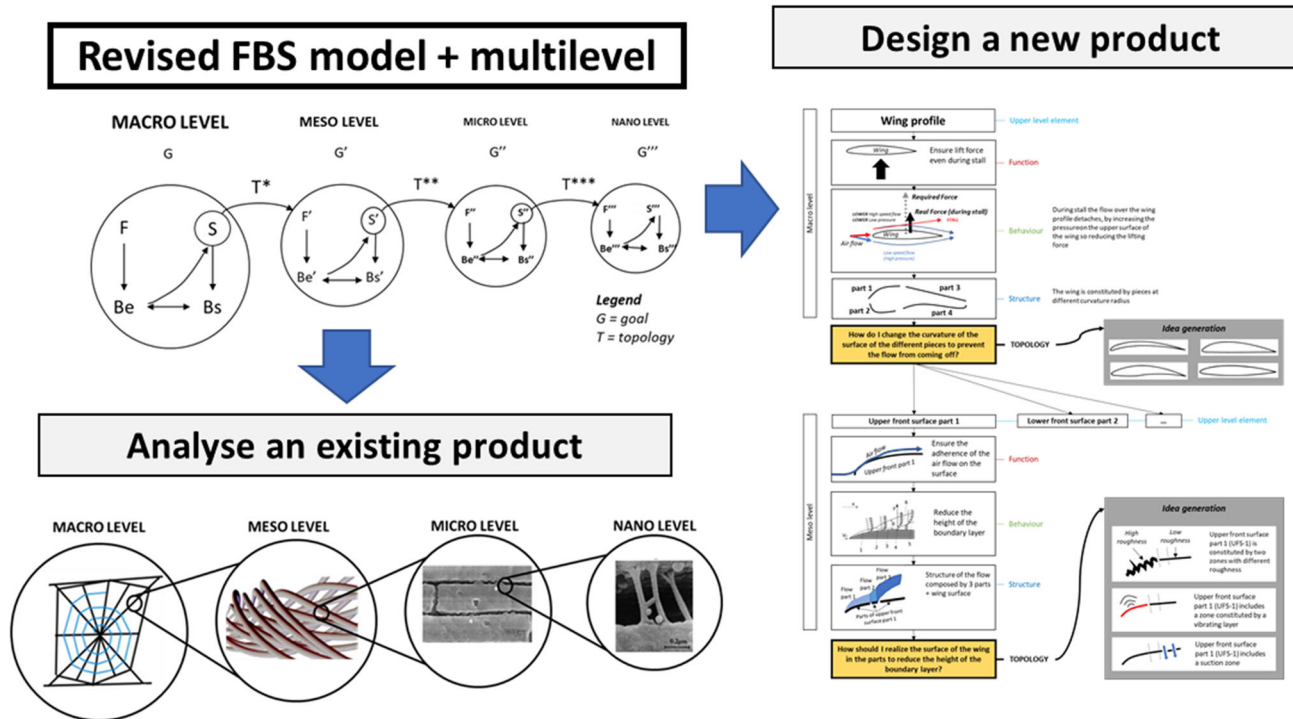
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## Graphical abstract



**Keywords** FBS · Multilevel design · Topology

### Highlights

- FBS model was reformulated to support multilevel design.
- Topology is used as the logical link to descent to sub-levels of detail.
- The proposed method allowed students to individuate a greater number of parameters on which to work.
- The solutions provided through the method exploited the available resources more rationally.

## 1 Introduction

The external world is universally acknowledged to be far too complex to be described with a single level of detail. For instance, many natural systems are the result of an optimization, which is incomprehensible to understand without going down levels of detail of the analysis. In this way, the perception of the problem results completely distorted, such as gravity that disappears into favour of intermolecular attraction forces.

Even the design of artifacts could be positively influenced by this change of perspective. Consider, for example, the problem of the stall of a wing profile, approached within a single level: if a wing profile cannot overcome the stall, the solution means the rethinking of the shape of the entire wing. On the contrary, approaching the same problem by involving

the descent at a sub-level, leads us to reformulate the problem in a more conscious way, e.g. by considering the air flow in the critical zone responsible for the stall, and to hypothesize specific solution to solve the reformulated problem, e.g. the modification of design only for that critical zone.

However, despite the many proposed design models and their evolutions, e.g. Function Behavior Structure (FBS) model [7], multilevel design is not yet supported by a pragmatic tool, supporting everyday industrial practice (see Sect. 2.1). In the few models in which the multilevel logic is present (see Sect. 2.2.), the complexity of the examples analysed is reduced to the bone, with applications in systems consisting of few components Hamraz and Clarkson [13].

To address these limitations, in this study, a reformulation of the traditional FBS model [7] at multilevel is proposed through the introduction of topology as a linkage to descent

the level of detail and reapply the model in a new perspective. The objective is to increase designer's awareness about new problems and to support her/him in finding new and more strategic solutions to solve the initial problems through reformulation and the refinement of the initial solution at macro-level. A test on a real industrial case study about an aerosol valve has been conducted with engineering students and the obtained solutions have been analysed to verify if the method meets its objective and to investigate the impact on the design practice.

The structure of the study is organized as follows. Section 2 presents a state of the art about FBS model its main reformulations and the intersections with the logic of multilevel design. Section 3 presents the proposed method. Section 4 shows an example of application of the proposed method. In Sect. 5, the results the test with engineering students about the application of the proposed method are presented and discussed. Finally, Sect. 6 draws the conclusions.

## 2 State of the art

### 2.1 FBS model

Among the reasoning schemas supporting new concept design and product re-design, FBS model [7] is one of the most popular. FBS model was initially introduced as a theoretical framework to analyse an existing product to be improved, as a preliminary activity to the design [25]. The turning point towards the modelling of the design activity is mainly due to the works of Tomiyama et al. [24] that shifted the perspective of analysis from device-centric to event-based, through the deepening of the concept of the functioning of the product, starting from previous studies (e.g. [4, 5, 15]).

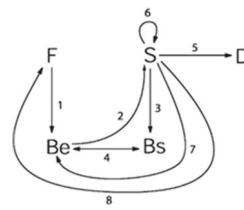
Precisely the description of the functioning of the product is the distinctive trait of the FBS model, which differentiates it from other design models, which, in the FBS ontology, takes the name of behaviour. The definition of the latter together with that of the other design elements of the FBS model and the modelling of the design process, provided by [7], are reported in Table 1.

During the years, FBS model was improved many times in order to make it more pragmatic and to ameliorate its application in supporting a design activity.

The definitions of the original design elements, i.e. Function, Behavior and Structure have been repeatedly reviewed at an ontological level, both on the semantic level (e.g. [6, 26]) and incorporating other concepts, such as physical effects or possible product faults in behavior (e.g. [21]).

The roles of the product designer and user have been integrated into the FBS model (e.g. [3, 9, 23]). These studies also

**Table 1** FBS model and definitions [7]



**Function (F):** The design intentions or purposes

**Behaviour (B):** How the structure of an artefact achieves its functions. Divided into Expected behaviour (Be) and Actual behaviour (Bs)

**Structure (S):** The components which make up an artefact and their relationships

**Design description (D):** is graphically, numerically, and/or textually representation to transfer sufficient information about the designed artefact so that it can be manufactured, fabricated or constructed

The **relations** are: (1)

Formulation, (2) Synthesis, (3)

Analysis, (4) Evaluation, (5)

Documentation, (6, 7, 8)

Reformulations

considered the roles of the designer and the user and started from the hypothesis that these two actors can understand and perceive the product and its design elements differently. Therefore, to keep track of this fact, the original FBS model has been significantly expanded by introducing new partitions of the already existing design elements (e.g. actual, expected, true intended, false intended), new elements (e.g. affordances, signals, needs) and new relations (e.g. perception, interpretation, simulation).

Qualitative and quantitative modeling has been proposed and integrated to describe the design elements and the design activity (e.g. [10, 27]), with the aim of reusing the FBS model in advanced systems to support the autonomous design based on artificial intelligence. The results concern the introduction of hierarchical taxonomies, the use of mass, energy and information flows, as in the energy-material-signal model.

Finally, there is a line of research, whose authors approached the description of the product with FBS and multiple levels of detail, described in detail in the following section.

### 2.2 FBS and multilevel

The first attempt to link FBS model and multilevel logic was made by Gero [7] with the division of the structure in multiple parts, i.e. the structure\_elements and their attributes, i.e. the structure\_element\_variables. While the first formalization of the levels of detail started with Gero and McNeill [8], McNeill et al. [16] and Song et al. [22] with the introduction of three “levels of abstraction”: system level, where the problem design is described as an integral whole, the level of

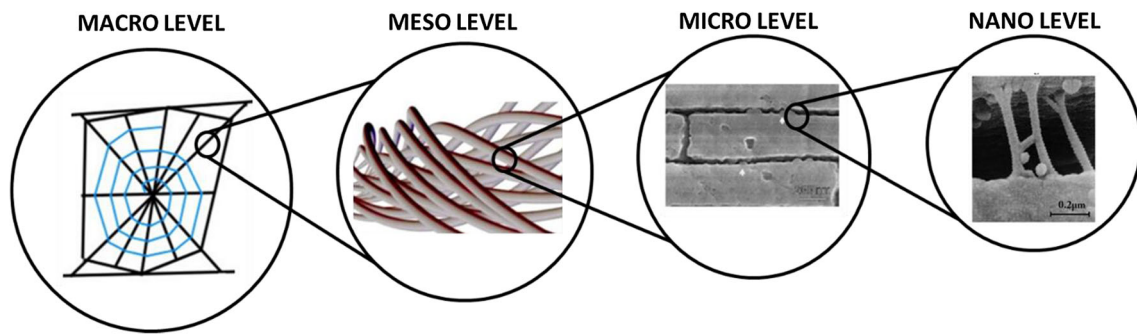


Fig. 1 Spider web described at different levels of detail

the interactions between the sub-systems and the level of the description of the details of the subsystems. On the nature of the logical passage from a level of detail to its sub-levels in FBS model, some authors provided different definitions. According to Hamraz et al. [12] and Pahl et al. [18], the descent of the level is a purely functional decomposition, where a function is decomposed in different subfunctions at different hierarchical levels, where each subfunction realize a certain specific behaviour. Other authors (e.g. [11, 25]) refer to descent of the level from a more structural point of view, by considering the hierarchical decomposition of the structures, where smaller attributes are identified from larger attributes.

However, FBS is not perceived as a real pragmatic tool in supporting multilevel design. According to Hamraz and Clarkson [13], FBS model is too rigorous for analysing complex systems with large number of components and to combine them to build a complete product. The same authors justify this hypothesis by showing how FBS model has been successfully applied in literature only on systems with a low degree of complexity consisting of few tens of unique components (e.g. gyroscope, nitric-acid cooler, copier, vacuum cleaner, buzzer).

Anyway, the number of components is only one of the aspects that define complexity of a system. There are at least two other aspects that contribute to this definition and which can undermine the application of the FBS model. A lot of products and natural systems are made by multi-material structures, where the materials collaborate between them both from a mechanical and thermic point of view, e.g. composite materials, allowing better performances than single material structures [2]. The main criticality in describing these systems lies in the ability of their components to collaborate each other dynamically to perform a common function, finding synergies between different specific physical properties, which difficult to explain through the shape. Second, in addition to the material and the shape, another complication to take into account regards the level of detail of the organization of the structures are organized, since it can difficulty been exhaustively described inside a single level. In general,

the biological systems and, in particular, the organisms are organized through a hierarchical multilevel, where in each level, there is an organization of their structure, at many different dimensional scales and organization principles.

For this reason, the organization that can be described at a macroscopic level is the collaboration of different systems inside the levels of detail, through determined hierarchical mechanisms. Consequently, the difference between simple mono-cellular organisms and higher vertebrates, is not in the nature of basic constituent, such as proteins, but in the level of complexity of the organization of their structure, so that, the higher is the level of evolution, the more organic matter is organized in cells, tissues, organs, apparatus, etc.

Finally, also the physical effects are distributed at different levels, since the scheme, in which all structures are organized, with a hierarchical logic, at different dimensional levels, involves different physical models in order to pass from a level to another. In natural systems, depending on the different scale levels of representation, shape and morphology change, modifying consequently also physical interactions. Nature in the multitude of cases includes all these problems. Living beings are an endless collection of examples of how the stunning mechanical characteristics of biological structures 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 behaviour of the structures at higher levels.

As an example, Raabe et al. [17] 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) behaviours. 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 (see Fig. 1) is another remarkable example. In fact, it would be a mistake

to consider 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 organizations of the organic material at various dimensional scales.

### 3 Proposed method

In this study, topology is introduced as a logical linkage to descent from a level of detail to its sub-levels. Topology can be defined as the way in which a structure is thought internally to determine its physical behaviour at a sub-level of detail, or the way in which a material is composed to confer the property that the structure needs to achieve a given function according to a given behaviour.

This because the physical properties are directly influenced by the geometry with which the components of the structure are made, both at macro and micro level. For example, wheat is a harmless material but if reduced to powder becomes a dangerous and powerful explosive. Gold is a material unassailable by most chemical compounds; however, studies are underway on the use of gold as a catalyst, because gold in the form of nano-particles dispersed on suitable supports shows great catalytic activity.

In this way, topology improves traditional ways to intend structural decomposition of technical systems based on the hierarchization of functions and their biunivocal correspondence with the substructures, by introducing a new perspective involving the physical-behavioural interactions. This aspect, can represent an undoubted advantage for the designer by increasing their awareness. Consider for instance the applications of titanium within product design. The same is among the most conventionally selected materials to ensure high rigidity of chassis along with lightness, while other applications (i.e. springs, eyeglass frames, bellows, tennis rackets) involve instead titanium due to its high flexibility. What discerns its features depends on its topology, and more specifically the thickness, as well as for any other materials. This aspect is particularly accentuated in auxetic materials because the modification of their molecular morphology can confer them a singular behaviour to traction, characterized by negative Poisson coefficient: unlike traditional materials that decrease their section, the auxetic ones become thicker.

The concept of topology helps us to explain the way in which a microstructure realizes a specific behaviour at a higher level. It is the explanation of how a structure must be made to assume a certain property: for this reason, it is directly linked to the superior Structure and the Function at lower level. In other words, in referring to Gero's FBS model (see Fig. 2), topology (e.g. T\*) links the structure (S) at a determined level (Macro level) to the function (F'),

because, by explaining how the sub-structures (S') are organised inside the structure (S), it provides the justification of their aims (F').

The nature of FBS multilevel is twofold. When it is used to analyse an existing biological system, the scheme can be declined through a series of sub-levels till the degree of knowledge of the designer is able to model the sub-domains. While, when it is used to support design activity, alternative models for each level of detail can be determined, which differ between them in the modality through with function, behaviour and structure are offered.

The two ways of use for the proposed method are presented in detail in the following.

#### 3.1 Application to analyse an existing system

As an example of the proposed methodological framework, a spider's orb web is analysed and modelled adopting the enriched FBS approach in a multilevel logic. Figure 3 shows how the orb-web has been divided into levels (macro, meso and micro); each level is explained with its own FBS model and how topologies allow to move from one level to another.

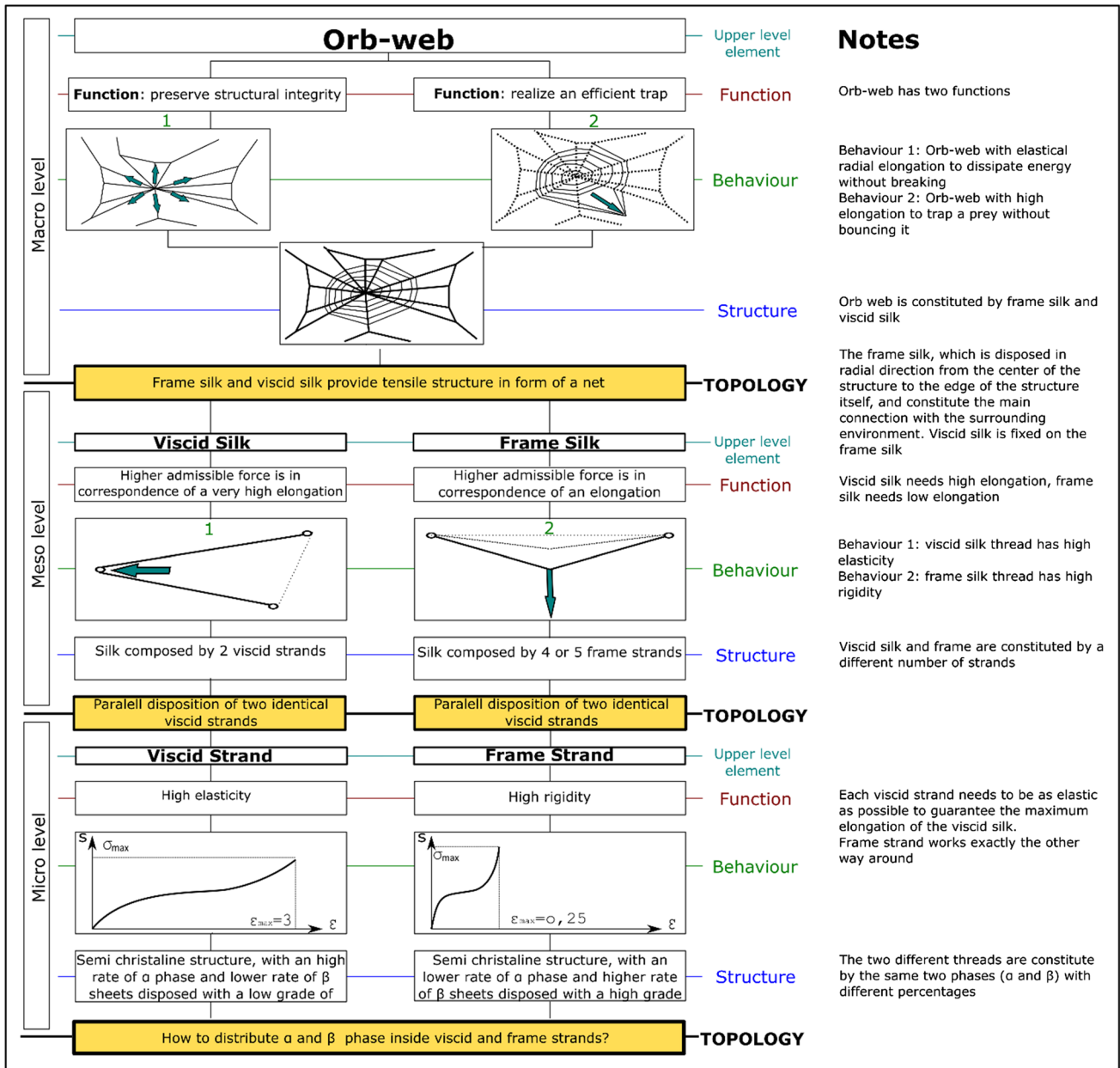
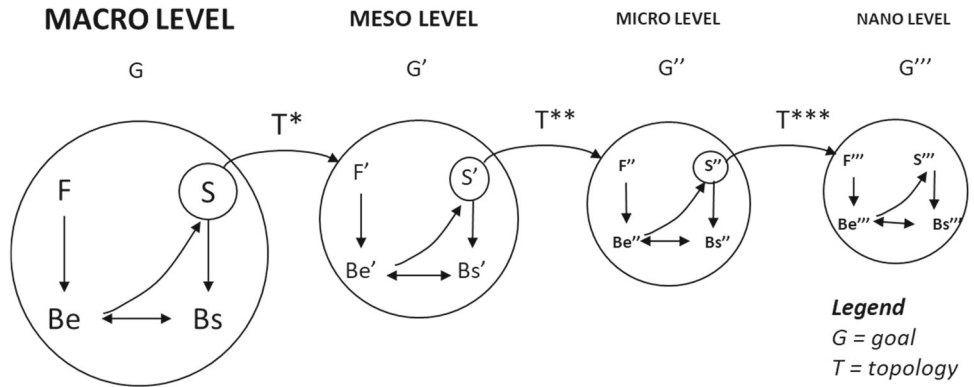
#### 3.2 Application to design a new system

In design process, according to Gero's FBS traditional model, once a structure, designed to accomplish a certain function, according to a determined expected behaviour (Be), has been realized and tested, if its actual behaviour (Bs) is not considered satisfactory from the comparison with Be, itself or its behaviour or its function need to be reformulated. The difference between the traditional model and the multilevel one, lies in the reformulation of the problem and more in general in the definition of the design alternatives. For simplicity, considering C-K theory [14] to describe a design activity, we can distinguish two distinct strategies, respectively related to traditional FBS approach and FBS multilevel.

The first one, called "breadth-first" strategy corresponds to an early expansion of concepts and favours exploration for new knowledge, whereas the other, called "depth-first" strategy consists instead in avoiding too numerous early partitions in the C-space by favouring the exploitation of existing knowledge. In referring to Fig. 4, in our case, in the "breadth-first" strategy, the conceptual bubble C1, C2, ..., Cn contains FBS triads at the same level of detail, where at least one of the elements of the triad (function, behaviour or structure) is different from the other, while in the "depth-first" strategy, the passage from the bubble C1 to the C2 represents the determination of a new FBS triad at a sub-level of detail. While for each FBS system the knowledge about FBS can be reached by the knowledge space, when available, according to the mechanism explained by C-K theory [14].



**Fig. 2** The proposed model of design links FBS scheme [7] with multilevel through topology



**Fig. 3** Example of description of an Orb-web through FBS enriched with topology concept and multilevel description

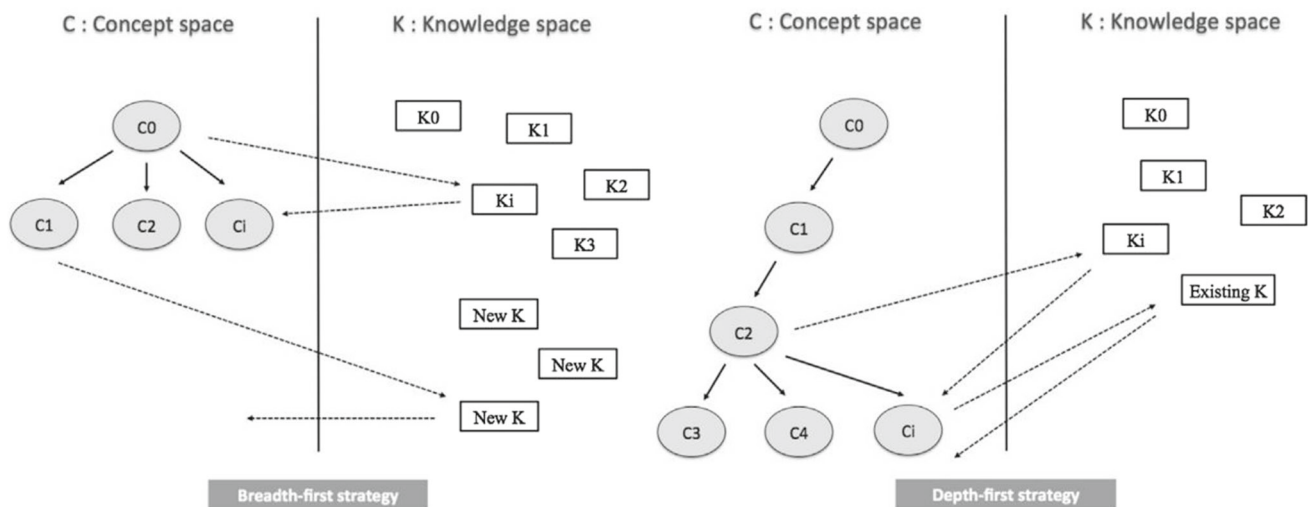


Fig. 4 Breadth-first strategy versus depth-first strategy [14]

The philosophy at the base of the proposed approach can influence the way designers conduct a problem-solving task. The tools to support the design such as CAD, Fem and Structural Optimizers, as well as the methods of conceptual design, among which FBS also push the designer to work in the same level of detail. Any creative process that calls into question one of the entities of the FBS will help to reformulate the problem with a new alternative function, behaviour or structure, and very rarely to go deeper to a new level of detail. Nature does not work in this way and inspired authors to work in a different direction.

The breadth first and deep first representation in Fig. 5 is used to map the designer's modus operandi in order to test if it is true that designer's diagrams tend towards the first strategy and more rarely towards the second one. What we are expecting is that giving the designer the awareness of the role that topology can have in making a technical system work correctly, it goes deeper in the (functional) analysis of the structure and makes more efficient use of the resources available to it.

In order to explain the mechanism that we try to recognize in a problem-solving phase, an exemplary case about the redesign of a wing is presented, see Fig. 6. The problem to be solved is about the stall of a wing profile, analyzed both with traditional FBS approach and the enriched one with topology-based triggers strategy. Starting from the same goal "Avoid stall", the designer formulates the function "Create lift on a wing" and a proper expected behaviour about the physical description of an air flow that meets a certain stretched body by dividing into two flows, one above and one under the wing. The different speeds and therefore the different pressures of the two flows, with the upper characterized by a lower value of pressure, is responsible for the generation of the lift force.

One of the possible compatible structures is that shown in Fig. 5.

However, we can suppose that the results from the experimentation of the hypothesized structure (a generic wing profile) are not satisfactory because the lifting force is less than expected. To solve this problem, one direction is to work on the shape of wing profiles in order to optimize the adhesion of the air flow to its surface, preventing it from detaching when stall conditions occur. From this moment, the problem-solving task will be mainly aimed at generating set of alternatives and introducing design tools for checking their efficiency.

Consider to face the same problem by using the FBS multilevel, by limiting the proceedings to one single descent at sub-level, from macro to meso (see Fig. 6). The first part of the problem-solving process does not change; problem solving will take into account the design of new wing shapes. What can open a new solution space is the way we think how the profile surface interacts with the air flow, systematically for all parts in which (macro level) structure is divided. Analyzing the system at a lower level of detail, by a new FBS model, designer will be forced to analyze more deeply all phenomena that influence the physical interaction between wing surface and air; therefore, it will be forced to find a solution in a more specific operative zone.

Moving to a new functional system, in a deeper level of detail, the set of technical parameters exploitable for solving the problems increase, so enlarging the solution space and the chances to solve the problem. In this case, the new formulation of the FBS describes the formation of the boundary layer around the upper front surface of the wing. The new (meso level) topology trigger suggests to think about the interaction among different sections of this part of the wing (i.e. the upper front part surface) and different zones of the boundary

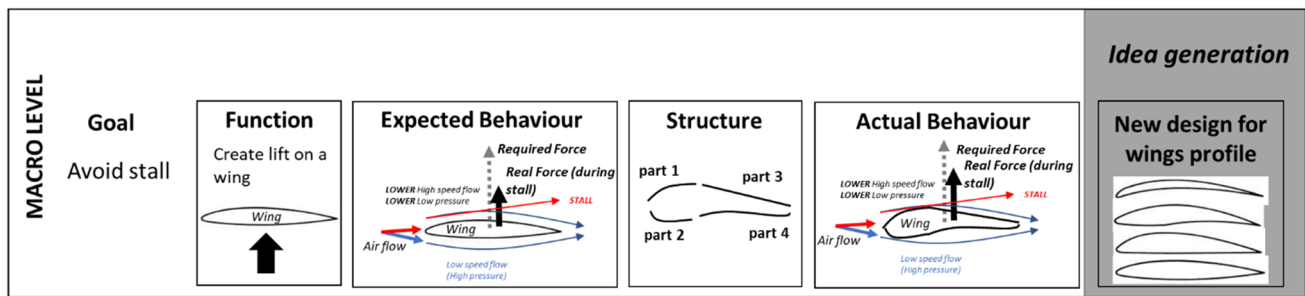


Fig. 5 Example of FBS traditional model to solve the design problem “Avoiding wing stall”

layer (laminar, transitional and turbulent areas). In addition to the shape of the profile, new control parameters should appear for solving the problem: attach the air flow by creating a sucking effect, working on local roughness, interacting with flow with new forces, like vibration, etc.

At a general level, the proposed method can be applied independently from the initial level of detail and several times in a consecutive way, to descend several levels of detail. Therefore, this study, the different examples shown so far and in the next sections show its application in different ways in relation to these two aspects.

## 4 Case study

In order to show the usefulness of the proposed method to find new solutions, a case study about the design of a system to open the cover of a greenhouse when the temperature exceeds a given value is presented in this section.

The starting point is the identification of solutions working at macro-level on the upper element, e.g. the greenhouse cover, applying the traditional FBS model to isolate the design elements of the solutions, i.e. function, behaviour and structure, and classifying the solutions according to these latter. These results are reported in Fig. 7.

Every solution that can be obtained from the combination of function, behaviour and structure at the macro-level is an alternative to another. What changes can be the different temporal reformulations of the problem: preventive solutions, solutions that work simultaneously with the evolution of the problem and solutions that mitigate the damage caused by the inability to solve the problem during its occurrence.

The application of the proposed method at macro-level, see Fig. 8 where the “Deform the cover (function) by flexion (behaviour)” branch has been considered, allows a better exploitation of the frame organization. At this level, the topology trigger can lead to the identification of solutions that replace a part of the structure with a new system providing the needed functions. The result is an increase in the number of parts, i.e. the central crosspiece substituted by telescopic

pistons, a pantograph, or made of iron and controlled by electromagnetic system.

Instead, at meso-level, the topology trigger can produce a different set of ideas. Central crosspiece can be redesigned allowing it to stretch (meso-level) in order to produce the cover flexion at macro-level. This new reformulation opens to a new set of solutions, exploiting new physical effects (e.g. thermal dilatation and flexion) for a new function (i.e. to stretch). Furthermore, topology can force the designer to introduce each solution in a multilayer organization, so reducing the operative zone only to one layer and so saving further material and volume.

## 5 Test of the proposed method

This testing procedure of the proposed method was carried out on 40 MSc students in mechanical engineering from the University of Bergamo on a real design problem. The results obtained by the students using the proposed method, constituting the testing group, have been compared to those extracted from a set of patents working on the same problem, which authors have not reasonably used the proposed method, constituting the control group.

### 5.1 Design problem definition

The assigned problem is a real industrial case study provided by a leading multinational company in the production of aerosol spray packaging solutions and filling equipment. The objective is the elimination of the post-foaming from shaving foam cans, dealing with the spill of a little amount of foam from the dispenser. The shaving foam is dispensed from these devices by actuating a common aerosol valve that causes gas to escape from inside the canister. In turn, by reacting with air within the distribution channel downstream of the valve, the gas creates the foam. However, some residual gas remains within the channel also after the closure of the valve, by producing a small excess of foam after the reaction with air, that remain within and just outside the channel. This



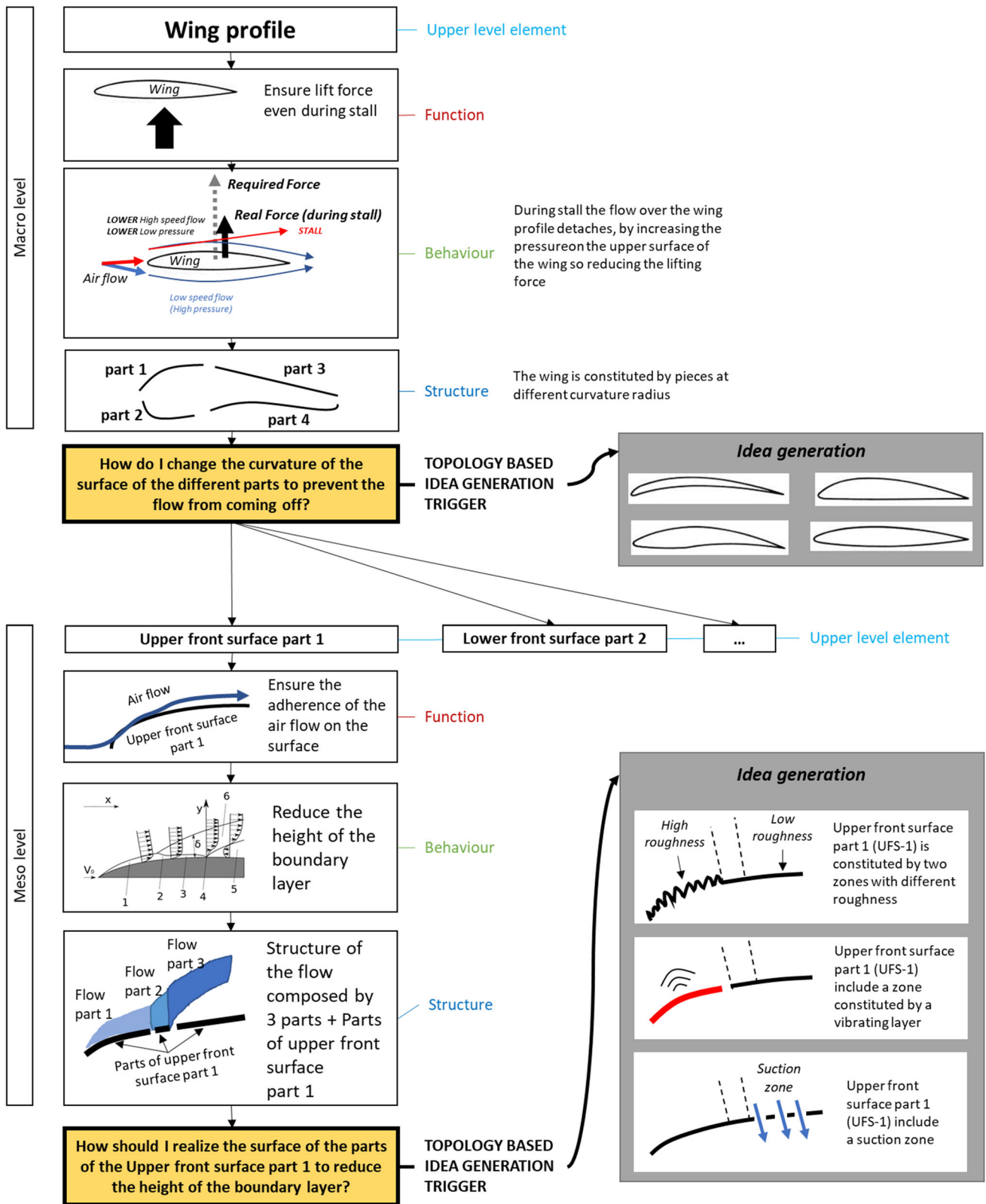


Fig. 6 Example of FBS multilevel model (two levels) to solve the previous design problem “Avoiding wing stall”

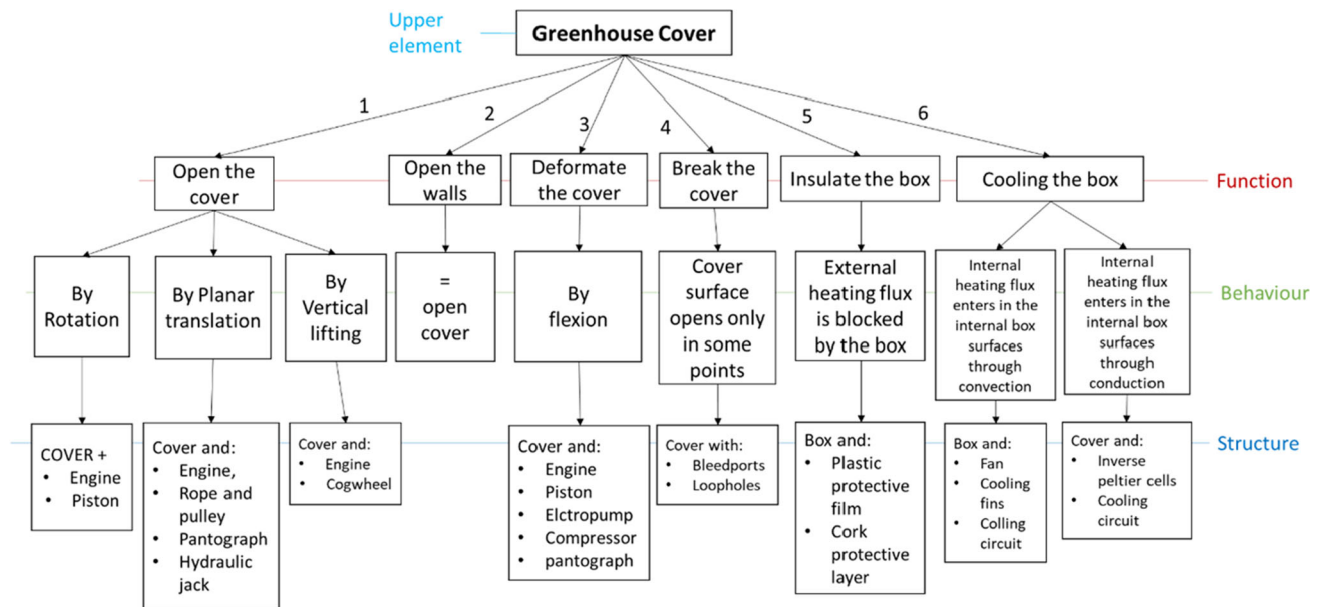


Fig. 7 Examples of solutions for “opening the Greenhouse cover” working at macro-level

problem affects both hygiene and appearance, since, evaporating, the residual foam can dirt both the channel and the exterior part of the dispenser. Finally, the solutions must not hinder the cylinder loading process from the top of the valve, during production, e.g. by throttling the stem too much.

Figure 9 represents the simplified temporal dynamic of the phenomenon of the post-foaming in three steps.

## 5.2 Test participants and tested material

The 40 students participating in this project were 38 males and 2 females, aged between 23 and 27, all educated in Italy and attending the M.Sc. in Mechanical Engineering at the University of Bergamo. All the students, during the university program, followed all the standard engineering courses related to the design and construction of machines and none of them has professional experience in the field of design. The students attended the course of Product and Process Innovation, which is dedicated to the teaching of models and tools for problem solving, design and patent analysis, through an 80 h program distributed over 4 months. The course ends with the evaluation of a final project about a real industrial case study to be carried out individually and supported by the methods and tools thought during the course.

The control group is constituted by the patented solutions about the same problem, i.e. avoiding the post foaming in aerosol valve. The patent literature related to this problem is quite varied and difficult to frame with targeted queries. Less than 20% of the selected patents relating to the described problem refer to the term “post-foaming”, which is also used to describe the industrial process of production of the

foaming substance, as well as in other technological sectors. Furthermore, the problem of post-foaming does not only concern products for shaving but also other fields of application related to foamy products with very similar characteristics in terms of pressure and temperature of the secondary reaction of post-foaming by the low boiling residues in the duct. For this reason, a generic pool of patents about aerosol valves for foamy products was collected by using queries with generic terms and their synonyms (e.g. valve, aerosol, foam) in Espacenet DB and by manually selecting only the relevant results. The latter are only the patents proposing, according to what is explicitly stated in title, abstract or claims, solutions to avoid post foaming in aerosol valves and provide sufficient descriptions of the same to be able to identify their function, behavior and structure. After this selection, the final patent pool counts 178 documents.

## 5.3 Test execution

The supporting design methods assigned to the students are different. In addition to the proposed FBS multilevel, the students also used some problem-solving tools provided by the TRIZ (Russian acronym for “Theory of Inventive Problem Solving”) method [1]: Minimal Technical System (MTS) model, Element Name Value (ENV) model, system operator, physical contradictions and inventive principles.

Each method was carefully presented to the students during a 4-h frontal lesson and a 3-h collective exercise carried out on two consecutive days. For each of them, an introduction was made only for its role within the TRIZ solution path, the principle of operation was explained and examples from

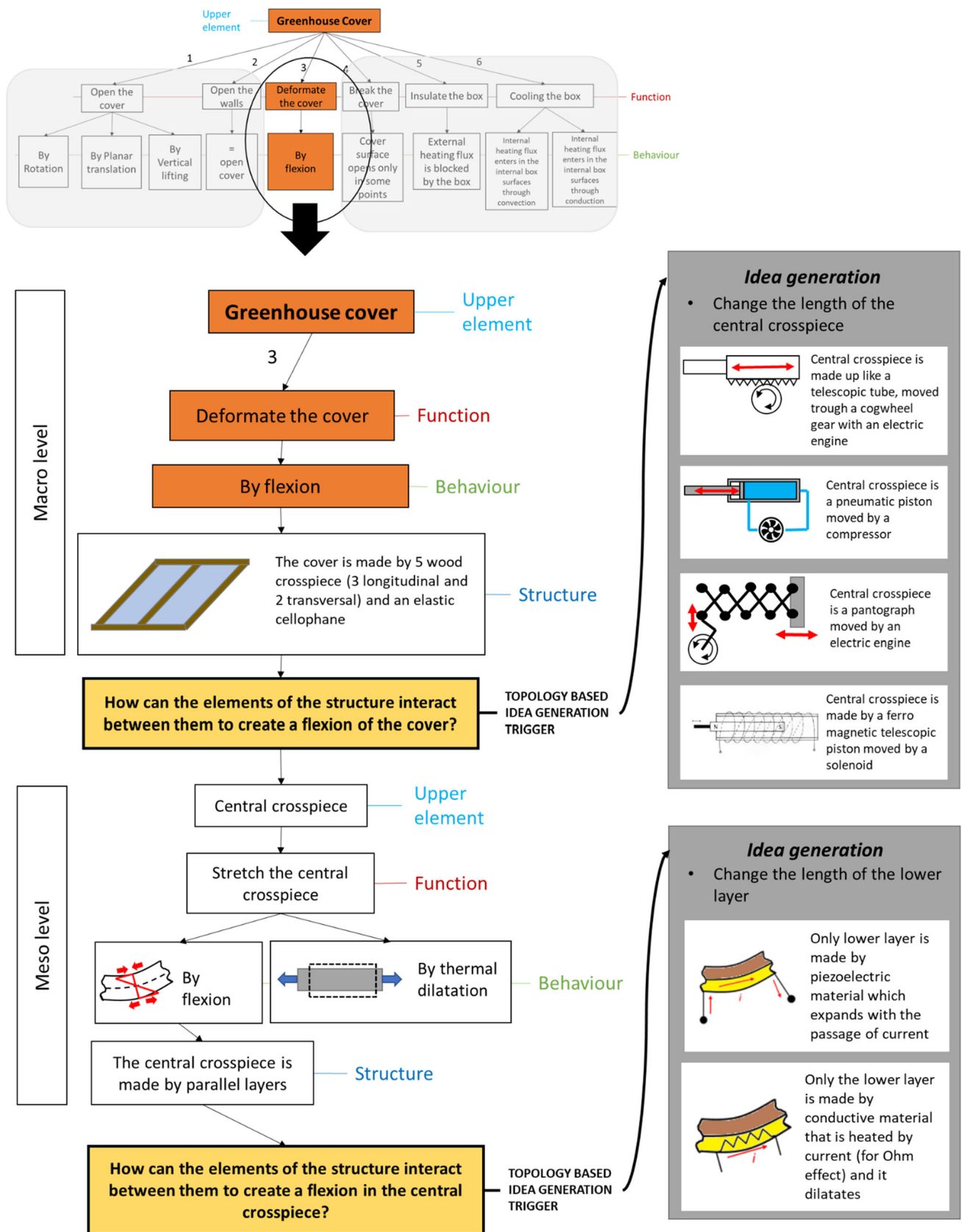


Fig. 8 Examples of solutions determined at macro and meso-level to solve the specific sub-problem “Deform the cover by flexion” by using the proposed method

the literature were presented. In addition, the students were provided with the basis for the patent search on Espacenet DB to verify if the identified solutions have already been patented and to gather design knowledge from patents.

All the case studies were presented in detail to the students by R&D technicians from the companies providing them, during three hours meeting where the students could ask questions about the problem and the requirements. In order not to influence the students in any way, no indication of the attempts undertaken in the company to solve the problem, nor the solutions currently developed in the state of the art and commercial and patent was provided to them.

During the final project, the students were asked to solve the problem individually in a maximum time of two weeks and to provide a detailed description about the obtained solutions and the followed resolute design path. The obtained solutions were presented by specifying their main functional and structural aspects. In this case, the students provided CAD drawings and detailed explanations and sketches relating to the Functions performed and the dynamics of the behavior and physical effects. The functional specifications relating to the materials and components to be used were also discussed by the students, without providing a sizing of maximum of the same. In addition, the students also had to provide any patents that are the same or similar to their solutions.

In addition to the presentation of the solutions, the students also specified the used supporting methods and tools and described, in natural language, the considered design purposes.

#### 5.4 Evaluation procedures

The authors personally analysed all the solutions proposed by the students and those collected from the patents. The testing hypothesis to verify through the test is to understand if the solutions provided by the students using the proposed method

explore more levels of detail than those collected from the patents. To do this, for each solution, any feature that can be associated with multilevel design logic prescribed by the proposed model was determined. In particular, the following design elements, taken from FBS ontology [7], were collected, if explicitly specified, or extrapolated by rigorously referring to the original definitions, and associated with the level of detail on which they are intended.

- **Upper element**, on which the solution works, can be a component or a part of a component. The identification of this design element in a solution is fundamental to understand if this latter works on the whole product or only a one of its parts or constituting elements. The descent of the level of detail could be assumed to coincide with the redesign of a specific part or component rather than the entire product, but this cannot be a sufficient condition.
- **Function, behaviour and structure**, which definitions were previously reported in Sect. 1, were instead exploited to investigate the focus of the design activity. In fact, we hypothesize that a multilevel design is based on the knowledge of physical phenomena and effects (behaviour) not considered at a higher level, and consequently, also on new needs to cope with the latter (function) and new structures to interact with these phenomena and govern them (structure). According to this assumption, multilevel design should therefore be based on a sort of doubling of function, behaviour and structure.

The evaluation of the collected solutions has been carried out by considering four metrics, defined by Shah [19, 20], typically used to assess design creativity:

- Quantity is the sum of ideas generated by each group (i.e. the testing group and the control group).
- Novelty is the measure of how unusual or unexpected an idea is in comparison to the others.

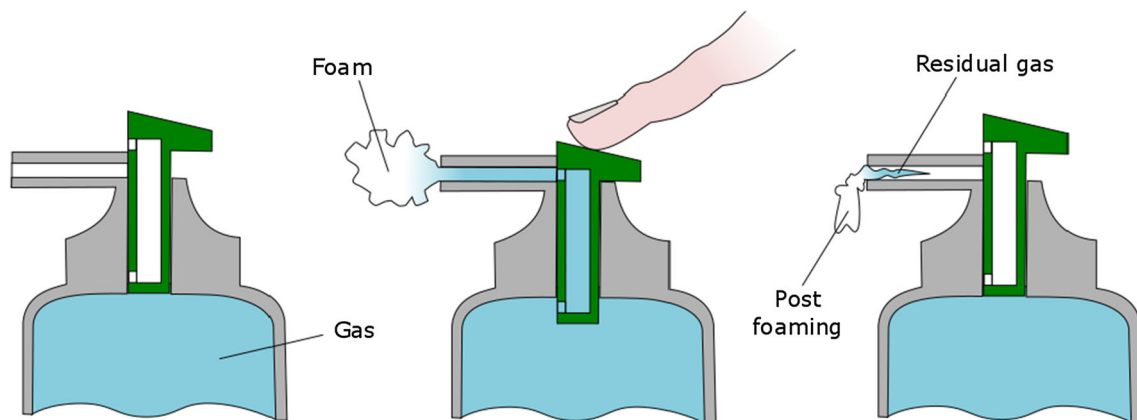


Fig. 9 Simplified representation of the post-foaming in aerosol valve

- Variety is the measure of how solution space has been explored during idea generation process.
- Quality is a measure of the feasibility of the idea.

## 5.5 Test results

To understand the effectiveness of the proposed method, the number of the solutions (i.e. quantity parameter in Shah metric) descending the level of detail proposed by the two groups, i.e. students applying the proposed method (testing group) and patent inventors without the proposed method (control group) were collected and compared in Fig. 10. In particular, in this comparison, the solutions working at a lower level of detail have been divided into two types depending on the transitions to sublevels: 1 (i.e. from macro to meso-level) and 2 (i.e. from macro to micro-level). In order to be able to compare the results, the numbers of the solutions of the different types proposed by the students and by the patent inventors were normalized, respectively as a function of the total number of solutions provided by the students and by the patent inventors.

Analysing the results shown in Fig. 10, it can be noted that the proposed method has obtained its results. The method should not be understood as a way to make the designer work always and only through the level of detail. But when stimulated in this sense, the designer is more inclined to descend more than one level. In fact, both the students and the inventors of the patents have proposed a comparable percentage number of solutions that descend only one level. While the students proposed a proportionally almost triple number of solutions that go down two levels of detail. Furthermore, it should also be considered that the students overall proposed more solutions that go down at least one level compared to the inventors of the patents, despite their lesser experience.

Going into the merits of the results, it is possible to draw more detailed considerations and some justifications for the results obtained.

In solutions that do not descend the level of detail, i.e. macro-level solutions, the students, while striving to do so through the application of the method, do not grasp a structural element (i.e. upper element) to explore in its microstructure. Therefore, the students limit themselves to the segmentation and recombination of its parts, by applying all the provided problem-solving tools (see Sect. 5.3) within few structural alternatives. For instance, most of the solutions about the elimination of the post foaming, working on the Function "Prevent the entry of air" inside the upper element "Duct" and by means of the behaviour "Reduce the diameter until it closes", structurally refer to the same ducts of the initial product, limited only to dividing it into two parts. These latter can be one fixed and one mobile, but rigid

which is brought closer to the fixed one, reducing the distance between them, by including pistons, springs and hinges.

In solutions that go down one level of detail, i.e. meso-level solutions, the students identified a new function and a new behaviour on which to work, typically thinking about how to flex and deform single-component parts. For instance, with reference to the previous example, to reduce the diameter of the duct by bringing two of its parts together, no systems are sought to move the mobile part of the duct. However, the function is reformulated, e.g. by thinking the ways to change its shape, by means of a new behaviour, e.g. by bending, and therefore looking for deformable structures due to their material or their geometry that can be used as a mobile bulkhead.

Finally, in solutions that go down two levels of detail, i.e. micro-level solutions, students actually explored the chemical and physical characteristics of product materials. The functions and behaviours that have been considered are more heterogeneous than those of meso-level solutions, which were typically confined to the mechanical field, since they also range from thermal, electric and magnetic. For instance, in the case study, going down a further level of detail means studying how to deform a portion of material so that its flexion can be obtained macroscopically. The possible solutions will therefore have to facilitate this deformation, for example through the use of porous materials.

In addition, the students who have been able to focus their application on the sub-level, considered more fields of application, also favored by the identification of the new reformulated Functions and new possible Behaviors to be exploited. Consider for instance the exploitation of the concept of porosity: when applying this principle to the Structure of the aerosol valve at the macro level, or the mobile rigid bulkhead, a useful solution could be difficultly determined. The porosity within this bulkhead could only lead benefits in the material reduction but without guaranteeing the Function "block air inlet" at this level of detail. While, the application of porous materials at the micro level can obtain a different purpose (i.e. Function at the micro-level) or to the change of volume. The validity of this principle for this purpose was verified by various applications in other fields (e.g. foams).

Furthermore, some solutions provided by the students at the micro-level, such as porous materials, flexible shells, and the nesting of substances, can also lead to solutions with a greater degree of innovation and not yet patented, as emerged from patent analysis.

Figure 11 shows and graphically organizes the design elements and some examples of solutions collected in the case study.

The novelty of the proposed solutions was evaluated by comparing them with the patent literature, in search of already patented solutions that make them precedent. From this it emerged that all the solutions of the testing group have already been described in the patents of the control group.



Fig. 10 Testing results

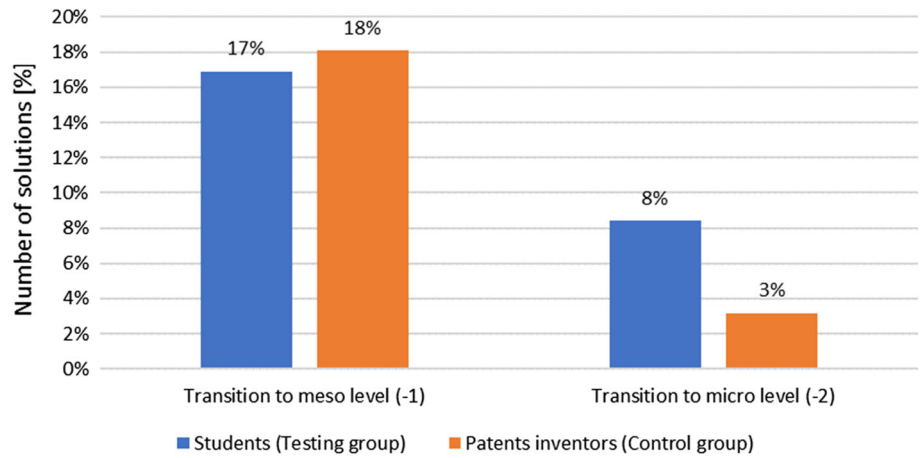
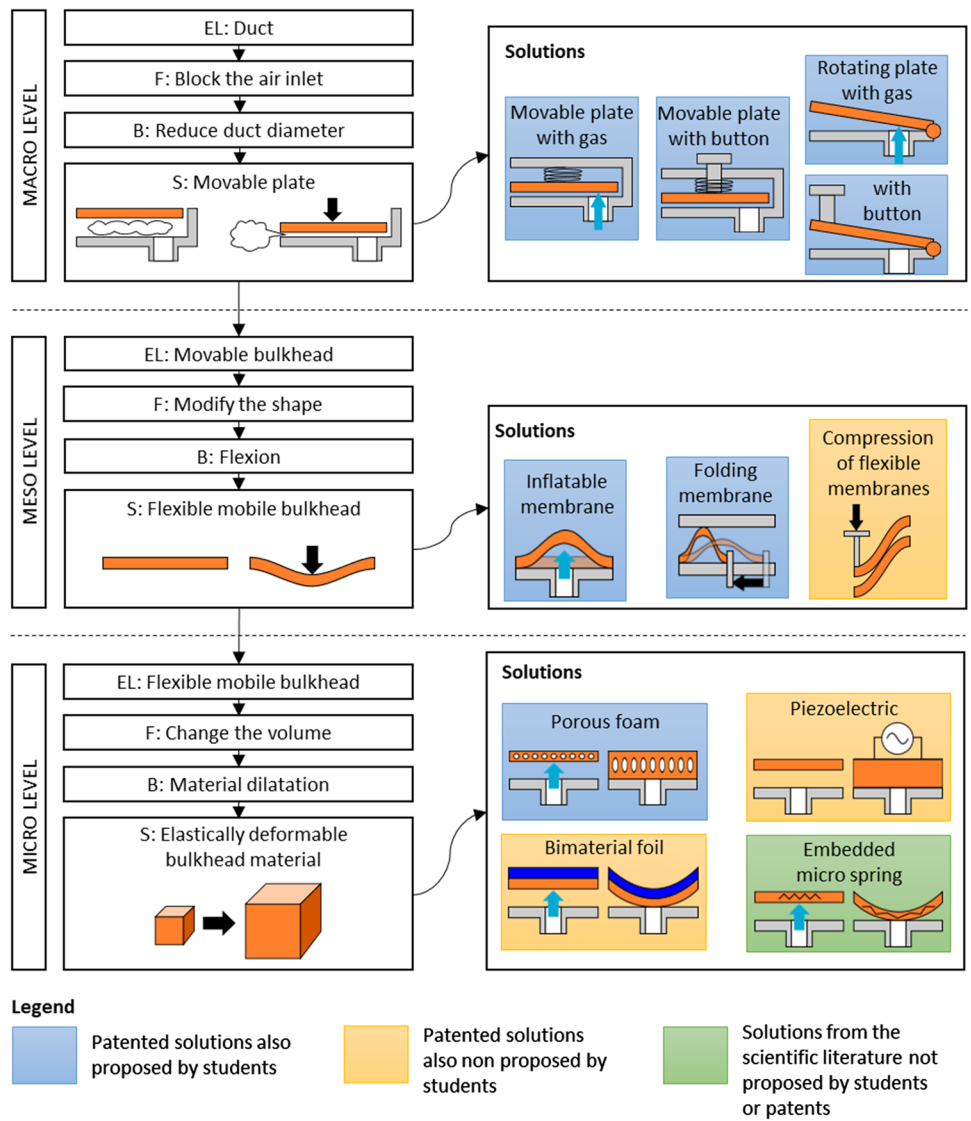


Fig. 11 FBS multilevel classification of the structures from students and patents working on the Function “Blocking air inlet in the duct” with the behaviour “Reducing duct diameter”



However, the interesting fact, which argues in favour of the proposed method, is that 55% of the solutions of the testing group are present in only one patent and 13% in only two patents. Therefore, most of the solutions that the students have come up with have been studied very marginally previously. This data therefore confirms the ability of the proposed method to support the identification of new ideas. Furthermore, this advantage is supported by the fact that the students found them in a very short time unlike the inventors of the patents, in the control group, which are spread over a period of several years.

The greater variety of the solutions of the testing group emerged instead from two aspects. On the one hand, there is their distribution on the different levels of detail (see Fig. 3), which shows that, in percentage terms, there are more student solutions that go down two levels of detail. In this case the method allowed the students to vary more the level of detail in which to solve the problem. On the other hand, there is a difference in the type of implemented behavior. To evaluate this, all the solutions have been classified according to their behaviors, which are: linear rigid movement, rotational rigid movement, deformation, vibration, fluid dynamic effects (e.g. pressure in communicating vessels), heating, chemical. Then the standard deviation relative to the distribution in the different classes of the solutions of the testing group and of the control group was calculated. The result is that the standard deviation of the testing group is 15% higher than that of the control group, thus demonstrating a greater variety (in relation to the type of behaviour) of the solutions obtained with the proposed method.

The higher quality of the solutions proposed by the testing group was evaluated through a more responsible, targeted and limited use of the available resources, which can therefore also make them cheaper. The students, using the proposed method, also thanks to the drop in the level of detail, worked within smaller structural portions. For example, the use of porosity in the cap in the students' solutions is limited to the sole area of the outlet of the duct, while in the patents it is wider.

### 5.6 Discussion, limitations and possible future improvements

From the analysis of the results obtained in this test, there are two generalized conclusions that can be drawn on the proposed method. On the one hand, those who have applied the proposed method, have been able to deeper analyse the system, to individuate a greater number of parameters on which to work and to provide solutions characterized by a more rational use of the available resources. On the other hand, the proposed method did not lead the students to descend the level of detail in all the proposed macro-level solutions, but only of a part which, although percentagewise larger than

that of the control group, still remains decidedly contained compared to the total of the solutions.

A cause of this inefficiency of the method can be the level of preparation of those who apply the method and the specific knowledge of the assigned problem. Going down one or more levels of detail implies gathering more detailed information on the structure that is developing and, on the problem, to be solved. Furthermore, the required skills become multi-disciplinary, since, for example in the problem addressed, the domain of mechanical engineering, mainly present in macro-level solutions, is replaced by the domain of materials engineering and chemistry in micro-level solutions. It is therefore plausible that the students who applied the method therefore found it more difficult to propose meso and micro-level solutions given their level of preparation. For this reason, this aspect represents a limitation of this test. Another cause can be found in the way the test is performed. The students, having developed their solutions at an educational level, in the context of a final project, and not at a professional level, did not develop them over a longer period of time and did not resume them after a certain period of time, as instead typically happens in industrial practice.

Therefore, the application of the proposed method within the industrial field, characterized by greater multidisciplinary, technical preparation and expertise on the addressed problem, could therefore lead to an increase in the number of solutions developed at multilevel. Similarly, the integration of the proposed method with knowledge databases could also be useful. However, in this case, to better facilitate the integration, even the knowledge databases themselves could be hierarchically organized, according to different levels of detail. In this way, the designer could be supported during the development of the solution through the descent of the level of detail.

## 6 Conclusions

In this study, a new FBS approach working on multilevel has been proposed in order to support the designer. This because, multilevel logic can lead advantages both in problem description and solution identification. In fact, the designer that attempts to model the complexity of a system by visualizing different levels of detail produces a better functional investigation of the system and an enlargement of the problem space. Watching how the nature designs vis a vis human attitude, solutions involving more level of details offer a better exploitation of the resources, and consequently, an increased efficiency in terms of energy, space, volume and time. To stimulate multilevel approach, the topology concept has been introduced to help the designer in defining how structures are

conceived and organized to achieve a function at an upper level.

The proposed method has been tested with engineering students on a real industrial case study and the obtained results have been compared with those extracted from patents aimed to solve the same problem. Apart from the limitations of the test, including the level of preparation of the students, the type of problem assigned and the test execution method, the proposed method showed its main advantages and some weaknesses to fill with some future developments.

In conclusion, by applying the proposed method, the students have been able to deeper analyse the system, to individuate a greater number of parameters on which to work and to provide solutions characterized by a more rational use of the available resources. In particular, the multilevel solutions highlighted that a greater awareness of the topology in the designer is crucial to descent the level of detail during the design activity. In fact, the knowledge of the constituent parts of a solution working at the macro-level and their organization allow the designer to hypothesize new functions and behaviors to redesign the same parts at a sub-level of detail. In addition, with the descent of the level of detail, both the problem space and the solution space are enlarged.

However, to provide the study with a greater statistical reliability and capture new useful aspects, a planned future development regards the expansion of the set of the analysed solutions, considering new case studies and test participants, like professionals from the industry. Furthermore, to respond to the increase in specialized knowledge that is required to the designer during the descent of the level of detail, the proposed method can be integrated with sources of knowledge, better if organized in a hierarchical manner, to align with the multilevel logic. In the same way, databases such as the biological ones, given their affinity with the logic of the proposed method, could be useful for making the designer better understand the role of topology and the organization of functions, behaviours and structures at different levels, and inspire her/him in the multilevel design.

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## References

1. Altshuller, G.S.: Creativity as an Exact Science: The Theory of the Solution of Inventive Problems. Gordon and Breach, London (1984)
2. Ashby, M.F., Bréchet, Y.J.M.: Designing hybrid materials. *Acta Mater.* **51**(19), 5801–5821 (2003)
3. Cascini, G., Fantoni, G., Montagna, F.: Situating needs and requirements in the FBS framework. *Des. Stud.* **34**(5), 636–662 (2013)
4. De Kleer, J., Brown, J.S.: Mental models of physical mechanisms and their acquisition. *Cognitive skills and their acquisition*, pp. 285–309 (1981)
5. Forbus, K.D.: Qualitative process theory. In: *Qualitative Reasoning About Physical Systems*, pp. 85–168 (1984)
6. Galle, P.: The ontology of Gero's FBS model of designing. *Des. Stud.* **30**(4), 321–339 (2009)
7. Gero, J.S.: Design prototypes: a knowledge representation schema for design. *AI Mag.* **11**(4), 26 (1990)
8. Gero, J.S., McNeill, T.: An approach to the analysis of design protocols. *Des. Stud.* **19**(1), 21–61 (1998)
9. Gero, J.S., Kannengiesser, U.: The situated function–behaviour–structure framework. *Desigstudies* **25**(4), 373–391 (2004)
10. Gero, J.S., Kannengiesser, U., Crilly, N.: Abstracting and formalising the design co-evolution model. *Des. Sci.* **8**, e14 (2022)
11. Goel, A.K., Bhatta, S.R.: Use of design patterns in analogy-based design. *Adv. Eng. Inform.* **18**(2), 85–94 (2004)
12. Hamraz, B., Caldwell, N.H., Ridgman, T.W., Clarkson, P.J.: FBS Linkage ontology and technique to support engineering change management. *Res. Eng. Design* **26**(1), 3–35 (2015)
13. Hamraz, B., Clarkson, P.J.: Industrial evaluation of FBS Linkage—a method to support engineering change management. *J. Eng. Des.* **26**(1–3), 24–47 (2015)
14. Hatchuel, A., Weil, B.: A new approach of innovative design: an introduction to CK theory. In: *DS 31: Proceedings of ICED 03, the 14th International Conference on Engineering Design, Stockholm (2003)*.
15. Hayes P.J., (1979), *The naive physics manifesto*, D. Michie (Ed.), *Expert Systems in the Micro-Electronic Age*, Edinburgh University Press, Edinburgh, pp. 242–270
16. McNeill, T., Gero, J.S., Warren, J.: Understanding conceptual electronic design using protocol analysis. *Res. Eng. Des.* **10**, 129–140 (1998)
17. Raabe, D., Sachs, C., Romano, P.: The crustacean exoskeleton as an example of a structurally and mechanically graded biological nanocomposite material. *Acta Mater.* **53**(15), 4281–4292 (2005)
18. Pahl, G., Beitz, W., Feldhusen, J.A., Grote, K.-H.: *Engineering Design: A Systematic Approach*, 3rd edn. Springer, New York (2007)
19. Shah, J.J., Smith, S.M., Vargas-Hernandez, N.: Metrics for measuring ideation effectiveness. *Des. Stud.* **24**(2), 111–134 (2003)
20. Shah, J.J., Kulkarni, S.V., Vargas-Hernandez, N.: Evaluation of idea generation methods for conceptual design: effectiveness metrics and design of experiments. *J. Mech. Des.* **122**, 377–384 (2000)
21. Shi, H.B., Huang, D., Wang, L., Wu, M.Y., Xu, Y.C., Zeng, B.E., Pang, C.: An information integration approach to spacecraft fault diagnosis. *Enterp. Inf. Syst.* **15**(8), 1128–1161 (2021)
22. Song, T., Becker, K., Gero, J., Deberard, S., Lawanto, O., Reeve, E.: Problem decomposition and recomposition in engineering design: A comparison of design behavior between professional engineers,

- engineering seniors, and engineering freshmen. *J. Technol. Educ.* **27**(2), 37–56 (2016)
23. Spreafico, C., Fantoni, G., Russo, D.: FBS models: an attempt at reconciliation towards a common representation (2015)
24. Tomiyama, T., Umeda, Y., Yoshikawa, H.: A CAD for functional design. *CIRP Ann. Manuf. Technol.* **42**(1), 143–146 (1993)
25. Umeda, Y., Takeda, H., Tomiyama, T., Yoshikawa, H.: Function, behaviour, and structure. *Appl. Artif. Intell. Eng.* **V 1**, 177–194 (1990)
26. Vermaas, P.E., Dorst, K.: On the conceptual framework of John Gero's FBS-model and the prescriptive aims of design methodology. *Des. Stud.* **28**(2), 133–157 (2007)
27. Xing, W., Pei, B., Li, S., Chen, G., Xie, C.: Using learning analytics to support students' engineering design: the angle of prediction. *Interact. Learn. Environ.* 1–18 (2019)

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