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Approaches to analyzing multi-functional problems

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Abstract

The acknowledgement of designers' appreciation of conceptualization approaches rooted in functional decomposition and morphological synthesis in addition to the criticism regarding sub functional focus and limited innovation facilitation ability of these approaches, is the theoretical starting point of this article. Inspired by the multi-functionality of fascinating principles found in nature (e.g. 'the skin' of some organisms containing, protecting and camouflaging), this article explores how multi-functionality is handled in engineering design to: Study the way inspiration can be found, thus improving innovation capabilities (1) and improve the way products are analysed, thus removing sub functional focus (2). The topic is explored by interviewing and literature studying as research methods. Using a multi-functional case, a pairwise pattern of function types appeared suggesting searching for multi-functional solution principles should be further investigated. Furthermore, with minor changes to the FM-tree, designers are guided in assessing a product's degree of complexity, informing decisions on which functions to disscover a multi-functional biological analogy corresonding to.

Keywords: Functional analysis, multi-functionality, conceptual design, bio-inspired design

1 Introduction

This paper is motivated by the fact that biological organisms often solve several functions with the same means resulting in simpler structures. However, biologically-inspired design is normally carried out by searching for analogies solving single functions, making it difficult to discover biological multi-functional analogies. We would like to explore how the process of analysing products to support usage of integrated means is supported in design research. Our assumption is that the process is presently not well supported as handling functions and means is usually done by complete decomposition. That is, the lowest level of a functions/means tree is constituted by a number of functions with a corresponding number of corresponding single-functional means.
Engineering designers develop innovative products, while considering requirements and perceptions from many stakeholders. Such requirements are accommodated by the materialization of the needed product functionality by technical means delivered by assembling different parts constituting functional units. The relationship between functions and means can be handled using the hierarchical functions/means-tree (FM-tree) such as the one displayed in *figure 1* (Tjalve, 1979).

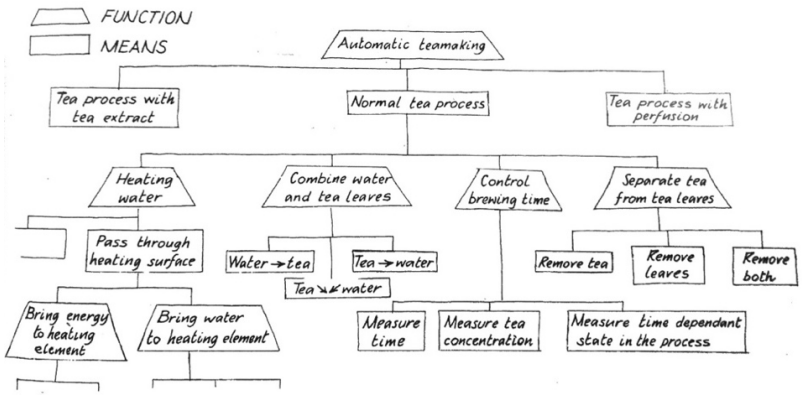

Figure 1. The function/means tree with automatic tea making as example (Tjalve, 1979).

In practice, the design problem is decomposed into functions at different abstraction levels and means corresponding to each function is explored. Solutions can be synthesized by selecting single means corresponding to the functions they support and organising the means in a morphological chart (Cross, 2008). The visual representation of the FM-tree will differ depending on the nature of the design problem at hand. When *designing*, where a designer is faced an open-ended problem with no existing solutions at hand, no means exist but only a functions structure. On the other hand, when *redesigning*, where a designer faces a design problem with existing solution(s), a complete FM-tree exist.

1.1 Limitations of the FM-tree

When employing the FM-tree to provide an overview of the design problem, the designer should be aware of the limitations regarding constraints/dependencies. Means solving functions at one hierarchy level in the FM-tree might simultaneously also affect sub functions other places in the FM-tree, which is not easily seen. The substitute mean(s) should contribute to the same function(s) across the FM-tree. Therefore, attention should be payed when replacing one or more means by the designer. Similarly, using the notion *design solution* interchangeable to that of the authors (i.e. means), the limitations of existing approaches‘ ability to integrate new solutions to existing products is outlined in a research effort supporting design space exploration (Müller *et al.*, 2019). Other research efforts point toward this fact of sub functional focus could have a tendency to distract designers from the main issues they face (Kroll, 2013). Accordingly, a multi-functional means compatible to the positions of the former means could in theory ease the design task, resulting in a better product from a range of different perspectives. The product could become simpler with fewer parts (more resilient to failures and reduced cost related to production, assembling and storage). Also, product reliability could improve with fewer parts, interfaces and simpler tolerance considerations. However, the handling of multi-functional means is difficult in the existing FM-tree, since single means are found corresponding to each function. Solving functions one by one is not optimal, since it is likely that more complex products with many individual parts will be the result. In continuation of this, critics also claim that the solution-independency of the FM-tree is questionable as the function structure of the FM-tree can vary, if other means are chosen for accommodating the design problem inhibiting innovation (Fiorineschi, Rotini and Rissone, 2016). Acknowledging the widespread usage of the FM-tree or approaches combining functional decomposition and morphological synthesis and the FM-tree criticism on sub functional focus and poor applicability for innovation will be this article’s theoretical starting point.

1.2 Multi-functionality found in nature

Biological solutions showcase intricate examples of multi-functionality as nature has evolved and accommodated the changing environmental needs over millions of years. Thus, nature constitutes an exciting source of inspiration for designers for finding integrated biological solutions capable of executing multiple functions with simple means. Since the same mean can provide several functions, it is likely to reduce the resulting product complexity.

For instance, the functionality of the skin serves as an example of multi-functionality found in nature. The skin (the mean) solves several functions such as it contain and protect the organism, it includes a variety of sensing elements and might serve as camouflage (Lakhtakia, 2015). In the present paper *multi-functionality* as a concept describes the situation where a single entity is used to realize more than one function.
Another example is shark scales where the corrugated surface texture on each individual scale supply the mean for achieving two functions: drag reduction and antifouling. Micro flow vortices close to the surface caused by the corrugated surface reduces the drag. The corrugated surface also physically prevents barnacles to attach due to insufficient contact area. If the curvature of the corrugated scale surface is changed it will affect both functions (Ball, 1999).

1.3 Crystallizing the research motivation

The present paper will explore the prerequisites for incorporating multi-functional means. The goal is to narrow down the gap between the task of analysing function-means structures and the identification of multi-functional means. The work is based on the following hypothesis: *Handling of multi-functionality in design work can be improved by mimicking nature's way of using integrated means*. The following research questions (RQ) will guide the work:

- *RQ1: How are the categorization of functions within engineering design research affecting the analysis and search for multi-functional means?*
- *RQ2: How can the analysis of the functions/means relationship from engineering design research support the handling of multi-functional means?*

1.4 A multi-functional case: The anterior eye-chamber (AEC)

To visualize the implications of the research questions, the multi-functional anterior eye-chamber model will be used as an example in sections 4.1 and 5.1.
The case is a development project made in collaboration with a university hospital who requested an ex-vivo model of the eye supporting research in corneal transplantations. The cornea is the transparent membrane through which light enters the eye – when it becomes unclear, the cornea needs to be replaced with a transplant from a donor.
The anterior eye-chamber (AEC) will help the surgeons making ex-vivo experiments to optimize the transplantation procedure. It is important that the eye-chamber model simulate the conditions in the eye as closely as possible, i.e. provide the right nutritional liquid to the endothelial (backside) part of the cornea while preserving a moist condition at the epithelial (front side) part of the cornea. The AEC needs to include the same functions as the eye namely to keep the cornea moist, to ensure a flow of nutritional fluid, to maintain a pressure behind the cornea and keep a constant temperature.
A principal sketch of the AEC is displayed in *figure 2* and will be elaborated later.

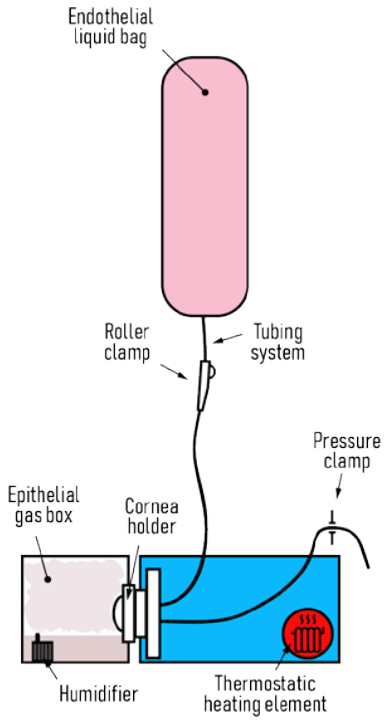

Figure 2. Visualization of the anterior eye-chamber model

2 Methods for data collection

The research questions have been explored in a three-step data collection procedure, including a literature screening, five semi-structured interviews and a literature review.

2.1 Literature screening

Initially an overview of the topic was established by consulting literature already acquired and by talking to colleagues at the DESIGN conference 2018, the ICED conference 2019 and two postdoctoral courses on design methodology and design methods. The result was a theoretical foundation aimed at supporting the interviews.

2.2 Semi-structured interviews

Next, a range of semi-structured interviews was carried in order to complement the initial knowledge. Prior to the interview, eight questions guiding the conversations were prepared along with a practical example of a multi-functional solution. The interviews were conducted with four engineering design researchers covering the following competencies and research areas:

- Conceptual design, problem solving, and functional reasoning.
- Product design, design theory, and design research.
- Designer behaviour and activity, innovation and design processes.
- Industry experience in industrial design and product development.
- Engineering Science and Mechanics within nanotechnology, electronics and complex materials.

The interviewees were carefully chosen due to their various backgrounds. Interviewees 1-3 was expected to provide academic information on terminology and functional analysis, interviewee 4 was expected to provide industrial experiences, while interviewee 5 was expected to provide information on design work and multi-functionality from another technical domain.

2.3 Literature review

Finally, a literature review was made to complement knowledge on functions and functional analysis. Two search blocks were constructed to discover literature in the research field: engineering OR "engineering design" (block 1) and dealing with functions: "functional modelling" OR "functional analysis" OR "functional decomposition" OR "functional reasoning" OR "function structure" OR "function carrier" OR "functional unit" (block 2).
The contents of these search blocks were derived from the interviews and the authors own experience from engineering design education and research. The search blocks evolved over time, but the terms above yielded the most relevant results when considering inclusion criteria (IC) and qualification criteria (QC). To ensure the eligibility of the discovered literature following IC and QC were developed:

- IC: The discovered publications must define what a function is (1), propose function types (2), describe how functions can be handled in design (3) and be written in English (4).
- QC: To qualify the discovered literature, only scientific literature published in journals, textbooks, dissertations or conference proceedings will be considered.

3 Outcome of data collection

Screening the literature revealed design related works by Tjalve (1979) and Cross (2008), where *functions* were addressed indirectly and practically, although no theoretical definition or differentiation of function types were presented.

The five semi-structured interviews provided useful information and a range of literature recommendations. For the two research questions, literature from Czech (Hubka and Eder, 1984) German (Pahl and Beitz, 2007) and Danish (Andreassen, 1980) engineering design traditions was recommended to explore the function terminology, function category types and function-driven design work. Furthermore, a range of relevant tools (TRIZ, DSM and QFD) and concepts (trade-off, unintended interactions/consequences, etc.) was proposed.

Analysing the responses, the function definitions only varied slightly amongst interviewees 1, 2 and 5 stating that a function is "what a product is capable of", "the ability to create an effect" and "the relationship between a cause and an effect". The answers from interviewees 3 and 4 displayed a more practical view of functions, by respectively adopting the terminology of (Cross, 2008) and stating that a function is "... sort of the natural thing in a thing that satisfies a need or a purpose".
Regarding function categories, interviewees 1-4 all operated with the categories 'how the product works' and 'how the product is used'. Categories related to 'how the product works were designated product functions, technical functions and action functions, while categories related to 'how the product is used' were designated use functions, behavioural functions and symbolic functions.
Discussing multi-functionality, interviewees 1-3 all indicated that a distinction between redesigning a product and designing a new product possibly should be made. This was crystallized from interviewee 1 and 2, stressing that for supporting product development with many functional requirements "You don't have multi-functionality before you look at an existing solution" and "It depends on the definition of functions. Whether it is related to the network within a product where functions interact causally or when objects (material units, parts, etc.) are capable of doing more things simultaneously".

The process of reviewing literature was focused at following up on the references of the initial found literature and the recommendations of the interviewed researchers. Additionally, literature found through executing the search string, constituted by the search blocks proposed in section 2.3., in an electronic database was evaluated with respect to the IC and the QC of section 2.3.

4 Categorizing functions in engineering design theory

Based on the data described in section 3, the function terminology of the Hubka, Andreasen et al. and a few other theoretical contributions are presented in addition to proposals for categorizing functions. An effort addressing research question 1.

Proposing the *Theory of Technical Systems*, the notions *Transformation System* (TrS), *Transformation Process* (TrP) and *Technical System* (TS) are essential to understand this theoretical view on functions, displayed in *figure 4* (Hubka and Eder, 1984).

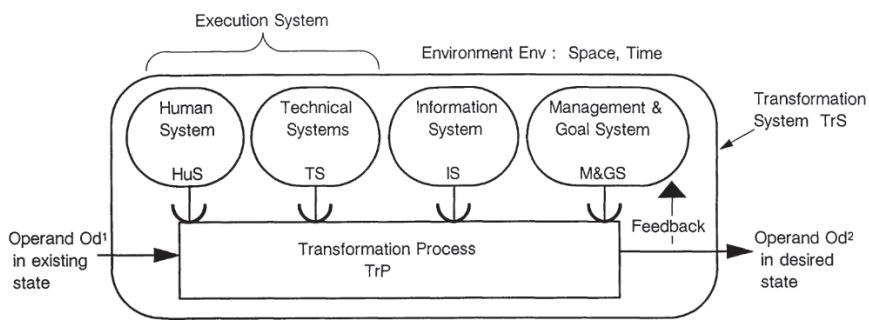

Figure 3. General model of the Transformation System [Hubka and Eder, 1984]

In the context of this paper, the focus will now be directed towards the operator, Technical Systems (TS), as this is defined as: "*an artefact, a product of human art and workmanship*" (Hubka and Eder, 1984), suited to explore the phenomenon of *functions* in engineered products. These actual abilities are performed by the TS to convert the input to the required output effect. Hubka define four effect types: Material effects, energy effects, information effects or biological effects. The abilities resulting in the conversion of the input to the output is designated *functions* (Hubka and Eder, 1984). *Mode of action* designate how functions work, i.e. how input effects are turned into output effects and is delivered by *organs*. While some organs directly deliver an effect on an operand, other operands are affected by effects from more organs, which is designated the *horizontal causality chain* (Hubka and Eder, 1984).

Inspired by Hubka's Theory of Technical Systems, Andreasen propose the Domain Theory supporting engineering designers in reasoning about an artefact's functionality and behaviour by introducing three domains from where an artefact can be analysed and designed. These domains are designated *the transformation domain*, *the organ domain* and *the parts domain* (Andreasen, 1980). Adopting the distinction between a system's structural elements and behavioural properties with Hubka's causality chain definitions for the transformation domain (horizontal) and the organ domain (vertical), the theory is extended to describe the *design object*, visualised in *figure 4*.

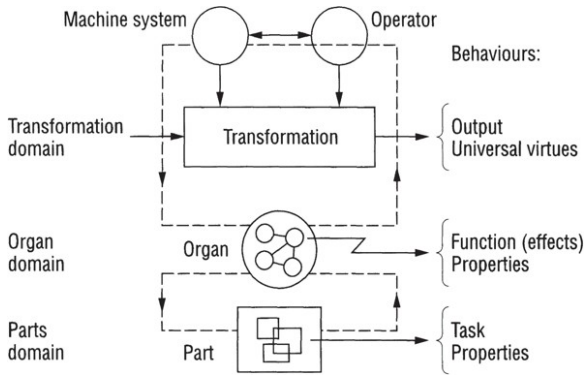

Figure 4. The design object (Andreasen, 1988)

This theoretical contribution to design theory should support designers in realizing the design causality between the domains, while underlining the non-existing nature of functions as a structural entity, but rather as a behavioural aspect in designing. Thereby, *function* is defined as the behaviour of an organ. For further explanations of the different domains' behaviours in the left side of *figure 3*, refer to (Hansen and Andreasen, 2002). Andreasen divides functions with respect to their purpose and operates with four categories inspired by the function complex law (Andreasen, 1980): Energy delivering functions, regulation functions, support functions (supporting the TS structurally) and auxiliary functions (aiding the transformation process).
Later work from the Danish research group expand the definition of functions to cover "a product's or an activity's ability to do something actively or be used for something", formalized in action *functions* and *use functions* (Andreasen et al., 2015).

In direct line with the function definition of Hubka many researchers position themselves. Roozenburg defines functions in relation to a product, by stating, *"The function of a product is the intended and deliberately caused ability to bring about a transformation of a part of an environment of the product"* (Roozenburg & Eekels, 1995). Likewise, for developing a functional basis, i.e. a function-related terminology useful for conducting functional modelling, a function is defined as a product's/artefact's intended reason behind its existence (Hirtz *et al.*, 2002). Similarly, in the research of Pahl & Beitz, the term *function* arises when dealing with a technical problem and the term is used to designate the relationship between input and output in a system intended to perform a task (Pahl and Beitz, 2007). In the function-structure-behaviour framework, the design object is the centre of the analysis as for Andreasen, and designers are supported in handling the design object in the dynamic context that design practice is carried out in. In this context, *function* defines what the object is for, *behaviour* defines what the object does and *structure* defines what the object is (Gero and Kannengiesser, 2014).

The fact that function terminology is ambiguous, is summarized well in the research by Pieter E. Vermaas on the varying meanings of function in engineering design. Adopting different authors' schemes for design reasoning for devices, design is guided by *goal, action, function, behaviour* and *structure*. The extent to which a design method is covering one or more of these phases is decisive for the adopted concept of function: *capacity-function, intended-behaviour function* and *purpose-function* (Vermaas, 2013). The concept of capacity function applies to methodological approaches considering all phases outlined above. The concept of intended-behaviour function applies to methodological approaches bypassing *action* with the device and *behaviour* of the device. The concept of purpose-function applies to approaches bypassing *action* with the device.

4.1 The impact of function categorization to a multi-functional case

For comparing the theoretical contributions' categorization of functions, the AEC is used as example (*figure 2*). Mapping the functions tree of the AEC is visualized in *figure 5*, where the overall function is, to simulate anterior eye-chamber physiology.

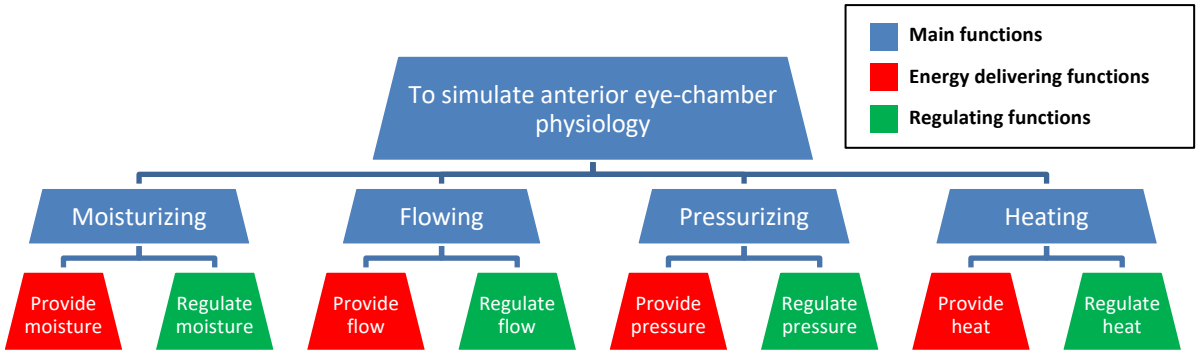

Figure 5. The functions tree of the AEC Model.

Beneath, functions related to moisturizing the cornea‘s front side, and flowing, pressurizing and heating of the liquid surrounding the cornea‘s back side is depicted. These functions are decomposed into a range of sub functions classified with respect to the terminology of Andreasen et al., where red functions indicate *energy delivering functions* while green functions indicate *regulating functions.*

Interestingly, all sub functions related of the parent functions occur in pairs, suggesting that more research should be executed to establish whether this is a random finding or searching for multi-functional means could be recommended if a mean for either supporting an energy delivering function or regulation function is needed.

5 Handling the functions-means relationship in engineering design theory

Initiated by the results of section 3, the academic engineering design practice recommendations are described below. This effort specifically addresses research question 2.

As previously described Hubka is engaged with how organs work individually and in coherence (horizontal causality chain), the TS’ *function structure* and *organ structure* is used to handle this. The *organ structure* is used to designate the means by which the functions of the TS are realized and the relationship between those means. The *function structure* unfolds the network of the TS’ functions and their interrelationship and is used for designers to map the TS’ operational states (Hubka and Eder, 1984). Thereby, partial functions can be resolved from different means, which make the function structure somewhat comparable to a morphological chart (Cross, 2008). However, the route to be chosen is not straightforward, but the purpose of this way of resolving functions into partial functions, should be to reduce the complexity of the function structure. This way of working with functions is termed Hubka’s 2nd law or the function-means law (Andreasen, 1980) and is operationalized as the Functions-Means Tree method (Tjalve, 1979).

Dealing with a design object in practice, Andreasen and the Danish research group extend the Domain Theory, based on its view on structural characteristics and behavioural properties from the the FM-Tree method (Hubka's 2nd) shown in *figure 1*, adopted by (Tjalve, 1979). Thus linking a product's main function, sub functions and corresponding means to establish the products basic structure recommended as conceptualization offset (Tjalve, E., 1979).
This work introduces the chromosome model (Mortensen, 1999), shown in *figure 6*, allowing designers to handle all domains and their relationship in one product model. This is achieved by integrating *the causality chain* concept of Andreasen (1980). Thereby, vertical causality exists between the domains, i.e. execution of a process requires a set of functions realized by a number of organs constituted through assembling parts in a certain sequence (Mortensen, 1999).

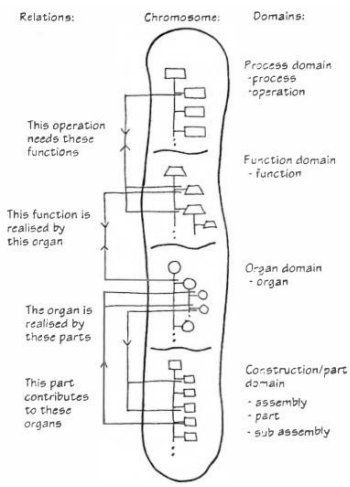

Figure 6. The chromosome model.

Quality function deployment (QFD), also termed House of Quality, is a tool for mapping and assessing the relationship between customer attributes (CA) and engineering characteristics (EC). These relationships are mapped strongly positive, medium positive, medium negative or strongly positive. The method is named after its visual representation, where the CA-EC relationship, CAs, ECs and the ECs' interrelationship are grouped in different areas of the house. Thus, by weighing the relative importance of the CAs and assessing competing products to the right of the house, this tool is used to display relationships inside the product and map these with respect to the customers' requirements (Cross, 2008). The ECs have similarities to both means and functions, making QFD applicable for a multi-functional product like the AEC model by revealing and quantifying how the means are affecting each other.

Design Structure Matrix (DSM) is another useful tool. The DSM matrix is used to indicate and model the relationship amongst different features (Pimmler, 1994). In its component-based version it follow the sequence: System-to-elements decomposition (1), element interaction documentation (2) and elements clustering (3). Proposing a taxonomy of the interactions (spatial, energy, information or material) and an interaction quantification scheme ranging from required to detrimental across 5 scores (+2, +1, 0, -1 and -2), Pimmler (1994) offers an interesting solution for improving the overview of a product's different elements' interactions.
As Pimmler (1994) elaborates what the goal of the systems-to-elements decomposition is to achieve *"functional and/or physical elements which achieve the product's functions"*. Like QFD, this tool provides an analysis approach to handling organ relationships and therefore is applicable for supporting decisions on redesigning existing products by introducing multi-functional organs.

Theory of inventive problem solving (TRIZ) developed by Genrich Altshuller, is also studying technical problems, and proposes the matrix for solving technical contradictions (Altshuller, 1997). The starting point of the usage of the matrix with the 39 solutions principles is the formulation of a technical contradiction, with two parameters – one parameter is preserved, while another parameter is optimized. Next, after the definition of the parameters, solution principles are discovered by following the advice proposed in the 39 solutions principles, that are founded by an extensive analysis of existing patents (Cavallucci, 2002). The contradiction matrix is therefore applicable for handling multi-functional problems. However, it is limited to suggesting inspiration sources rather than providing guidance on the functional analysis of a multi-functional problem.

Trade-off is another important concept to acknowledge the existence of in design practice (Andreasen et al, 2015). Similarly to TRIZ, the context where trade-offs become important is in balancing opposing demands, through the act of balancing sets of properties to achieve the optimal solution. Related to functions, the situation occurs when one or more functions cannot accomplish the desired function properties. This concept is definitely applicable for redesigning, however as a

design engineer one should notice that the concept aims at seeking optimum using the existing organ structure rather than supporting functional analysis.

5.1 Qualitative assessment of the FM-tree's degree of multi-functionality

For comparing the view on the the functions/means relationship, the AEC-example is used (*figure 2*). Mapping the FM-tree of the AEC-ecample is visualized in *figure 7*. To simplify the figure and concretize, the means constituting the organs executing the functions for *Moisturizing* and *Heating* is intentionally left out. These organs are in principal multi-functional as the humidifier is used to provide and regulate moisture level (moisture organ), while the thermostatic heating element is providing and regulating temperature (heating organ). However, when analysing multi-functional products, the flowing/pressurizing organ (FP-organ) marked with grey constituted by the means marked with orange is more interesting.

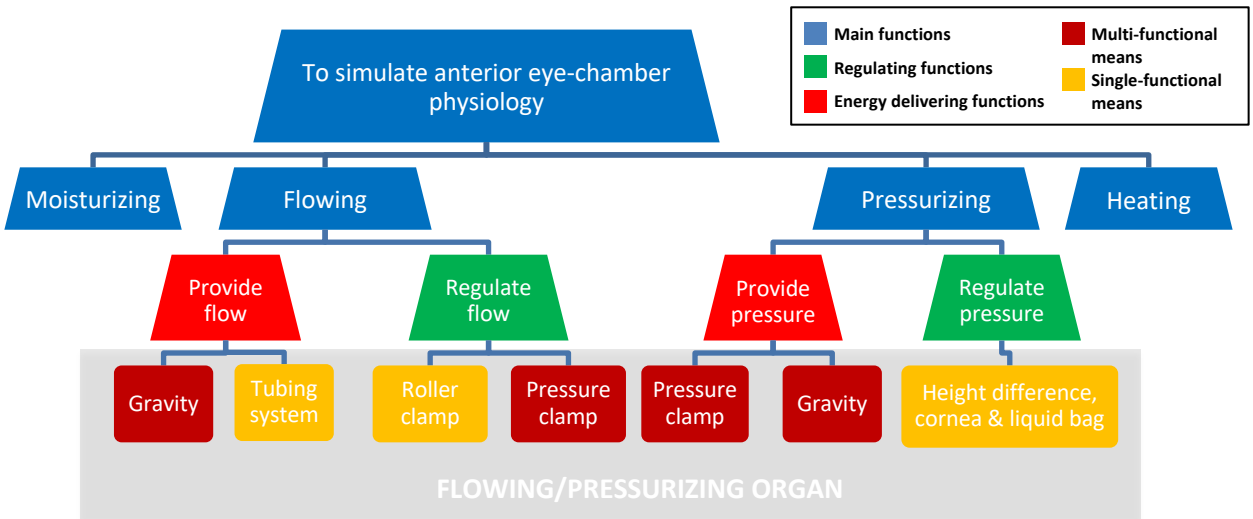

Figure 7. The FM-tree of the AEC-example with organ labels attached.

The FP-organ is constituted by following components: the pressure clamp, the roller clamp and the tubing system. However, gravity and the height difference between the cornea and the endothelial liquid bag are also means affecting the FP-organ's ability to execute flowing and pressurizing:

- The liquid *flow is provided* by gravity
- The liquid *flow rate is regulated* with the roller clamp and pressure clamp, i.e. by varying the tubing system's inner diameter
- The liquid *pressure is provided* by a combination of gravity and the pressure clamp – when the pressure clamp is working, the liquid is under pressure
- The liquid *pressure is regulated* by varying the height difference between the outlet of the endothelial liquid bag and the cornea – the pressure (in mmHg) corresponds to the height difference (in cm)

Thus, the FP-organ is multi-functional on a higher abstraction level than the organs for heating and moisturizing. All the means for heating and moisturizing are single-functional affecting their parent function only, while the means for the FP-organ are multi-functional. Therefore, using this extension of the FM-tree, designers are supported in mapping multi-functionality and thereby suggesting areas of improvement where a multi-functional biological analogy and be integrated corresponding to the existing single-functional means.

6 Discussion

Examining the different theoretical perceptions of function terminology with respect to the notion *multi-functionality* adopted from biological organisms, *function type* and *function purposes* in general represent an interesting angle for further study. Obviously, as action functions are the *mode of action* of technical systems, this comparison has been driving bio-inspired design already. However, function purposes could potentially inform whether mono- or multi-functionality should be pursued, if function purposes are related to the complexity of the organs delivering this function. On the other hand, it appears unnecessary to relate multi-functionality and use functions, as use functions only exist during context-dependent product interactions, which are arbitrary and not easily quantified.

The notion of multi-functionality is applicable for redesigning, the context where a solution exists. For redesigning purposes, the FM-tree and the Chromosome model are somewhat limited in their ability to handle complex products as the functional relationships are only disclosed in a binary fashion, i.e. are the functions related or not. However, while the FM-tree and the Chromosome model do not handle the degree of connectedness between functions and means, visualizing multi-functional organs or means on the FM-tree can support designers in focusing on which functions to merge and search for a multi-functional biological analogy corresponding to. In further improving and shaping this design support, inspiration will be drawn from a research effort from Chalmers University also evaluating structural relationships between means and functions qualitatively (Müller *et al.*, 2019). However, as our motivation is to finalize the functional analysis process by proposing multi-functional means, our functional decomposition is run top-down. On the other hand, the motivation of the Swedish research group is to support single-functional design space exploration, whereby the functional decomposition process is run bottom-up (Borgue, O., Müller, J., Panarotto, 2008).

All the support measures presented in section 5.1, are all well suited for the incremental design context, where a solution to a design problem exist already, but an incentive to redesign this solution is present. While TRIZ is pointing designers towards useful solution spaces comparable to the designer's problem at hand, it only embraces a design context with two contradictions. Furthermore, as TRIZ is dealing with technical contradictions, this method is addressing properties in the terminology of Andreasen (1988), the behaviour of organs or parts even. Likewise, the concept of trade-offs addresses properties, although this concept offers support for situations with more entities at a time.
Contrary to these contributions, the DSM and QFD provide quantifiable design support (like trade-offs). However in both instances the analysis inputs are on organ level. Thus, these methods are capable of dealing with more inputs than TRIZ, while also supporting designers on a more abstract level than TRIZ and the trade-off concept by addressing organs. Therefore, QFD and DSM are more suited to aid the FM-tree and when redesigning with highly integrated products constituted by organs contribution to many functions simultaneously. Therefore, QFD, DSM and similar tools useful for handling many organs, functions and their relationship across the FM-tree, will be suspect to further study.

The research questions in this paper have been analyzed from the perspective of engineering design researchers. An additional study aimed at engineering design practitioners would be an interesting supplement to obtain a broader perspective on the topic.

7 Conclusion

Our initial assumption was that the process of identifying integrated means corresponding to the needs of multiple functions in design is not supported well. We have shown that this is partly true.

Our first research question was how the categorization of functions within engineering design theory was affecting the analysis and search for multi-functional means. We found a range of

definitions and ways of categorizing functions and evaluated them by applying them to a concrete product: an artificial eye chamber (AEC). In design theory a *function* describes the behaviour or effect exhibited by an organ converting an input to an output, i.e. multi-functionality is executed on organ level. The AEC example displayed that it was meaningful to use the two functional categories 'energy delivering functions' and 'regulating functions' as sub functions for 4 main functions. Whether this relationship is more general should be explored in upcoming research. Since biological organisms often utilize multi-functional principles, we propose to analyse the applicability of combining energy delivery and regulation in the functional descriptions when searching for biological analogies.

The second research question was how the analysis of the functions/means relationship from engineering design theory can support the handling of multi-functional means. Arranging functions and means hierarchically to establish the product's functional and organ structure constitute the traditional engineering design practice, independent of the design context – whether designing new solutions or redesigning existing products. This is exemplified by the Chromosome model and the FM-tree. However, using the AEC-example displayed that dealing with a multi-functional case, having a binary, hierarchical analysis tool like the FM-tree is insufficient in its present form. Although, with a relatively simple mapping of the FM-tree's multi-functionality – visualizing means and/or organs affecting more than one function, the complexity of the product is assessed qualitatively. Thereby, designers are capable of making a more informed decision on which functions to merge to benefit from the multi-functional biological analogies of nature.

Thus we propose an extension to the FM-tree that will help designers in visualizing multi-functional means/organs. The extended FM-tree will guide subsequent searching for multi-functional biological analogies. The extension of the FM-tree is working for the AEC example, but a more comprehensive justification should be made to analyse the effect of complexity, products type or other parameters.

Further work will focus more quantitatively on the functions/means relationship using analysis tools like the QFD and DSM. This will be an addition to the extension of the FM-tree in order to propose a procedure for analyzing products with the goal of making an informed decision on which functions to search for a multi-functional biological analogy corresponding to.

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