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ON THE LINK BETWEEN FEATURES AND FUNCTIONS

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ABSTRACT
A critical issue in design theory is the relationship between the abstract functions and purposes of a product and its physical behaviours, structures and features. A more recent and parallel topic is the dialectics between user, designer and artefact. In the traditional approach systematized by Pahl and Beitz, the main focus is on the functions, seen as actions on flows, i.e. as objects' modifiers. While such paradigm proved very useful and has been tested and applied in a myriad of practical design cases, it shows various limitations when dealing with not purely mechanical artefacts, since it overlooks the role of structures and the relationship between the user and the product. On the other hand, there is a whole family of theoretical frameworks, from Gero's Function-Behaviour-Structure to the more recent Affordance-based design, that insert the concept of function in a wider and more sophisticated picture, including the physical features, the designer's intentions and the user's perceptions and actions. However those models are too often studied only theoretically, trying to improve the model as per se, without actually presenting practical applications (real objects are described only in short examples to illustrate theoretical concepts, there is not any detailed, exhaustive analysis of products as in the other approach) or showing how the paradigm can actually be useful in the everyday design practice. Such practical applications, apart from being a good test for the theoretical models, would also help to resolve ambiguities, clarify the understanding of problematic issues, and even suggest new directions of analysis or forgotten entities in the overall picture.
The present paper is an attempt to build a bridge between the two contrasting approaches. Features, with their characterization rooted in physical principles, play a pivotal role and possess a deep connection with both functions and users actions. By relating the functional map of a real, simple object to its behaviours and geometrical features, and taking into account the user's perspective, we try on one hand to enhance the possibilities of the functional map approach and on the other hand to provide a rigorous, detailed, practical application of the FBS paradigm that illustrates the various critical issues and suggests possible directions of investigation. Of course the present analysis does not claim to be complete, it is only a first step towards the long-term goal of developing a more powerful framework that fully integrates the two approaches.

Keywords: Functional Analysis, product representation, functional modelling, affordance, design theory, FBS model.

1 INTRODUCTION

A fundamental issue in design theory is the relationship between the abstract functions and purposes of a product (as perceived from the user's or the designer's point of view) and its physical behaviours, material structures and geometrical features.
While traditionally design and manufacturing had been based on the physical properties of structures and materials, aiming at their proper choice and optimization, a large part of the modern theories of design have shifted the focus on the concept of function. Indeed, functional analysis is considered the most effective way to capture both the physical behaviour of a product and its purpose, thus guaranteeing the satisfaction of the user's needs and improving the manufacturing process at the same time.
In its classic formulation, functional analysis (hereinafter FA) concentrates on functions only, regardless on their actual implementation in the physical device. Any product can be associated with a list of subsequent functions, organized in a functional map according to their causal relationships. Such approach has a great abstracting and generalizing power and is very useful especially during the conceptual phase of design.

However on a practical level, when passing from the conceptual stage to actual prototyping, manufacturing and, last but by no means least, use of the product, the relationships between the abstract functional description and their physical realization become very important.
At a deeper level, the bias towards abstract functions comes from the fact that the classic version of FA was developed having in mind mainly mechanical or electromechanical products. Such class of artefacts can indeed be effectively described as a series of operations and transformations, and in this context the classical understanding of the function as an action on a flow, and of the relationships between functions as an algorithmic flow-chart is well founded. At the same time, this representation becomes much less adequate in describing non-mechanical products (or products where the mechanical aspect is just one of the many), and even more products with strong user-related characteristics.
As correctly pointed out by various authors (see for example [1],[2]) there are important requirements that are not functional, at least not in the traditional way. Some requirements may not be related to the main functions of the product, such as for example health and safety requirements. Their fulfilment is delegated to collateral sub-functions and to the way the various components of the product are realized. Actually this kind of requirements are very difficult to represent with the traditional functional lexicon: only few very generic functions can be used, such as *protect* or *prevent*, without any precise description on how that protection can be achieved, and a description in terms of unwanted functions (avoiding certain actions to happen) may be more appropriate. Other requirements can be even more difficult to express as operations, such as those related to costs or to the life-cycle management. As an additional issue, any indication of the efficiency and of the extent to which a desired characteristic is implemented is totally missing.
Moreover, even within FA's traditional applications, the description in terms of actions on flows becomes particularly ambiguous (see for example [3],[4]) for all those tasks that involve a direct interaction with the user or more generally with the external environment. It is the case of many functions concerning a signal, which often is such only for the user. For instance, the electromechanical function (action) of a radar is merely *converting electromagnetic energy into optical energy*, while from the user point of view that translates into *detect airplanes*, or *monitor position*. Other examples are those requirements that are realized only when the user is actively involved, such as the above-mentioned health and safety ones.
One of the first attempts to introduce a less monolithic and more articulated concept of function is Gero's Function-Behaviour-Structure paradigm [5] and its various subsequent variations and evolutions. In this approach, the relationship between the functions and the physical properties of the product are explored as part of the design process even at the conceptual stage.
Since the first version of the model, many authors have introduced other elements in a picture that is becoming more and more multi-sided (goals, actions, intended and perceived behaviours, environmental variables and so on). In parallel to the FBS paradigm, other approaches appeared that rearranged those design entities in different frameworks. Moreover, in time the focus has shifted more and more from the product towards the user, taking into account his needs and goals and his perceptions (both positive and negative) of the product, for example with the recent introduction of the affordance concept [1],[6].
All these directions of investigation have the merit of deepening and enriching the analysis. However almost all the paper in the literature propose refinements of a previous model, or new alternative models, only as purely theoretical constructs.
The traditional functional approach, in its simplicity, may loose some important, user-related issues, but on the other hand provides a very efficient and helpful tool that has successfully been used in everyday design practice, and has been tested and applied to thousands of real products (for example the repository of functional maps of [7] counts over 6000 artefacts' decompositions).
The more articulated paradigms instead, may propose interesting and useful insights, but do not provide any practical indication on how to implement themselves into the everyday practice of design, there is no ready-to-use tool, and the few products actually analysed in the literature are used only as short examples to illustrate theoretical concepts. These few given examples allow the user to understand the framework, not really to use it in a clear and proper way. As of today, there are no such things as structured maps of objects, decomposed according to FBS-like models, at least not as articulated as those for classical FA.
Moreover, the various approaches present different choices for what are the basic, fundamental entities to study, and there is no general agreement even on the definition of the basic concepts. The application of each methodology to a practical case study, to a real life object, with a detail and rigour comparable to that achieved by functional maps, apart from being a good test for the theoretical models, would have also helped to resolve ambiguities, clarify the understanding of problematic issues, and even suggest new direction of analysis or forgotten entities in the overall picture.

A complete treatment of all unsatisfactory issues in present day models is far beyond the aim of the present paper. Not to mention the proposal of an improved model that could integrate the power of abstraction and simplicity of the traditional approach of FA with the wider and more flexible understanding of the relational and situated more recent approaches, a long-term task that will require the joint effort of the whole community.

The purpose of the present paper is actually to invert the terms of the problem: instead of constructing a theory from first principles, we try to illustrate the complex relationships between functions, behaviours and physical features in a practical example, hoping to provide some useful insight towards an improved model starting from an operational perspective. On a more short-term scale, our analysis is an attempt to build a bridge between the two contrasting approaches: the practical functional analysis and the theoretical FBS-based class of frameworks. By relating the functional map of a real, simple object to its behaviours and geometrical features, and taking into account the user's perspective, we try on one hand to enhance the possibilities of the functional map approach and on the other hand to provide a rigorous, detailed, practical application of the FBS paradigm that illustrates the various critical issues and suggests possible directions of investigation. On the theoretical side, the main contribution to the discussion is to show how features (more than generic "structures") are rooted into physical laws and can therefore be used as a solid ground for both functions and users' actions. On the practical side the real case analysis provide a first example of how a complete (in the sense described above) decomposition of an artefact may look like.

The plan of the paper is as follows. In the next section we give a short review of the state of the art for the two major approaches we have discussed so far. In section 3 we define and discuss the various basic entities that we will use in the analysis (functions, behaviours, features) and see them in a slightly new perspective. In section 4 we present the detailed analysis of a common glass in order to highlight all possible relationships between its functions and features, including the user's perspective. Afterwards, we frame those relationships in the context of the various theoretical approaches and discuss some critical issues and possible direction of investigation.

2 STATE OF THE ART

A large part of modern design theory, and the one we are interested in the present paper, is based on the concept of function, and on the assumption that studying the functions captures the essential features of a product. The first to point out the relevance of functions was Miles, in the context of Value Engineering [8], while Collins developed the first functional database (*i.e.* a codified list of the possible functions) [9]. From those earlier investigations onwards a series of school of thought developed during the years, differing not just in the methodologies but in the way functions themselves are conceived.

A classical approach is that of Pahl and Beitz [10], that identify each electromechanical function with a pair of words, a verb plus an object, where the former indicates an action and the latter the three possible flows of material, signal and energy. This way, even the most complex product can be divided into its functions, *i.e.* into a series of simple single operations connected to each other through the flows (namely the inputs and outputs of each function). The series of functions and flows are often graphically organized in so called functional maps or functional flow block diagrams. In this picture functions are as abstract or general as possible, and therefore merge in the same entity (not without a certain degree of ambiguity) the goal (from the user or designer point of view) of the action and its physical realization.

The original proposal by Pahl and Beitz was quite articulated and identified a number of requisites on motion, type of materials or geometry that could affect the way in which general functions act on flows. They also stated the need to derive sub-functions directly from the corresponding requirements of the problem and represent their relationships using Boolean algebra. However, these extremely important aspects of their proposal were somewhat lost in the subsequent literature, and only the understanding of functions as modifications-on-flows remained (and therefore a shift in relevance from the goal to the physical realization of the action).

Researcher following this approach concentrated their efforts to further improve the model not on deepening or articulating the definition of function but on uniqueness and reliability of the functional decomposition. Hence the huge effort for the development of standardized taxonomies and databases of basic functions and flows (started by [11],[12] and further developed in [13], [14], [15]), and the quest for grammar rules that could generate functional maps in an objective way and could be implemented in software tools (see for example [16],[17]).

We briefly mention that also the Theory of Inventive Problem Solving (TRIZ in Russian) [18] independently identified functions as a central point in design, distilling around 30 functional descriptions after a massive study based on 2 million patents. For our purposes we note here only that TRIZ defines the function as the “positive meaning” (that is its usefulness) of an “object” to the outside world. The accent here is therefore on the user’s goals and needs more than on the physical process.

We have seen that functional relationships can be organized into a functional map, following a top down procedure: first abstract functions are identified and arranged in a causal order, then the functional blocks are graphically connected through flows. The focus is on functions and the various parts of a product are seen merely as possible flows, regardless of any structural connection. A parallel type of diagrammatic representations, named Functional Analysis Diagrams (FAD) is also possible. Here the logic is reversed in a bottom up fashion: the starting point is the structure and functions are considered as interactions between its various parts. Graphically, the blocks are the various components, connected through functional relationships. FAD maps were first introduced in TRIZ practice, in order to highlight useful and harmful functions; a more elaborated version was independently developed in [19].

With respect to functional maps, FAD maps stress the connection between functions and structure, and in principle it is easier to include the user and the environment in the picture. The potential connection between FAD maps and the relational theory introduced in [1] is explored in [20]. However, at the present stage of development, FAD maps add very little to the traditional approach, while losing generalization power. Finally, in such representation functions are seen even more as physical actions rather than goals.

Trying to address some of the limit of the previous approaches, and to propose a more flexible and general theory of design, Gero proposed in [5] a different model, expanding the dialectics between function as a goal and function as an action on physical objects. The basis for the FBS framework consists in three classes of variables, each describing different aspects of the design object. Functions (F) now takes charge of the teleology of the product, what it is for; Behaviour variables (B) describe the attributes derived from the structure, i.e. what the product does; finally the Structure (S) variables describe the components, what the object is. The FBS framework represents designing by a set of processes linking function, behaviour and structure together, which can now be seen as different states of the developing design.

Since its first formulation the framework has evolved in many directions. Gero himself has further developed and integrated his model as in [21] to include the importance of the context of use. The introduction of the product use context requires to manage a series of different entities (actors, interactions and environments) and more comprehensive models to represent them.

A series of authors concentrated on introducing new actors and relations in the paradigm: the user needs [22], the “working environment” with its boundaries and resources in the FEBS model [23], or the human interpretation and previous knowledge. Another interesting analysis [26] introduces the notion of wirk elements, that is the elementary features that account for functionality at the smallest meaningful level.

Another approach has been to concentrate on a relational theory more than on the single entities, with the introduction of the concept of product affordance [1],[6]. Affordances are defined as “possible actions” and in particular “the affordances of a device are the set of all potential human behaviours that the device might allow”. Affordances can be recognized from experience, learned or inferred by analogy. Perceived affordances are context dependent manipulation possibilities from the point of view of the actor.

Other researchers took as starting point the user perception and knowledge to include in the picture alternative uses, failures and misuses [24],[25]. All the above approaches shift the focus from functions as operations to functions as interactions and relations between entities.

3 FUNCTIONS, BEHAVIOURS, STRUCTURES, FEATURES.

Before engaging in the detailed analysis of a real object, it can be useful to re-examine some key concepts of functional analysis that will be used in the next chapter.

Every product is designed and manufactured with the precise purpose of satisfying certain needs (of any kind: material, spiritual, social) of the user. The product’s aim at addressing a specific need is conventionally referred to as a **goal.**

One of the essential ideas of functional analysis is that each goal can be translated in one or more **functions** that the product must carry out in order to fulfil that goal. In this sense the functions are not separable from the human perception: they are nothing other than the result of the user’s interpretative process about the product’s physical behaviours. To put it into other words, the user’s interpretation of the product’s behaviour is always conditioned by the goal that the user himself wants to achieve by using the product, and functions implicitly embed all the above information.

In turn, **behaviours** can be defined as the way the physical and chemical state of the product evolves in time and in its environment. Thus, if functions are a description of what happens to objects within the system from the user's point of view, behaviours can be seen as what happens to the same objects from the point of view and as consequence only of the physics that is at their basis. Functions are behaviours that happen for a goal, behaviours themselves just happen.

Behaviours express how the **structure** of the product reacts while carrying out specific operations and therefore they are strictly dependent on both the external environment in which the product is used and the characteristics of the structure itself. The latter can be analysed down to its basic constituent parts, and these in turn can be further decomposed in their features. **Features** can be defined as the specific characteristics of a single part of the product, in terms of the geometrical entities that define it and in terms of the properties of the material it is made of. Every substance will have specific physical properties (mechanical, such as for example the Young modulus; chemical, such as resistance to acids or to flames; optical, as the transparency to certain frequencies; thermal or electrical conductivity, porosity, and so on) that are often relevant if not essential for the fulfilment of a certain function.

Very often more than the single features what really matters are the interrelationships between them. Indeed, rather then being performed by a single feature, a function is usually the result of a synergy between various features. According to the SBF model, the structure itself is represented as a hierarchy of these components, substances, and their relations. The relations are expressed with terms such as "part-of," "includes," and "parallelly connected" [27].

A very important concept that is sometimes overlooked is the strict relationship between features and functions. In a good design, *to each and every feature of a product, corresponds at least one function to which the feature contributes.* Indeed, if no function performed by the feature existed, we would have introduced in the design at least one information (the one necessary to produce or define the feature) without a rationale for it. Therefore such a useless information/feature can be removed without affecting the product performance and actually saving manufacturing time or cost.

Since the same component of a product usually present more than one physical characteristic, it is important to define a rigorous criterion to individuate the single, distinct, individual feature. In other words, it is important to decompose the object down to features that can be considered the *elementary particles or bits of information* for the physical representation of the product. Therefore, we state that two features are distinct if there is at least one geometrical or physical **parameter** that changes abruptly when moving from one to the other.

The above statement is very useful also because sheds new light on the relationship between features, behaviours and therefore functions. As we have seen behaviours are defined as the evolution of the physical state of the product, and can thus be associated as well to changes in certain parameters. In fact, behaviours are just an heuristic representation of a **physical effect**, that has a rigorous description in terms of physical laws and equations. Hence the logical chain is clear: parameters defining the various properties (features) of the product enter as variables or constraints in the equations that rule the product's physical evolution (behaviours). Although not always one-to-one, the relationship between the two sets is now very precise and well defined. One or more behaviours produce an overall effect that is then interpreted as a function.

It is obvious that relating functions with physical laws gives a solid conceptual foundation to them, and will help constructing more rigorous functional databases. Such connection between functions and physical laws is obtained through features. Existing models tends to miss that link, since they involve either too generic "structures" (FBS) or the parts of the product (FAD), without connection with the physics; alternatively, they concentrate either on the abstract behaviours/functions (FA), either on the user's behaviours (affordance based models).without connecting them with the artefact's features.

As suggested in [4], linking abstract functions to parameters and physical effects can suggest new directions of investigation, and maybe lead to a deeper understanding of functional analysis.

Studying the way the above mentioned entities interact between themselves, with the user and with the environment defines already a large part of the design process. We note that the same approach could be advantageously extended to include also "not functional" entities such as the affordances or "harmful functions", differently known as failures; such extension, although very interesting, it is however slightly out of scope with respect with the aim of the present paper. Yet we note here that the enriched role of features helps creating a bridge between the user perspective (as in FBS-like models) and functions as abstract entities (as in classical FA).

4 CASE STUDY

So far, functions and behaviours, as well as their relationship, have been studied in the literature only on a purely theoretical level. In the present section, our goal is to review the above concepts in detail and find out their critical issues, by mean of a practical example, that is the analysis of a relatively simple object: a common plastic glass like the one shown in Figure 1.

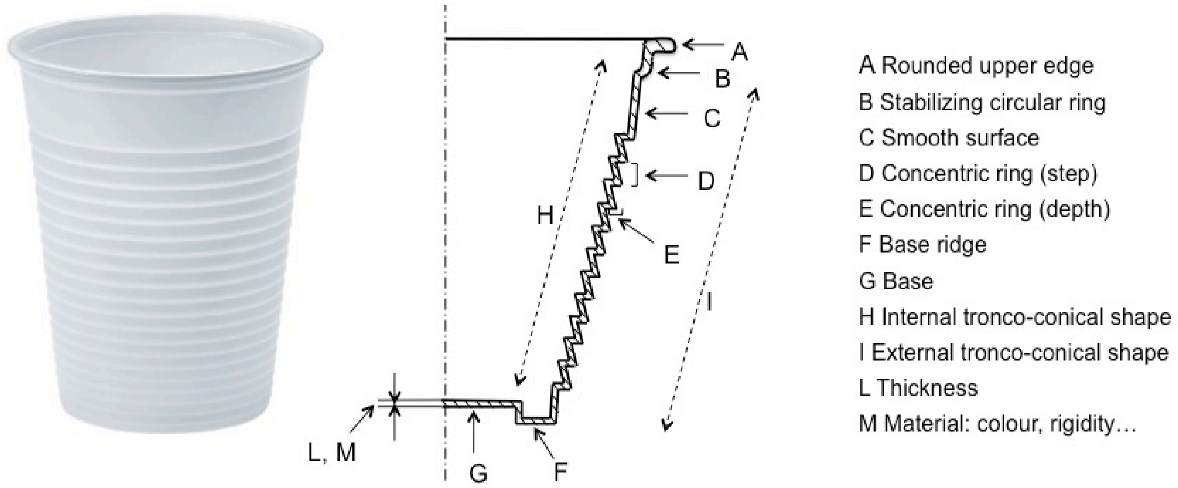

Figure 1. A plastic glass and its section, with description of all the relevant features

The figure illustrates all the relevant features of the product. Some are obvious, while others may require a little clarification. For instance, the vertical, tronco-conical wall of the glass is of course a single distinct part of the overall object, but it accomplishes several functions, each one associated to only one geometrical or mechanical properties of the wall itself. It is thus necessary to single out all the elementary features, as discussed in the previous section. Moreover, the role of each feature depends on the interactions it has with the user or the environment. Therefore, we have to distinguish between an internal side of the wall, which interacts with the liquid, and an external side, which interacts with the user's hand. At the same time, the tronco-conical shape fulfils two totally different aims on the two sides: it creates a volume to store the liquid in the interior, and makes easier the holding of the glass by the hand at the exterior (since the glass is prevented from falling by geometrical reasons there is no need for creating a strong friction force). Alongside with the shape, we have to single out the surface as well: the interior surface guides the liquid and the exterior provides a pleasant yet efficient contact with the hand. Finally the mechanical properties of the material are fundamental in preventing the glass from collapsing or breaking under the pressure respectively of the liquid and of the hand.

In order to identify all the functions of the product it is very useful to consider the various phases that occur during its use. In the case at hand, starting from the initial condition (the glass resting on the table), the following phases are: the user fills the glass with water, he grasps it, brings it near the mouth, lean the glass' rim against the lips, rotates the glass and pours the liquid into the mouth, and finally removes the glass and puts it down on the table. The following table sums up the procedure.

Phases expressed in natural language	**Phases in functional language**
The glass is on the table	Table supports glass
The user fills the glass	Glass imports water
The user grabs the glass	User grasps glass
The user raises the glass	User transport glass
The user lean the glass against the lips	Lips mate glass
The user rotate the glass and drinks	Glass export water
The user move away the glass	User transports glass
The user put the glass down	User position and release glass

In each phase of the usage the product is designed to cope with some critical situation. For example, when water is being poured the glass should not capsize, or when the glass is put on the user's lips it should not hurt them. From a functional point of view, an artefact must be designed to fulfil the useful functions and prevent the negative functions, considered harmful for the user or the environment, from happening. For each phase then the functional decomposition is performed according to all the function perceived (and interpreted) by the user.
The functions identified in this way are finally connected with flows representing the subjects and the objects of the action. An extract of the functional map for the plastic glass can be seen in Figure 2.

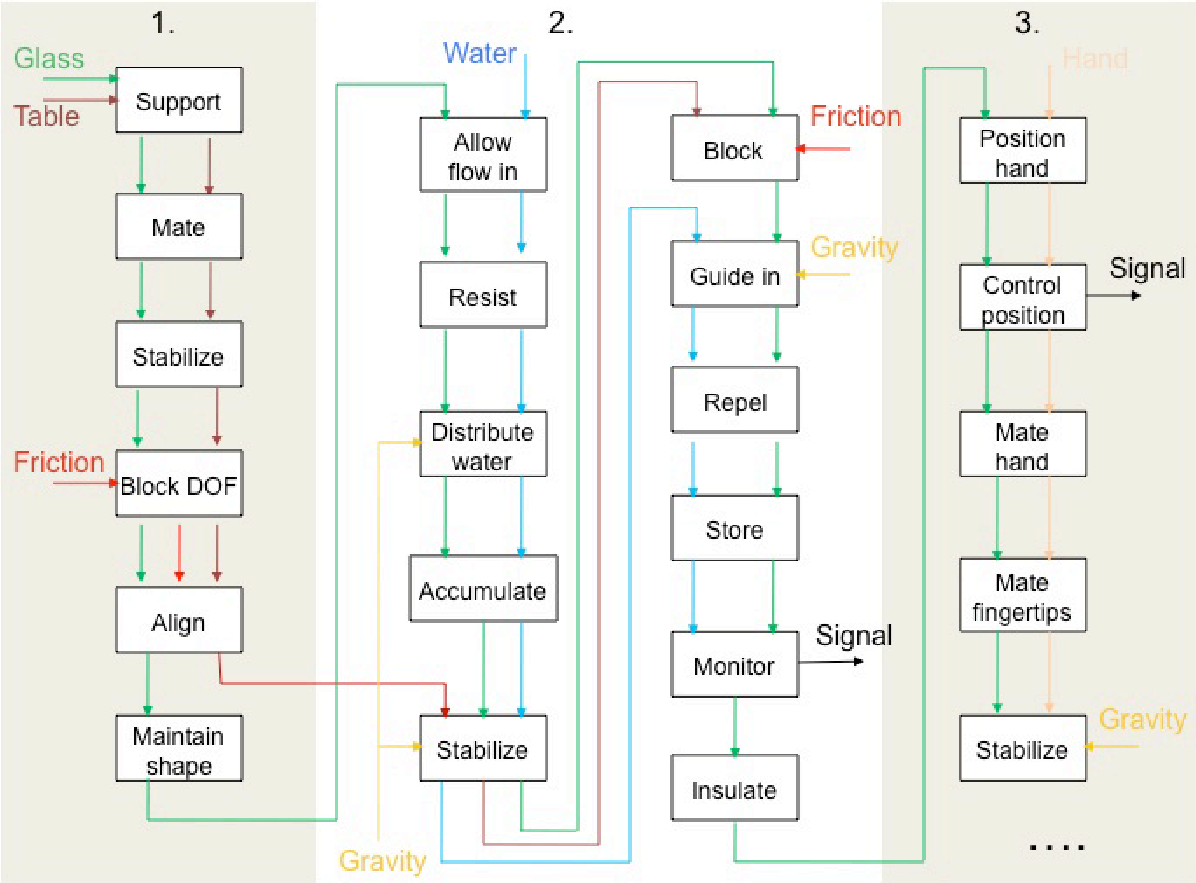

Figure 2. Excerpt of the functional diagram of the glass usage.

Since functions are the user's interpretations of artefact behaviour, we have then investigated the main behaviours associated with the perceived functions previously determined.
Often, however, the user is not aware of all the behaviours belonging to the artefact because, during its standard use, he/she is not able to perceive some of them. Actually, many of the behaviours cannot be perceived at a hasty glance or without using particular instruments. Therefore, a second subset of behaviours not linked with any perceived function has been determined. Such subset can be particularly wide since it can contain all the possible behaviours belonging to a product.
Some of the behaviours belonging to this second class are clearly useless for the analysis (infrared radiation coming from a hot body) since they can not be perceived by the user in any way, while others (deformation of the fingertips' pulps) are neglected by the user during the routine usage, but are instead fundamental from a design point of view.

In the electro-mechanical field, each behaviour can be described on the basis of the physical effects involved. In general it is possible to associate a behaviour with an equation (or a system of equations) able to describe it in detail. The equations represent the physics, the mechanics, and the overall logics that determine the behaviour of an electromechanical apparatus.

Such behaviours (or sometimes the result of a behaviour acting on a artefact) are interpreted by the user and expressed as a function.
Behaviours are strongly linked with the product features. In particular, since features interact with the user they are:

- the activation elements of the behaviours;
- the elements able to carry out the behaviours;
- the elements able to interact with the external actors (environment, user, etc..).

A behaviour can be carried out by a single feature or, more often, it is performed by several features activated simultaneously. Hence functions and behaviours can be determined by using a bottom up approach that moves from the geometrical features, material characteristics, etc. to the activated behaviours and the interpreted functions. Such process moves from physical entities towards physical effects to more and more abstract concepts as the product functions. The bottom-up process is particularly robust since it can be done in a very systematic way, can be easily supported by CAD system and performed also during the (sketching) conceptual phase.
A full-fledged methodology that can guide the designer in such decomposition is currently in development, as well as software tools that can support the analysis. As for the software, they can for example aid in the construction of functional maps, not just speeding up the representation with standardised objects but also suggesting possible matches and rules of combination and signalling mistakes. In the long term the aim is to integrate the functional insight into CAD objects.
We have already shown the relevant features associated to the glass in Figure 1. Each of them, as discussed, will contribute to a distinct function. The detailed analysis is presented in Table 1, which is organised as follows: all the functions belonging to the same phase of use are collected under the same class. Each function stays in a separate row of the second column while the behaviours perceived (even of small entity) by the user are located on its right. The related physical effects and key features are listed in the last two columns.
The entries in italic represent the user's functions or, more precisely, those preparatory functions performed by the user without interacting with the artefact (glass, glass+water). In such functions the glass plays the role of a reference system without showing any behaviours excepting the sensory feedback. (mainly visual). Such human behaviours have been listed and inserted into the table in order to supply a more complete and clear picture of the entire decomposition process.

A few comments to the table are important.
Function and behaviour can coincide if the user has the total perception of the physical behaviour that is at the basis of the function (though theoretically there still is a distinction since in the behaviour the goal is missing while it is present in the function).
On the other hand a function can be the result of more than one behaviour, and the user quite often cannot perceive all behaviours during a normal use of the product (of course we are referring to average users in everyday use of a common object).
We can distinguish between the behaviours of the glass, the behaviours of water, and even the behaviours of the user (e.g. deform fingertips). Indeed, the boundary of the system in exam has been conventionally chosen to include the user's hand, since we can see it as a "tool" that is needed for the proper functioning of the product.
When a signal is present, the definition of function can present some ambiguity and may not be univocal. Let us consider for example the glass' behaviour: "allow the passage of certain λ (optical frequencies)". Two different definition of the function associated to it can be provided: "allow the passage of a signal" and "monitor the water level". Choosing the proper one depends on the context of the analysis. The function "to monitor" is the closest to the user's goal, and indeed in order to check the water level he needs the glass to be transparent. The other function, "allow signal" is instead closer to the designer point of view that has to deal with the actual behaviour.
We remark that such ambiguities are almost always present when the flow involved is a signal, since from the physical point of view signals are characterized by the transport of material or energy, it is only the user that interpret them as information (see for example the discussion about the concept of carrier in [16]). Moreover, functions involving signal are often not general abstract action that can be applied to any flow, but are restricted to signal only (more on the concept of flow-restricted functions can be found in [13] and [28]).

Table 1 - Map of the relationships between functions, behaviours and physical features

Phase	Function	Behaviour	Physical effect	Features
1. Support (the glass stays on the table)				
	support glass	compress-repulse	compress-repulse (weight)	base ridge, material (rigidity)
		transfer load	compress-repulse	base ridge, material (rigidity)
		deform (imperceptible)*		base ridge, material
	glass mates table			base
	stabilize	distribute load	distribute load	base ridge
	block dof	block dof	friction	material (friction coefficient, weight)
only the glass load is acting	align/stabilize	positioning 3 theoretical contact points	equilibrium(geometric), gravity	base ridge
the glass does not collapse under its load	maintain shape	maintain shape	balancing of internal and external forces (statics)	thickness and material (rigidity)
2. Import water				
	allow flow in	-	$d<d$	d glass
the glass bottom supports the water hit	resists	compress-repulse	compress-repulse	base, thickness, material toughness
	distribute water	water moves	water equilibrium, gravity	base, internal truncated cone
	accumulate	contain	water equilibrium, gravity	base, internal tronco-conical shape, material, empty space
	stabilize	distribute load	distribute load	base, internal tronco-conical shape, material (weight)
	block	block dof	friction	friction coefficient, weight
	guide in	deviate	momentum, compress-repulse	internal tronco-conical shape
	repel	repel		material (impermebility)
	store	contain	compress-repulse	base, internal tronco-conical shape, thickness, empty space
	monitor water level	allow λ	$\lambda 1 < \lambda < 2\lambda$	material transparency, thickness
	insulate	obstacle thermal flow	thermal conduction	conductivity, thickness
3. grasp glass				
	position hand	*move hand*		
	control position	*sense visual signal*		
	mate hand	*set shape (hand)*		
	mate fingertips	deform macroscopic (glass and *fingertips*)	compress-repulse	external tronco-conical shape, material stiffness
		deform microscopic (glass and fingertips)	compress-repulse	concentric rings (step+depth)
	stabilize shape	compress-repulse	compress-repulse	concentric rings depth, material
	increase friction	distribute pressure	normal load, coulomb's friction	external tronco-conical shape, material stiffness

4. Transport glass				
	transport glass-water	move		the entire glass takes part to the function
the glass becomes more stable when lifted	stabilize glass-water (vertical sliding)	move	force and torque equilibrium, glass-water weight	external tronco-conical shape, weight
	align	rotate-translate	force and torque equilibrium, glass-water weight	external tronco-conical shape
	control position			
	position glass near the mouth			
5. mate				
	mate (glass on lip)	deform lip, deform glass, compress-repulse	compress-repulse	smooth surface
water does not exit from the mouth corners	stabilize shape	compress-repulse	compress-repulse	stabilizing circular ring
the glass does not cut the lips	decrease pressure	distribute pressure		rounded upper edge, material hardness
6. export water				
	rotate	rotate		
	distribute water	water moves	water equilibrium, gravity	base, internal tronco-conical shape
	guide	deviate	water equilibrium, gravity	internal tronco-conical shape
	export	water moves	water equilibrium, gravity	
7. transport glass				
	move glass	move		
	rotate	rotate		
	align	move		truncated cone
	guide water	deviate	momentum, compress-repulse	upper rounded edge
	…			

* this behaviour fulfils the aim of avoiding an unwanted function; the user does not want the glass to deform sensibly and change its shape while standing on the table.

We also note the conventionality of the boundary between the system and the external environment. Indeed the product interacts with the user and the environment, and what can be considered system and what not is often a matter of convention. In our case for example the user’s fingertips are so deeply interacting with the product that have to be included in the system considered. In the table we chose to include only a few of the functions associated to the user, skipping for example all the functions related to the pouring of water from the bottle. Reasoning *ab absurdo*, if one considers all the user’s behaviours, as well regardless of their link with the product’s functions, one may end up describing even breath and heartbeat, even if they do not interact directly with the product or produce a measurable voluntary effect.
To conclude, the description in table 1 allows us to highlight the strict and deep connection between functions, behaviours and structure, a connection that has been somehow overlooked in the traditional approach started by Pahl and Beitz, that focus mainly on the concept of function alone. At the same time, the table provides an example of how the FBS paradigm can be applied in practice and can give useful insights not just at the conceptual stage but also in the context of a detailed design process.

A very important use of a thorough analysis such as the one outlined here is to highlight missing elements or elements which are in contradiction.

The construction of the table indeed allows to search for all the relationships in a systematic way.
On a practical level, finding out that the designer has forgot to take into account, say, a particular function associated to a feature, or its affordance, and so on, would help designing better products, avoiding failures and improving performances and user satisfaction.
Moreover, given the connection between features and functions, the careful design of each distinct feature can allow optimise the product, removing unnecessary features or changing them to realize the function in a more efficient way.
When considering the theory and the various models of functional analysis instead, a detailed analysis can help, among other things, to discriminate which model suits best the particular problem at hand. Indeed every theoretical model has its advantages and disadvantages, and its utility in the design phase largely depends on the context of use, the purpose, and the object to analyse.
On an even higher level, each of the existing model is able to capture only a subset of the entries in the table. Some will mainly describe mechanical functions, other the user's needs, and so on.
Therefore case studies as the present one can be used to improve each model, showing what important relationships are missing, and highlighting possible inconsistencies.
For example, in classical FA, there is a certain degree of arbitrariness and ambiguity in the choice of the representative functions. Connecting each function to real features, to physical principles or user's needs as we have done will help constructing more reliable functional database.
Moreover, it is not always clear which point of view should be taken to define the function and/or the boundary of the system to be considered, whether the point of view of the object, or that of the user, or even that of the designer (see [3],[28] for a more detailed analysis). The case study presented allows not just to show the limits of the various choices, and the design mistakes that they can lead to. It actually provides a new framework to take automatically into account all the various points of view, and use the most convenient one for each design purpose.
We remark however that the final goal is actually not to improve the single models, each following a different philosophy, but to reconcile them in a wider, more coherent framework, and we hope that the analysis performed can show a possible direction for developing such new approach.

5 CONCLUSION

In the present paper we have highlighted the close relationship between functions, behaviours (of the product but also of external elements such as the user, the external flows needed by the product to operate properly and so on) and the product structure, emphasizing how every feature (or set of features) performs certain functions and shows different behaviours during the use of the product. We have presented a practical example in detail in order to show how the various single entities and their relative connections can be identified.
The first advantage of a similar analysis concerns the theory of design and its application. We hope that our approach can help the construction of a bridge between two main schools of thoughts, and maybe help to converge towards a more complete theory of functions in engineering design.
Secondly, the study of the relationships between functions and features is very useful during the design or analysis phases, and allows an instant passage from functions (and hence goals) to the determination of the proper product' structure. The process of analysis moves from the geometrical features, material characteristics, etc. to the activated behaviours and physical effect to more and more abstract concepts as the interpreted functions. Such bottom-up process is particularly robust since it can be done in a very systematic way, can be easily supported by CAD system and performed also during the (sketching) conceptual phase, with great advantage for the design activity.
A methodology to guide the decomposition as well as software tools to aid it are currently under development.

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