INTEGRATING DESIGN AND ENGINEERING, I: FUNCTIONAL ABSTRACTION AND PRODUCT ARCHITECTURE

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ABSTRACT
Effective product design demands cross–functional teams comprised of industrial designers, engineers, marketers, and others who can effectively speak a common language. Here we propose a method of adapting conceptual tools from the field of systems engineering to form a set of design tools that can be used across disciplines.

Keywords: Design methods, functional decomposition, product architecture

1 INTRODUCTION

As educators in two historically distinct fields of design, we recognize the limitations that the university structure imposes on how our students learn. In the best case, product design students would interact as much and as often on campus as they will in practice, when many of them will find themselves working on multi–disciplinary teams that may span continents as well as cultures. The best we can hope for at present is to bring our students together as often as possible, and to develop common methods for thinking about product design, so that when they encounter each other in their careers, they will be better prepared to communicate.

It is in this spirit that we have worked for the past few years to develop methods of teaching design based on product functionality. This idea in itself is nothing new; our emphasis is on adapting techniques from industrial design and product engineering to make them more readily understandable by students from a range of specialties. What we present here are some ideas for applying conceptual tools from the field of systems engineering to the task of product design. The basis of this effort is creating clear and concise functional descriptions of products *as they are used*. We have found that while recent product engineering texts promote the idea of functional product descriptions and architectures, they typically neglect the larger context in which the product operates. Product designers, on the other hand, tend to be less familiar with the techniques of functional products analysis, and tend to shy away from these methods, feeling that they are ‘too numerical’, ‘too confining’, or ‘too reductive’.

In truth, the idea of using functional descriptions to develop product architectures fits well with the goal of designers to situate products in context. Techniques such as field observation, usability studies, and scenario modelling have all contributed to greater emphasis on the product’s interaction with its use environment, and less attention to the product in isolation. These techniques are becoming common practice among industrial designers, but much less so among engineers, whose focus tends to be on the function of the product itself. We strongly believe that an increased emphasis on educating students in the use of these techniques will result in greater integration between the disciplines of product design and product engineering.

If we visualize products as a pyramidal structure of interacting functional blocks, it seems logical to assume that product engineers will tend to focus on the base of the pyramid, at the component level, while designers will concentrate on the upper levels, where the interaction of product and user is made clear. Our interest in these ideas is based on a perceived need to create tools that will encourage greater integration and collaboration among engineers, designers, and others who work on design teams. In this paper, we provide some ideas for introducing these methods in the classroom; an accompanying paper describes how they can be applied to consumer products. We also show how the functional description can clarify design decisions, and in so doing, lead to better and more sustainable designs over the long term.

2 FUNCTIONAL DECOMPOSITION: AN ENGINEERING PERSPECTIVE

Functional decomposition is a well–established engineering tool that can be used to make complex systems intelligible by iteratively breaking down higher–level elements into their composite parts. The specific role of each functional element in a system hierarchy, down to the most basic level, is defined through the repeated application of this method. The process begins at the top level of the system with the definition of the product in functional terms. Figure 1 shows an example of a top–level functional description of a vacuum cleaner. The highest–level function is decomposed into secondary sub–functions, each of which is disassembled into its own set of sub–functions; the process is repeated until the most basic functional level is reached. At each level, both intended and incidental connections among the individual functions and the higher level functions are explicitly defined. This technique has been applied as a tool for analyzing complex systems, as well as in software development [1].

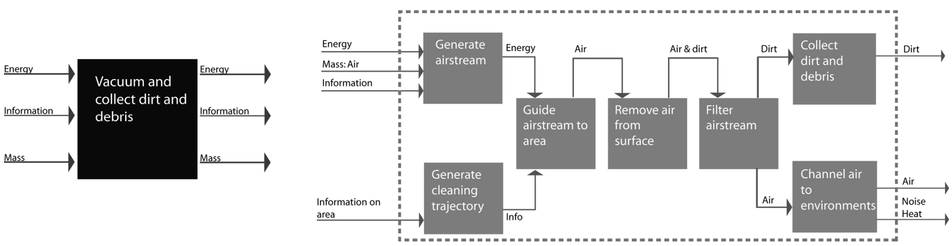

Figure 1 Top level and second level functional descriptions

The idea of applying functional decomposition to product design was noted by Jones in the original 1970 edition of *Design Methods*, where he introduced it as a method for creating innovative products by abstracting the functional essence of existing products [2]. Pahl and Beitz further developed functional decomposition as an engineering design tool in their text, *Engineering Design*, a decade later, adding the idea of mapping flows of energy, mass and information through the system [3]. More recently, the method has been adapted as a method for relating customer needs directly to product features and functions by Ulrich and Eppinger [4], and Otto and Wood [5], and in the context of developing rational product architectures [6], [7].

2.1 Creating the functional hierarchy

Creating detailed functional decomposition charts of real products is a useful exercise for design and engineering students, but it is not intuitive. The authors have used this teaching method with students ranging from first–year engineering students to NASA technical staff, and have encountered difficulties in every case. Students are quite often initially baffled by the complexity of the task, even for relatively simple products like the Kodak single–use camera [8]. After several years of applying this method in class, we continue to refine and develop our pedagogical methods. At present we concentrate our efforts on our graduate students, our intent being to develop effective tools that we can later migrate to lower level students.

The first step in creating a functional hierarchy of a product is to define the exact purpose of the product, in functional terms. While this might appear to be a simple task, students often struggle with the inherent conflict between abstraction and specificity. It often requires care on the part of the instructor to make sure that the definition of the product's purpose captures the functionality of the system concisely and clearly. The goal statement must be written in the form of verbs acting on a noun phrase: for example, our definition of the function of the camera is 'to capture and record visual information'. It is important that the verbs used in the statement precisely convey the required action, while the noun phrase is abstract enough to not impede creativity. This point is important when the ultimate goal is to have the students use the functional decomposition diagram as a tool for ideation.

At this point, it is essential for the instructor to discuss how the system relates to its context, and to the constraints that apply. We find that we repeatedly ask students to reflect on constraints that apply at each level of the system – indeed, this is crucial when discussing how system resilience can be built into a product family. While some authors (see, for example, Otto and Wood [5]) explicitly define constraints as criteria that can only be satisfied by the total system, we believe that it is more useful to think of constraints that apply specifically to sub–functions throughout the system.

The next step in developing a functional hierarchy is to create an event sequence chart that captures the operation of the system in discrete steps. We have found that developing a sequence of events is perhaps the best method for convincing students to 'think functionally'. This sequence chart becomes the map for the second level of functionality. At this point, we introduce the idea that every system involves flows of matter, energy, and information both across the system boundary and among the functional groups within the boundary.

A crucial point to emphasize is that these flows can be both intentionally designed into the system, or can inadvertently result from design decisions. In our experience, this is one of the more difficult aspects of this method for the students to grasp. The difficulty may be due to the fact that engineering students in particular have been taught to think by reductionist methods, where every problem is solved by breaking it down into the simplest possible components. Instead, we ask them to 'think systemically' by looking for connections that may not be apparent at first glance. When analyzing existing products the intended connections are in general much easier to spot than the incidental ones. Nonetheless, it is essential for the students' growth as designers that they develop the ability to predict the unintended consequences of design decisions, and to appreciate how often the incidental connections lead to product failure.

While design students tend to be more vocal in their dislike for this kind of thinking, the engineering students struggle with these concepts as well. Thinking functionally and looking for connections between functions is not familiar to either field of study, and it is often a struggle to convince the students that anything is to be gained from doing so. Nevertheless, we have found that by persevering, most students will eventually see the benefits of analyzing products in this way, and in fact the more perceptive students will understand that they are learning an entirely new way of thinking about design.

Once the second functional level of the chart is complete, it is typically just a matter of repetition to fill in the lower levels. We have found that it is rarely necessary to extend the hierarchy beyond three levels, even for fairly complex systems. However, at this level it is a challenge to prevent students from thinking in terms of physical components rather than functions. Once the most basic level is defined *in functional terms*, physical components can be mapped to functional groups, creating the product architecture [9].

One of the most valuable aspects of this method from a pedagogical point of view is the clarity it gives to designing the product architecture. By defining products in terms of the functions they perform, it is relatively easy to convince students that modular architectures result when a single physical component performs a single function, and that integrated architectures result when single components perform several functions, or conversely when several components perform a single function. Once the architecture has been defined, topics such as design for assembly and disassembly, and development of product families can be introduced into the curriculum more readily.

2.2 Advantages and limitations of the current method

2.2.1 As an analytical tool

The process outlined above is ideal for analyzing existing products at a systems level, and in fact the method is best introduced as an analysis tool used in the context of 'reverse engineering' exercises, in which students disassemble an existing product of sufficient complexity to make the exercise interesting. In the best case, the product is chosen so that it has flows of mass, energy and information, as well as a few unintended connections between components. However, we have had great success with applying the method to the single–use camera, which has no flows of mass, and which lacks obvious unintended connections.

Because decomposition is inherently reductionist, it can lead students to believe that an optimal system will result if they focus their attention on individual components. For this reason, it is essential that the instructor continually remind the students that they are analyzing a coherent *system*, not merely an assemblage of parts that happen to work well together by accident. A limitation of this method as it is typically presented in engineering texts is that the product is most often viewed and analysed in isolation, as if the product operates by itself, without a user and without context. We believe the real power of this method only emerges when the product is embedded in another, larger system diagram that includes the user, the product, and the choices and constraints that the user faces [9]. It can be a useful exercise to develop a decomposition diagram for a product in isolation, and then compare it with a diagram of the product and user in context. Quite often, additional features that were initially overlooked in the design of the product become apparent at this stage.

2.2.2 As an ideation tool

While the discussion to this point has dealt with decomposition diagrams purely as a tool for analysis of existing products, there is a clear need to apply this conceptual tool to the creation of totally new designs. Students can break down even a fairly complex existing product into discrete functional levels relatively easily. When creating a system map for a new product in the conceptual stage, however, the problem is much more daunting.

Perhaps the most obvious question is, at what point in the conceptual design does this process apply? It should be clear that the functional description of a product must follow and depend on the sort of activities – persona and scenario models, usability studies, etc. – at which design students excel. Most of these tools and techniques are completely unknown to engineers, unless they have prior experience working with industrial designers. The functional method outlined here works best when the entire user experience has been thought out in detail, and the possibility of creating a family of products around a related set of activities is considered.

There are also questions about the nature of the diagrams themselves: how many levels will the system have when it is complete? How does the design team know when to stop? One must also question whether the levels created in the diagram actually correspond with reality. System maps created by engineers (see, for example, [1]) tend to be strictly hierarchical, with well–defined levels – an apt metaphor would be a pyramid constructed by stacking layers of bricks. How well does this model actually apply to real products? Might a more realistic model look more biological, for example, more tree–like?

Another interesting question is how we can best include design constraints in these hierarchical models. The relatively simple 'black box' model that has been used by systems engineers for decades was never intended to convey the role played by local constraints. Indeed, many engineering texts explicitly define constraints as applying only globally, and regard constraints that apply only to specific sub–functional groups as functions [5]. This approach often leads to tried and true solutions rather than truly innovative designs, and we question whether it is in fact accurate. We believe that explicitly defining the constraints that apply to each functional group throughout the system hierarchy might be an effective method for generating new designs, and is an idea that bears further study.

Finally, our experience has shown us that some care is needed in introducing functional decomposition methods, because they tend to reinforce the existing tendency of our students, especially the engineering students, to focus only on 'the black box' and to ignore the larger context. We develop this idea further in the next section.

3 INCLUDING THE USER AND THE CONTEXT

Functional decomposition is a powerful technique for analyzing existing products and for moving new product concepts from the brainstorming stage to more definite form. On the other hand, in the relevant engineering literature (see [3] – [7]), its use has been restricted to the device itself: the system boundary is almost always defined by the actual dimensions of the product. The user is treated as an input to the system, and the product's interaction with its environment is considered to be the desired output. As we show in [9], this use of the method, without considering the wider range of user activities, can result in products that are optimized for only one part of a wider task.

This conceptual tool and similar systems engineering tools can be made much more useful to product designers by expanding the boundary of what is considered to be 'in the box'. To be truly effective, these tools also must force the design team to consider the user, other possible actors (e.g., persons who are affected by the product), the market in which the product family operates, and the physical and biological environment that is impacted by the product's use. Mapping the flows of energy, mass, and information through the expanded system representation of a product family is a powerful method of revealing the hidden effects that inevitably attach to products.

We plan to continue to apply systems engineering tools in our design classes. In particular, we are beginning to use sequential process diagrams and function trees to augment the function decomposition chart and place it in a larger context. We are also investigating the use of Design Structure Matrices [10] to create different sequences of activities, resulting in possible design variants.

In addition, we seek to apply design constraints throughout the functional hierarchy, not only at the total system level. By defining the constraints that affect each sub–functional group, design teams can create coherent product families and seize product opportunities that might otherwise be overlooked. By expanding the scope, the opportunities for innovation in individual products and entire systems of products is also expanded.

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