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FLOWCHART-ASSISTED FUNCTION ANALYSIS OF PRODUCTS TO SUPPORT TEACHING OF THE EXACT SCIENCES

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ABSTRACT
To reintroduce function analysis into the curriculum of Industrial Design Engineering (IDE), we developed a systematic approach suitable for interaction-intensive products. By strengthening the link between high-level design considerations and exact-science-based engineering calculations, our goal was to make the students more aware of the relevance of the exact sciences for designers. We started out from the problem that conventional function analysis approaches are difficult to apply to products interacting with users, while the user-oriented approaches that have come to replace function analysis in our curriculum do not easily connect to engineering aspects.
The proposed approach involves a procedure to extract functions from the process tree that our students commonly use in design projects, and which allows mapping of transformations performed by the user to functions of the product. Putting functions on a gradual scale from 'good' to 'bad' points out directions for reconsideration. The approach is 'open': established methods for idea generation based on functions, and for configuration and analysis of transformation processes can be used in combination. It was embedded into a new, recently developed engineering-oriented course. Student evaluations have shown that the new course more effectively communicates the relevance of exact sciences than previously taught courses did. In the near future, our plan is to make the approach suitable for application in design projects. Another aspect to be addressed in future work is assessing the impact of our approach on the competencies that our students are developing.

Keywords: function analysis, interactive products, industrial design engineering, education

1 INTRODUCTION

Background: a new curriculum
Historically, a persistent problem of the Industrial Design Engineering (IDE) program has been the gap between theory and practice. IDE students take courses in engineering sciences, human sciences, mathematics, statistics and the like; however in tackling practical design projects, they failed to apply this knowledge to the benefit of their design work. In the old curriculum, mechanics, mathematics, material science, as well as ergonomics and consumer behaviour, etc., were taught in isolation and often with an emphasis on abstract theory without much reference to concrete practical problems. As a consequence many IDE students were not motivated to study these topics, and tended to postpone the courses concerned. Moreover, even students who passed these courses were often unable to apply their new theoretical knowledge to their design work. It is for that reason that the developers of the new curriculum, which was launched in September, 2007, decided to abolish the compartmentalized disciplinary structure that characterized the former IDE curriculum [1].
The new curriculum pays more attention to the development of the students' competencies. Knowledge, skills and attitudes are no longer conveyed in mono-disciplinary courses in isolation from practice. Instead, the mandatory part of the new curriculum comprises sixteen large thematic multi-disciplinary courses in which new knowledge and skills are acquired in the context of realistic problems typical of the practice of product development.
In the curriculum, a series of five interlinked courses can be distinguished that are mainly rooted in the exact sciences. These courses cover design knowledge and design skills also commonly required in mechanical engineering. The courses fall under the responsibility of the Department of Design Engi-

neering at the IDE faculty, and they are conducted in cooperation with staff from other faculties who teach mathematics, mechanical engineering, and materials science. To achieve true multidisciplinarity in the curriculum, some additional topics of exact science appear in other courses where they have been combined with social sciences and/or design assignments [2].

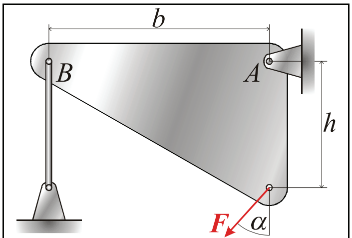

Figure 1. Example of a typical mechanics problem (statics).

The 'Products in action' course

'Products in action' (PIA), the new course discussed in this paper, is taught in the second quarter of the first year, and it is the first in the series of exact-sciences oriented courses. It covers the following topics formerly covered by separate courses: (i) basic mathematics (mainly linear algebra and vector algebra), (ii) basic mechanics (mainly statics), and (iii) an introduction to design engineering (systems engineering and design methodology with a focus on technical systems). In the old monodisciplinary courses, students' performance on mechanics and mathematics exams has always been a problem. Apart from the fact that the theory presented in these courses was perceived as 'difficult', we have assumed that this was also caused by motivation problems, because neither the course material nor the assignments and exams provided adequate connections to the application of the knowledge and problem-solving skills to product design. Traditionally, mathematics assignments involved computations with the goal to find unknown variables which were presented as abstract symbols. That a vector can represent a force or a velocity was not explained. In the case of statics, the situation used to be slightly better. As early as in the 1940s (or possibly even earlier), practical application examples started to appear in mechanics textbooks to support the relevance of the theoretical content [e.g., 3]. Although one might expect that today's textbooks have carried these developments even further, the current situation is still somewhat unsatisfying. The main problems are, firstly, that the majority of the assignments is still not practice-related and therefore uninspiring for students, and, secondly, those problems addressing application cases do not appeal to industrial design engineering students, whose primary focus is design and development of durable consumer goods. To illustrate the first issue, Figure 1 gives an example from statics that is, unfortunately, still typical for contemporary textbooks – [e.g., 4,5,6] and even [7]. The relevance of such a problem to real-life practice is hard to grasp because it is about a *fictitious* structure fulfilling *no explained function(s)* in an existing product or system. Therefore (i) it is unclear why it was designed like this, and (ii) it is unclear what the given and requested quantities mean: is the outcome supposed to be good, bad, surprising, striking…?

Regarding the second issue, a brief survey of application cases discussed in the above-mentioned textbooks confirmed an inclination towards heavy equipment and structures such as forklifts, tower cranes, bridges, and airplanes, while only a small number of problems involves consumer products such as bicycles, car headrests, wheelbarrows, and hand tools – most notably in [7]. Compared to problems like the one in Figure 1, the application cases in the textbooks have the advantage that, at least in some cases, the relevance of the requested calculations is obvious (e.g., whether the wheelbarrow will tip over, which is clearly to be avoided). However, obviously, higher-level design considerations of the given structures in the practical applications do not belong in mechanics textbooks. Since our objective for the new course was not only to bring together mechanics and mathematics but also aspects of design engineering and design methodology, we decided to include this connection to the *functionality of products* in the presented theory and address it in newly developed assignments. In these assignments (and also the exam questions), the mechanics problems were put into the context of a specific everyday consumer product, and we compelled the students to use the newly introduced mathematics (i.e., linear algebra and vector algebra, which are not taught at secondary school) to solve a specified subset of these mechanics problems.

The remainder of this paper has been organized as follows. In Section 2, the need for function analysis in our curriculum is explained based on its historical and current role, and our objectives and requirements for a new approach are stated in Section 3. In Section 4, existing approaches are reviewed. Then, in Section 5 the fundamentals of our approach are elaborated, after which the implementation into PIA has been accomplished. Section 6 presents results from student evaluations comparing the new course to its predecessors. Section 7 rounds off the paper with concluding remarks.

2 FUNCTION ANALYSIS IN IDE EDUCATION

In design education at the IDE faculty, function analysis has been traditionally based on the Pahl and Beitz approach [8,9]. However, consideration of functions has been losing its importance since the mid-1990s, as curriculum builders decided it was better to integrate all design methodology into design projects. Function analysis was suggested as a possible 'tool' in a lecture accompanying a design project, with reference to a textbook. Additionally, functionality was considered in a loose, informal way during an engineering project in which example products were disassembled to analyze various aspects. The motivation behind this increasing lack of attention to functions seems to have been that the applicability of function analysis to typical design problems in IDE was perceived as limited, for reasons we will discuss in Section 4. Nowadays it is possible for students to absolve a Master in industrial design engineering without ever having explicitly considered functionality in any design project, and without having acquired any experience in abstraction of design problems to describe fundamental needs of end users. Moreover, for their own designs they often failed to formulate the engineering problems that require quantitative verification, not being able to connect their informal notion of the product's purpose to models that can be created based on knowledge of the exact sciences.

3 OBJECTIVES AND REQUIREMENTS

To reintroduce these systematic abstraction skills in PIA, our goal has been to implement some kind of function consideration that pays attention to the specific needs of application to industrial design engineering. As an abstraction skill, functional reasoning is to be considered together with basic modelling and model simplification, which are also taught in PIA to enable quantitative assessment of real-world products and systems.

Our first objective for the introduction of function analysis has been to make the students aware of the fact that the physical phenomena involved in engineering calculations (in PIA this applies to forces in particular) serve a purpose in design, by enabling abstract thinking about the underlying purpose with a critical mind. Apart from strengthening the link between design, engineering, physics and mathematics, and raising the awareness that the exact sciences are relevant in the curriculum, a secondary goal has been to provide students a method that can be useful in design projects and that they may use as they see fit. The current implementation does not involve mandatory use in design projects. Once we can confirm that our requirements (see below) have been met, this is under consideration for the near future as a major operation involving intensive training of dozens of design teachers.

In re-implementing function analysis in our curriculum, we started out with the following requirements:

A. Identifying functions should systematically enable *abstract thinking* about what is absolutely needed, what is not really needed, and what should be avoided or should *have been* avoided (in a product).
B. Functions should conform to what people (designers) *intuitively* attribute to the 'functionality' of a product
C. It should be possible to *map* functions to function fulfillers (solution elements, parts, geometric features)
D. Identifying functions should be an *easy* and straightforward job.

Note: In this paper 'function analysis' refers to consideration of functions in both *analysis* and *synthesis* activities. Its use in synthesis activities is to be interpreted here as 'analyzing what a product should do by considering its functions', while the object of analysis may range from 'a design brief' to 'an existing product on the market'. For now the focus is, however, on analysis of existing products since the course does not include a full-scale design project.

4 EXISTING APPROACHES TO CONSIDERATION OF FUNCTIONS IN PRODUCTS

Obviously, the Pahl and Beitz approach [8] is not the only approach to function analysis. Some of the many other approaches are value engineering (VE) [10,11] and the related FAST method [12], the theory of technical systems [13], which has recently been updated in [14], NIST's functional basis [15], function-behavior-state modeling [16], the function-behavior representation language [17], and the function-task interaction method [18]. Several other approaches can be found in a recent review by

Erden et al. [19]. What the majority of the approaches agrees upon, is that functions of a product (i) are performed by that product, (ii) that they are expressed using a verb-noun combination (or more accurately, a predicate-object combination) with the product as the implicit subject of the verb, and (iii) that they are intentional. At some point, all the approaches aim to couple functions to physical function fulfillers belonging to the product. VE prescribes such couplings to identify cost-saving options in the form of parts fulfilling dispensable functions, or no functions at all; the other approaches are typically aimed at finding solution elements for the intended operation of the product. For all the approaches, the abovementioned characteristics (i-iii) of function descriptions effectively filter out what the product should *not* do. Consequently, function descriptions typically neither show interest in what the user does nor in product failure.

Another point in which the approaches agree is that, with the exception of VE, they take the perspective that the noun in the function description should express a flow of matter, energy, or information, and that the verb expresses a transformation of that flow performed by the product.

In industrial design engineering we are typically dealing with products involving intensive interaction with users. Interaction means that both the product and its user perform activities in the achievement of a common goal (of the user). It appears that many components in these products take part in transformations that are not performed *by the product* but *by the user*. For instance, the on/off switch of a coffee maker is flipped by the user, and the jug is also manipulated by the user when filling the reservoir or when pouring coffee. Using the Pahl and Beitz method and other function-based solution-finding approaches, it is difficult to formulate functions that would justify the existence of the involved components in interactive products, since the methods appear to focus on products taking over tasks otherwise performed by humans, a problem also identified by Warell [20]. VE could have been an attractive alternative if its focus would not have been so much specifically on cost reduction.

This inability of functions to deal with user tasks is a possible reason why these methods have become less popular among industrial design engineers, and why approaches that offer more opportunities to consider user actions, such as the process tree [9] and, increasingly, informal storyboarding [21] and scenario-based [22] approaches, which originated from human-computer interaction [23], are gradually taking their place. Yet, we felt that the informal nature of the current user-oriented approaches does not stimulate our students to systematically draft abstract descriptions of what products should do, as the 'old' transformation-oriented function-oriented approaches do. Especially in our exact-sciences oriented courses we still consider such abstract descriptions indispensable.

In recent years, the issue of function identification in interactive products has also been recognized in the transformation-function modelling community, and the following workarounds have been proposed to include transformations performed by the user:

1. Drop the requirement that the product is the subject of the function-defining verb. We sometimes encounter this workaround in our students' work when they try to apply the Pahl and Beitz method on interactive products, but it is also found in the literature, for instance in [24]. An example of this approach is to consider 'place food' a function of a barbecue, even if it is performed by the user. This workaround conflicts with our requirements, especially because it is counterintuitive (against requirement B in Section 2). It may also be difficult to map user tasks to function fulfillers (against requirement D).
2. Use import and export functions. As soon as human 'parts' (such as the hand) enter the system boundary around the product, the product performs an 'import' function on human matter, human energy, or human signals. Human presence and activity is temporarily 'transformed' to an imported something that is considered part of the product, until the product 'transforms' it back by 'exporting' it. The barbecue in the previous example might perform the functions 'import human hand with food', 'input human energy', and 'export human hand'. This workaround is often recommended in combination with function modeling according to NIST's functional basis [25,26]. Again, this workaround is counterintuitive (against requirement B). After all, products do not really 'import human hands', and it is also unnecessary to find solutions for such functions (against requirement C). Moreover, the number of functions increases: many imported items must also be exported, which makes the approach less straightforward to use (against requirement D).
3. Adopt the concept of *affordances* from ecological psychology [27,28]. Affordance-based approaches afford the designer to define a transformation performed by the user as something the

product should afford [29]. In our example, the barbecue would 'afford the user to place food'. Affordances are typically considered a supplement to functions: they cannot replace them. Affordance-based design approaches offer little guidance to the designer in how affordances should be formulated (against requirement D). For example, as positive affordances of a self-cleaning floor, Gaffney et al. [30] mention 'allow use of carpet', 'dirt removal', 'quiet', and 'ergonomic'. The freedom to use a mix of verb-noun combinations, nouns, and adjectives also complicates abstract thinking (against requirement A). Another issue is that 'affordance', while not counterintuitive, is not such a widely accepted (and as intuitive) concept as 'function' (somewhat against requirement B). Moreover, our course is currently offered in Dutch, and a straightforward translation of 'affordance' is not available in our language, especially because the English verb *to afford* unites several meanings – in particular *to offer*, *to enable*, and *to allow* – which are all essential but which cannot be captured in one word in Dutch. The same problem has been recognized in German [31].
An interesting point is that so-called artefact-user affordances, such as 'to afford placement of food' – and, in general, 'to allow/offer/enable [user task / user opportunity]' – can also be considered verb-noun combinations describing a function according to VE conventions. This means that for our problem area, i.e., transformations performed by the user, the 'affordance' viewpoint appears to be interchangeable with a particular 'function' viewpoint.

We had to conclude that none of the existing approaches with known workarounds offered a ready-to-use solution that would enable us to reintroduce function analysis into our curriculum. Therefore, we decided to develop our own approach, but we took those elements from the existing approaches that we could use and we took advantage from the observation that many of the existing methods share fundamental concepts and notions. This means that we did not have to develop something completely new and completely incompatible with the multitude of existing methods.

5 ELABORATION OF THE NEW APPROACH

We developed our approach as a procedure that supports students/designers in the following ways:

- to offer guidance in identifying functions: if a description is not a proper function description, how can it be reformulated?
- to offer guidance in assessment whether a function is really needed - if it is not needed, to offer guidance in finding ways to eliminate it.
- to be open towards existing function-related approaches: especially, block diagrams of transformations are still supported. Additionally, it seems also possible to support formulation of affordances, but this has not been considered explicitly.
- to be open towards other tools and instruments commonly used by our students and by professionals, such as the process tree, the morphological chart, block diagrams, value engineering, and failure modes and effects analysis (FMEA).

To achieve this, we took elements from existing approaches, and combined them to a pragmatic recipe, together with elements we found currently unsupported. For instance, we borrowed other-than-transforming functions and the notion of 'necessary function' from VE. One of the most important new elements we added was a straightforward distinction between 'good', 'bad', and 'ugly' functions. A good function is directly needed by the end user and therefore it can be kept; bad functions need reconsideration because they only serve as a fix for undesired effects that can be attributed to design decisions and that can possibly be prevented or eliminated. 'Ugly' functions are identified because they, though perhaps indispensable for the product concept in its current form, do not serve the needs of the end user, and might therefore need reconsideration as well.

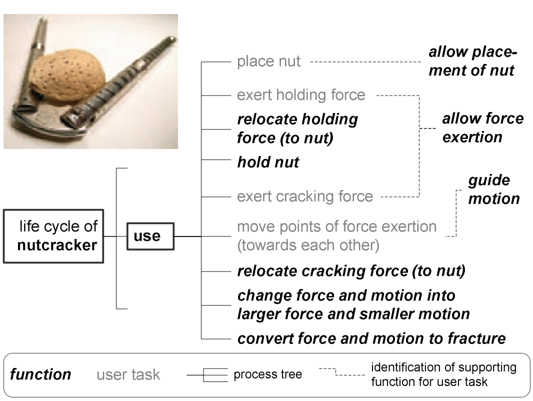

Figure 2. Process tree and elaboration of functions of a nutcracker.

To perform function analysis, the student/designer is supposed to go through the following steps:

1. Create a *process tree*. A process tree is a chronological and hierarchical account of the lifecycle of a product (Figure 2). In the design projects at IDE, making a process tree is a common step in the problem definition phase. It is used as a checklist for requirements and wishes. In our case, only the *use* stage of the life cycle needs consideration. An additional demand in the case of our approach is to use verb-noun combinations to define the items in the tree (this was not done in Figure 2). At this stage, it is not needed to distinguish activities performed by the product and activi-

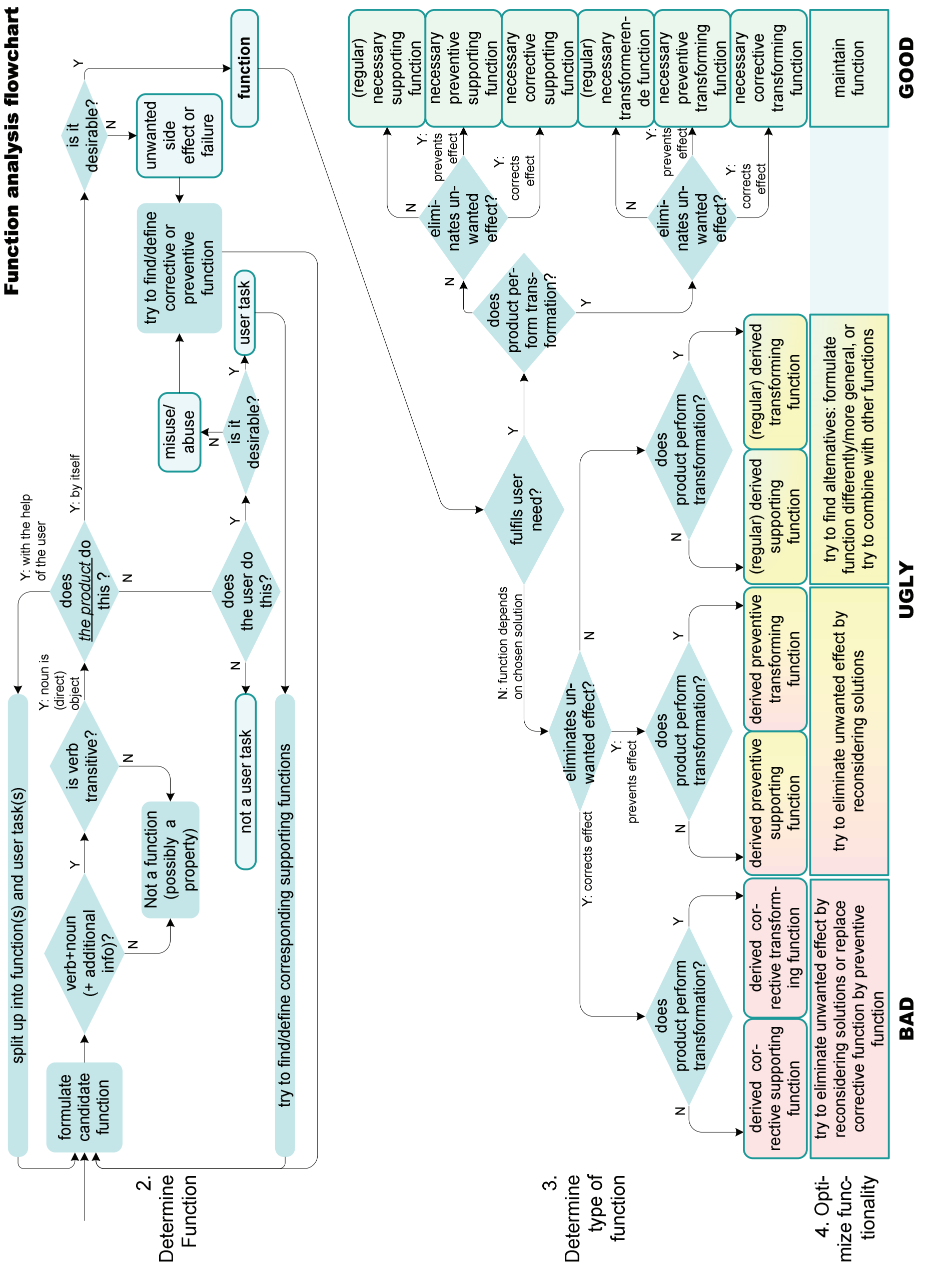

Figure 3: Flowchart for function analysis

ties performed by the user or by others.

2. Determine functions of the product. This is done by taking each item in the process tree and going through the first group of questions in the flowchart in Figure 3 (see page 6). The objective of this step is to filter out user tasks (transformations performed by the user), unwanted side effects, forms of failure, and forms of misuse. Confusingly, the latter three are sometimes also called 'negative functions' [12,32]. For non-functions it is typically possible to identify associated functions, i.e., functions that support the user in performing a task, and functions to eliminate possible unwanted effects. The flowchart guides the designer in finding these functions. Additionally, the flowchart helps to check for proper grammar use in function definitions. Although our functions do not need to express transformations on flows, it is still required that the verb in the verb-noun combination is *transitive*, i.e., it accepts objects. Intransitive verbs as well as transitive verbs expressing possession ('to have') are rejected. Inclusion of meaningful additional information to the verb-noun combination is allowed. This step requires some knowledge of grammar/linguistics, which is a possible bottle-neck. After all, for designers and engineers this is not likely to have been their favourite subject in secondary school.
3. Determine the type of each function. This is done by taking each function from the previous step and going through the second group of questions in the flowchart. We distinguish *necessary functions* vs. *derived functions* and *transforming functions* vs. *supporting functions*. Additionally, if a function serves to eliminate an unwanted effect, it can be *preventive* or *corrective*.
   In accordance with the definition in VE [11], *necessary* functions fulfil a need of the end user. If a function is not necessary, it is *derived*, because it depends on choices that have been made in the product concept. For instance, 'hold nut' is a derived function of the nut cracker in Figure 2. It is needed because the current design allows cracking only if the nut is positioned in a specific way. *Transforming* (or *transformation*) functions perform operations on flows, just like in many other approaches. Other functions are called *supporting* functions, because they support or enable transformations not performed by the product. For instance, a user can adjust a desk lamp to aim its light beam at his workspace. The lamp enables (supports) this user task by offering grip, and by offering flexibility in positioning. Table 1 shows the possible combinations of function types, with an example of each combination in a product. (Note that preventive and corrective functions are not always derived functions: if the undesired effect originates from outside the product's system boundary, these functions are considered necessary.)
   We applied a scale to the function subtypes ranging from *good* (green) via *ugly* (yellow) to *bad* (red). In principle, all *derived* functions are candidates for reconsideration, since the underlying choices in the product concept can be reconsidered. Corrective derived functions are the best candidates for reconsideration, because of the undesired effects involved *and* the potentially available options ('bad'). The designer can consider eliminating the function completely by replacing the design decision that lead to the undesired effect it corrects. If that is not possible, the second best

Table 1. Classification of types of functions and their combinations, with examples

functions	transforming			supporting		
	regular	preventive	corrective	regular	preventive	corrective
necessary	*Electric kettle:* heat water	*Hot plate:* supply heat	*Sprinkler system:* extinguish fire	*Desk lamp:* enable aiming of beam	*Fire door:* prevent spreading of fire	*Crash-barrier:* guide uncontrolled car
derived	*Refrigerator:* compress coolant	*Cooling ribs (on CPU):* carry off heat	*Espresso machine:* collect drip water	*Computer mouse:* enable rotation of ball	*Heat fan:* prevent injury	*Slicing machine:* enable blade exchange

option is to find a *preventive* function instead. After all, preventing something before it happens is better than correcting it when it has already happened. For the ‘ugly’ functions, reconsideration of the underlying design decisions is the only option. For instance, *hold nut* is a regular derived supporting function of the nut cracker in Figure 2, and can therefore be considered ‘ugly’. Note that the distinction between ‘bad’ and ‘ugly’ does not consider the severity of unwanted effects. If an unwanted effect in product is corrected, this must mean that it is reasonably harmless (as the dripping water mentioned in Table 1), and if it is successfully prevented, then it does not happen and severity is not an issue. FMEA can be applied additionally to assess the risk and severity and check whether the effects must be eliminated.

4. Take action according to the type of function (i.e., reconsider as needed, following the basic suggestions in the bottom row of Figure 3), and iterate 1-3 if necessary. For instance, the ugly function *hold nut* in Figure 2 can be avoided if the nut cracker allows placement on a horizontal surface with above it a large crushing surface that will strike the nut regardless of its exact location. This would also eliminate the user task to exert a holding force, and the additional ‘ugly’ function *relocate holding force to nut*. However, the latter function elimination does not bring any advantage, because it uses solution elements that are also needed for the ‘good’ function *change force and motion into larger force and smaller motion* (at cracking).
   Note that it is not always possible to eliminate bad and ugly functions successfully, and that some of them might survive. The green/yellow/red scale is gradual; it gives indications *why* and *how* functions *can* be eliminated; it does not provide absolute judgement on which functions *should* be eliminated.

Completing these steps should result in a reasonably complete list of functions that the student/designer can use as a starting point to identify function fulfillers. In the PIA course, the focus is on identification of function fulfillers in existing products. In future application to design projects, ‘identification’ stands for finding new function fulfillers based on the existing methods that have been extensively documented in textbooks (e.g., [9,14]). Typical tasks here are to generate possible arrangements of block diagrams for the transforming functions and to find function fulfillers by using, for instance, a morphological chart or matrix.

For analysis of existing products, and from the first steps of embodiment onwards, the transforming functions can also be used as a starting point to create block diagrams with mathematical rather than linguistic function descriptions. These can be used for quantitative evaluation and simulation.

6 IMPLEMENTATION IN THE COURSE

In the PIA course, we introduced the function analysis approach in a series of lectures. In the first of these lectures we also interactively tested the students’ understanding of the course matter by using a wireless classroom response system. To start with, we have assessed the students’ understanding of the common grammatical concepts behind function definition: *verb, noun, subject, object* and of their initial, intuitive understanding of ‘function’ before explaining any theory. As the results in Table 2 show, the majority of the students understood the grammatical terminology involved, although identifying grammatical objects appeared to be somewhat difficult. Surprisingly, the students’ initial understanding of what a function is and what is not, was even better, although a considerable fraction of the

Table 2. Grammatical concepts and functions. Left: initial understanding of first-year students. Right: Understanding of ‘functions’ after explanation (translated from Dutch).

*Question/requested item (**correct in bold**)*	*% correct*	*respondents*
Nouns in "the **baker** bakes **bread**"	**79**	126
Object of "the baker bakes **bread**"	**89**	128
Verb(s) in "the baker **bakes** bread"	**87**	128
Predicate of "the baker **bakes** bread"	**63**	125
Object of "the chair is green" (**none**)	**74**	125
Object of "the chair is used" (**none**)	**59**	121
Object of "the chair stands in the room" (**none**)	**63**	126
Object of "the chair supports **the user's bottom**"	**65**	119
Is "to be a chair" a function of the chair? (**No**)	**86**	118
Is "to be green" a function of the chair? (**No**)	**85**	117
Is "to be used" a function of the chair? (**No**)	**69**	112
Is "to stand in the room" a function of the chair? (**No**)	**92**	107
Is "to support the user's bottom" a function of the chair? (**Yes**)	**93**	113
Is "to support the user" a function of the chair? (**Yes**)	**90**	109
Is "to have an armrest" a function of the chair? (**No**)	**87**	110
Is "to scratch the floor" a function of the chair? (**No**)	**55**	106
Is "to move chair" a function of the chair? (**No**)	**79**	109

*Question/requested item (**correct in bold**)*	*% correct*	*respondents*
Is "to vibrate" a function of a cell phone? **No**: verb is intransitive; no object	**31**	108
Is "to select number" a function of a cell phone? **No**: it is a user task	**73**	86
Is "to convert radio waves to sound" a function of a cell phone? **Yes.**	**77**	92
Is "to store entered number" a function of a cell phone? **Yes.**	**73**	99
Is "to go fast" a function of a car? **No**: verb is intransitive; no object	**75**	101
Is "to keep people dry during rain" a function of a car? **Yes**	**80**	99
Is "to keep people dry during rain" a function of a bicycle? **No**: a bicycle does not do this	**67**	95

Table 3. Mechanical transformation functions that can be considered quasi-statically

verb	noun	additional information
change	force torque	into (larger/smaller) force into (larger/smaller) torque
change	displacement rotation	into (larger/smaller) displacement into (larger/smaller) rotation
redirect	force / torque / displacement / rotation	
relocate	force / torque / displacement / rotation	

students mistook the unwanted side effect ‘scratching the floor’ as a function of a chair.

After an explanation of the main principles of function analysis, the students’ understanding of ‘function’ was tested again with different questions. As can be seen in Table 2, we found no significant progress, but this might be attributable to the fact that this time the questions were more difficult, and perhaps, to be fully understood the theory needs a longer ‘incubation time’ than is available in a lecture. A remarkable observation was that most students wrongly considered ‘to vibrate’ a function of a cell phone. A possible explanation is that the actual function ‘to notify user through vibration’ is often marketed as ‘vibration function’. Apparently, the (mis)use of the word ‘function’ by advertisers and marketers had sidetracked our students. Anyway, we have to stress that the presented numbers are purely included here as an indication of the students’ understanding, and that it was not our intention to conduct (and report on) empirical research.

We did not test the students’ understanding of types of functions in a classroom setting. We expect the students to use the flowchart in Figure 3, which means that identifying types of functions is a too complex task for interactive response during a lecture.

After the first lecture on function analysis in the third week of the quarter, we started to include func-

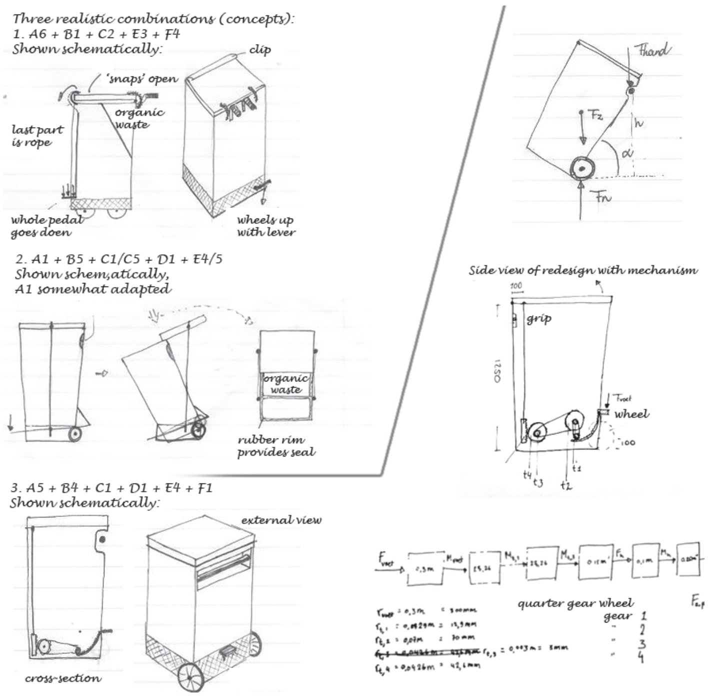

Figure 5. Pedal bin

Figure 4. Student’s conceptual redesign of a garbage container: three concepts derived from a morphological chart, with provisional engineering studies of the selected concept, No. 3. Top right: a free-body diagram to investigate user loads when moving the container. Bottom right: investigation of transmission ratios needed to lift the lid with a foot pedal, based on an introduction to block diagrams. English translations by the authors; adapted from [1]

Figure 6.
Cake decorator

tion analysis questions about the featured products in our weekly assignments. In the third assignment, which was about a handtruck, the students had to draft up a process tree to derive the functions and to determine types of functions. The fourth assignment was about a pedal bin (Figure 5) with a serial transmission from pedal to lid involving three consecutive levers. In this assignment we focused on transformation functions. Since the physics in PIA only covers statics (as an introduction to mechanics), the only transformation functions that we could fully address were mechanical transmissions, in which the effects of motions are considered quasi-statically. Yet, as Table 3 shows, this still leaves plenty of transformations in products that could be considered within the scope of our course, involving a large variety of potential solution principles (lever, wedge, pulley, etc.). In the pedal bin, a small displacement of the foot is eventually transformed into a large rotation of the lid, through two displacement redirections, three displacement magnifications, three displacement relocations, and one change of displacement to rotation. One of the students' tasks was to make a block diagram that could be used for fast assessment of input-output relations without having to evaluate all the equilibrium equations.

The next assignments involved combinations of transforming and supporting functions. In the fifth assignment, the students were asked to make a concept design of a large size pedal-operated waste container, starting with a process tree, deriving functions from it, and selecting combinations of solution principles from a morphological chart (Figure 4). The final assignment was about the cake decorator shown in Figure 6. The functions to be identified by the students had to express that the product selectively transforms forward motion (but *not* backward motion) of the thumb into a flow of icing, that it facilitates dispensing of equal dosages of icing, that it offers the possibility to change the icing profile, etc. A jamming mechanism, which selectively invokes friction, plays an important role, and the students had to calculate for which values of the friction coefficient this would work. As a minor redesign assignment, the students were asked for solutions to allow an adjustable (but still equal) dosage instead of the fixed dosage that the product offers. After the weekly assignments the students took the exam, in which function analysis issues were assessed in multiple-choice questions.

7 EVALUATION RESULTS

The main objective of implementing the approach in its current form of development was to foster awareness of the relevance of the exact sciences taught to product design. We were able to verify this through student evaluations which the courses at Industrial Design Engineering are subject to once every two years. These evaluations are based on electronically processed questionnaires. One of the standard items on the list is *'The relevance of this course to the curriculum is clear to me'*, which has to be ranked on a five-point scale ranging from – – (totally disagree) to + + (totally agree). The results shown in Figure 7 clearly indicate that our primary aim, i.e., raising the awareness that the exact sciences are relevant to the curriculum, has been achieved. It has to be noted that this should be attributed all the integration efforts in the new course, of which the introduction of function analysis was only one aspect.

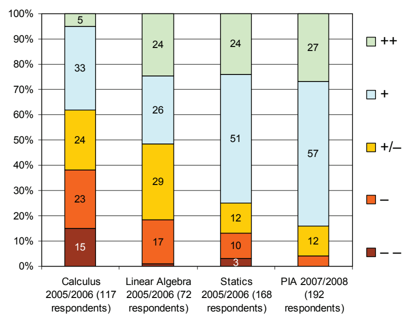

Figure 7. Evaluation of the relevance of old monodisciplinary courses and PIA, as perceived by students

8 CONCLUDING REMARKS

Functions provide a subjective view of what a product should do. After all, even for a given existing product there is no unambiguous way of defining its functionality. Yet, consideration of functions forces students to look at products design problems in a more abstract way, and to consider the needs of end users and avoiding the unquestioning acceptation of given physical-artifactual manifestations. Other approaches, such as scenario building, focus on end users in the first place, but function analysis provides a more straightforward link to the engineering aspects of design, which makes it meaningful in the context of our first-year PIA course.

In this paper we presented an approach to function analysis, combining and extending existing approaches to support application to interactive products, i.e., products of which the use process involves transformations performed by the user. Specifically, our approach offers a straightforward recipe to extract functions from the process tree, which is already routinely used by our students. It is supported by a flowcharted procedure, which also helps to find functions associated with (i) transformations performed by the user and (ii) unintended behaviours. The flowchart leads to identification of functions on a scale from 'good' to 'bad' and points to options for reconsideration of (past) design decisions and their unwanted effects in functions that are not 'good'. After consolidation of the functionality, the student can use other methods for idea finding and/or for configuration and analysis of transformations, which are well-documented in textbooks. This is possible because we allowed our approach to be 'open' to existing approaches by not introducing incompatible elements.

At its current stage of development our approach could successfully be implemented into assignments and exam questions of the PIA course. Evaluations have confirmed that students who have followed the new course are more aware of the relevance of the theory than students who have followed the old monodisciplinary courses.

This work is an ongoing effort. After two years of deployment we consider both the new course and the function analysis approach to be still in their infancy. Based on feedback from colleagues and students we intend to build further on what we developed so far, and to actually include function analysis in other courses, in particular in major design projects. One of the aspects we may need to consider more in our approach is the organization of functions into hierarchies based on how-why logic, ends-means logic and/or procedural logic, especially when complex products need to be considered. However, for the simple products that we can address in this first-year course, such extensions might just needlessly distract the students. Another modification that we might consider is to introduce a fixed vocabulary for function descriptions as supported by some other approaches [12,15]. This might encourage students to treat similar functions the same way and attain a higher level of abstraction. Another issue is that correctly describing functions supporting user tasks leads to somewhat awkward formulations ('allow user to ...'). Eventually it might be a good idea to accept functions and user tasks together in descriptions of intended use, under the condition that they are explicitly labelled – i.e., not only the grammatical object but also the grammatical subject (product or user) is included in the description.

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