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CREATING EQUATION HANDBOOKS TO MODEL DESIGN PERFORMANCE PARAMETERS

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Abstract

In an attempt to reduce product design time, engineers are currently exploring alternative ways to design and engineer their products. In the next century, tools that are able to capture general knowledge about the design process will replace the CAD tools currently used in engineering design. These new tools will capture not only a geometric representation of a product, but also a product's function, behavior, simulation models, and mathematical simulation models. One challenge in developing these tools is relating specific product function to their design equations. This paper discusses the initial research of extracting performance parameter equations from a product's functional model.

1 Introduction

Constructing models is a fundamental challenge in engineering design. Practical challenges include developing sufficient understanding of physics and nature to enable the construction of design models, determining a relation between the underlying physics and customer relevant performance, and selecting model of the appropriate complexity for the problem at hand. The focus of this paper is on the second of these challenges: through product function, the underlying physics, and thus design parameters, are connected to performance, and thus customer needs.

To allow the generation, storage, and eventually computation, of knowledge that connects physics to design function, a common language is needed. Stone and Wood [10] have developed a common language to describe the mechanical design space. Their language, which they refer to as the functional basis, contains a set of definitions for functions and flows to describe a product function in a verb-object format. Their language will allow for the storage and retrieval of design information. Using the functional basis language to describe the product's function, a method is developed to generate descriptive equations for performance parameters during the conceptual design of a product.

In this paper, five different products were reversed engineered to provide function and equation data for a preliminary handbook for extracting performance parameters. One product, a water filter, is presented in detail to illustrate the validity of describing a product in terms of performance equations. It clearly illustrates our approach to creating mathematical models from functional models for conceptual design or product redesign. The results show that it is possible and useful to translate functional models into equation chains that relate back to customer performance parameters. Concepts like functional modeling and customer needs evaluation take the idea of design as an art that may or may not be successful and mold it into a science that consistently gives good, repeatable results.

2 Background

The high demand and relatively low supply seller's market of the 1950s and 1960s led to the, at the time, binary decision to produce innovative or mass produced products. Today, the market demands that businesses parlay into both types of production, creating high volume products that are tailored to customers' needs [2]. Thus, what used to be considered abstract, thought-provoking ideas about design are being developed into useful, consistent, repeatable processes for producing robust and successful products.

References on the history of functional design show research as far back as 60 years. Value engineering research performed during the 1940s as well as research into a common vocabulary for helicopter failure information during 1976 led to recent research into creating a functional basis for design [7,1,10,3]. The current form of the functional basis is shown in Tables 1 and 2. Using the basis, a functional description (often called a sub-function) of a product is formed as a verb-object pair where a function word fills the verb spot and a flow fills the object position.

Table 1. Flow classes and their basic categorizations.

Class	Material	Signal	Energy		
Basic	Human	Status	Human	Electrical	Mechanical
	Gas	Signal	Acoustic	Electromagnetic	Pneumatic
	Liquid		Biological	Hydraulic	Radioactive
	Solid		Chemical	Magnetic	Thermal
	Plasma				
	Mixture				

Table 2. Function classes and their basic categorizations.

Class	Basic	Class	Basic	Class	Basic
Branch	Separate	Control Magnitude	Actuate	Signal	Sense
	Distribute		Regulate		Indicate
Channel	Import		Change		Process
	Export		Stop	Support	Stabilize
	Transfer	Convert	Convert		Secure
	Guide	Provision	Store		Position
Connect	Couple		Supply		
	Mix				

Many reasons exist for starting product design with a functional model. Two of the main reasons addressed in this paper are maintaining the focus on the goals set by the customer performance parameters and increasing exposure to the possible incorporation of technology from other *similar* products. Product similarities can be somewhat surprising. For example, a SKIL screwdriver is 0.64 similar to a Krups cheese grater in terms of customer needs and functionality [11]. Another benefit is the ability to break the overall device function into easily solved sub-functions. Historically, smaller problems are easier to solve, and the flow interconnectivity allows these smaller problems to present themselves without losing the overall goal of the device function. Other benefits of functional design include having records of the product design to refer back to in case of similar product design/redesign and benchmarking [6] and increasing communication ease between different designers [4].

Product repositories are currently being developed to help classify products into families that share sub-functions and customer needs. The repository provides a quantitative measurement to determine the similarity of products based on their functionality and customer needs [5, 11]. Similar products are termed *families*. The products within these families can then be compared to each other during redesign to determine possible improvements to solutions for customer need satisfaction.

3 Approach

For this research, five consumer products operating on fluid flows are investigated as a potential product family. These products, which include a water filter, a portable electronic paint roller, a juicer, an air filter, and a pneumatically powered plane with a pump, are anticipated to share similar sub-functions. The functional models for each product are obtained by first finding customer needs and using the needs to create a black box model describing the material, energy, and signal flows that travel through each product [8, 9, 10]. A black box model treats the product as a box that describes the basic overall function of the device. No flows internal to the product are described during this step; rather only input and output flows are specified. The next step is to develop chains of sub-functions that begin as an input flow, end as an output flow, and describe the flow internally through the product. These function chains are easiest to define by "being the flow" as it moves through the product, describing each operation and transformation to the flow as it travels through the product. The active verb-object sub-functional description format and the functional basis are utilized to derive the function models. The final step combines the individual sub-function chains into a comprehensive functional model of the product. The functional model derivation method is shown schematically in Fig. 1.

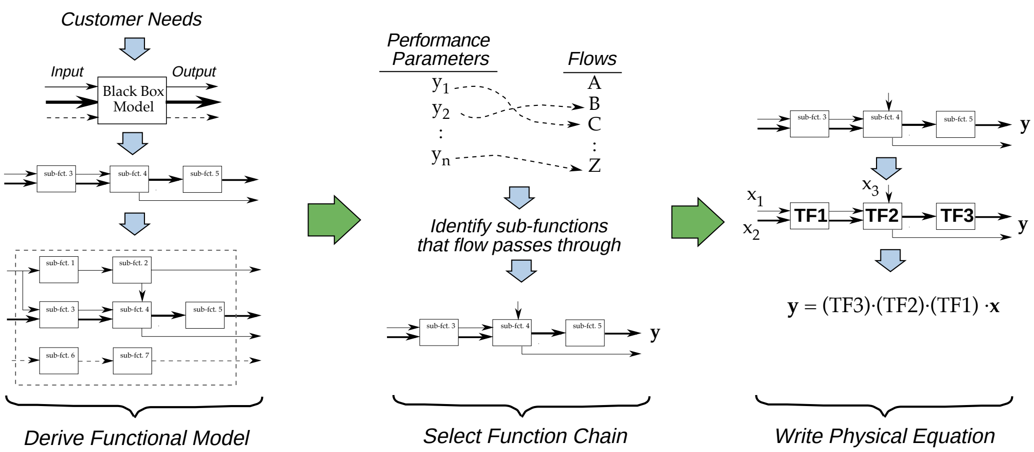


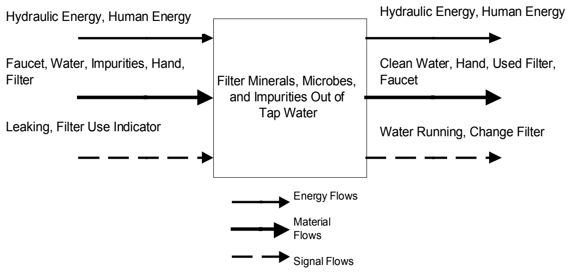
Figure 1. An overview of the approach taken to map customer needs to a physical equation.

Once a functional model exists, the physical equations describing a performance parameter of interest are extracted. Each sub-function of a functional model is in fact a high-level transfer function (TF) of the form $\mathbf{y} = \mathbf{C}\ \mathbf{x}$. The input flows, $\mathbf{x}$, represent the input variables and the output flows, **y**, will contain the performance parameter of interest. The sub-function description, such as *convert hydraulic energy to mechanical energy*, is a high level description of the TF dynamics, **C** (using the function and flow words from Tables 1 & 2). Placing these equations into a functional flow diagram similar to the functional model allows us to the see the mathematical equations behind the flow operations and transformations. From this diagram, chains of sub-functions relating to customer performance parameters can be extracted. The performance parameters given specific numerical requirements can then be used to determine constraints within the product design. These steps are illustrated in Fig. 1 as well.

4 Results

In order to illustrate the methodology followed to derive the functional model and equation model, we focus on the water filter first. The remaining four products will be presented at the end of the results section in order to show the product family relationships between devices.

(a)



(b)

Figure 2. The PUR® water filter (a) and its black box model (b).

The black box model created for the water filter is shown in Figure 2. Based on customer needs, input flows are identified as the impure water with its hydraulic energy, the filter, the water faucet, human energy and hand. Signal inputs include the ability to tell if the device is leaking at the faucet junction and if the filter needs replacing. Outputs to the device include the purified water, any hydraulic energy not lost within the system, human energy, hand, and the full filter. Output signals include the visual cue of running water and filter status.

Next, function chains are created to show operations and transformations that occur with the flows as each one travels through the product. For instance, following the water as it flows through the water filter, first it is regulated by a hand-operated switch that determines whether the water is guided into the filtering system or guided directly through the nozzle and out of the system. If the water does not bypass the filtration system, it is guided down a tube and up into the core of the device where the water is measured by a turbine and gear system. If the water measurement exceeds the design specification for the amount of water that can safely be purified by the filter, then the water flow is stopped by a ball valve. Otherwise the water continues into the filter where it is refined, and the impurities are stored in the filter. Finally, the water is guided through the exit tube and is exported from the system by the nozzle at the end. If this verbal description of the path of the water flow is broken down into the verb-object form, a chronologically ordered chain of sub-functions can be created. The material branch of water shown in Figure 3 (as part of the complete functional model) illustrates the sub-functions associated with this verbal description of the water flow.

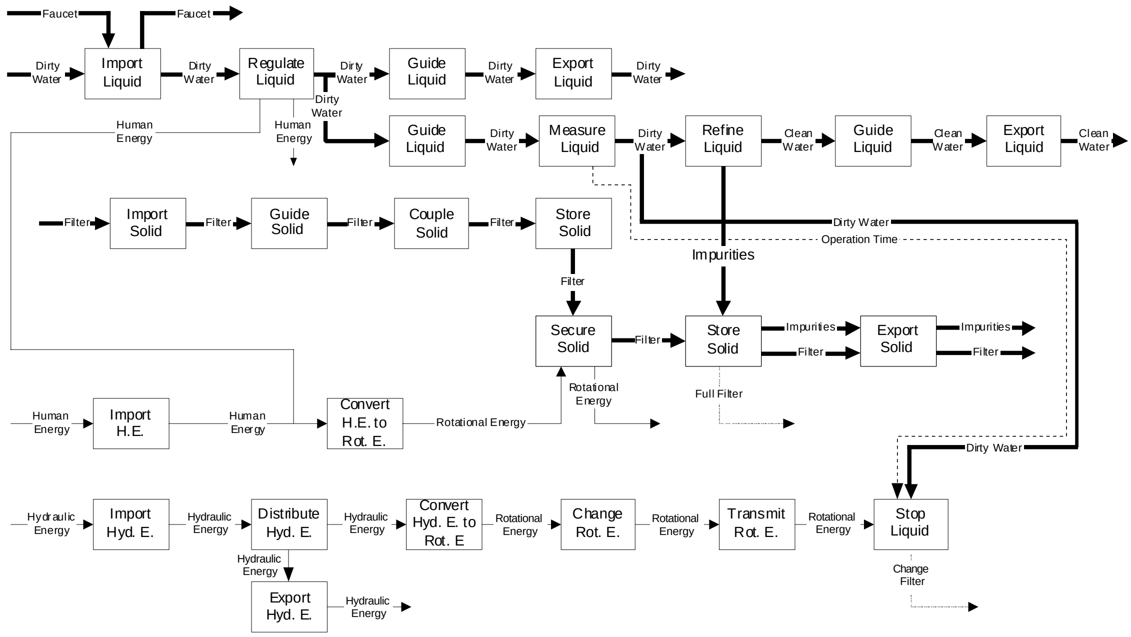


Figure 3. The functional model of the PUR® water filter.

From the functional model presented in Figure 3, the next step is to create a corresponding set of physical equations in place of the verb-object language used in the original sub-functions. The basic operation of the filter is to detour tap water through a filtering device until the filter is full, at which time the flow of water through the device stops. A potential redesign, based on customer need, is to increase the amount of water that the filter can process before reaching the filter's capacity. It is fairly easy to identify important sub-functions related to the redesign need: *refine liquid, store solid, measure liquid* and *stop liquid*. *Refine liquid* and *store solid* address the filter component and generate geometric constraint equations (i.e., volume, mass, filter porosity, etc.). The remaining two sub-functions address the dynamic issues of measuring and eventually stopping the unfiltered water. Converting *measure liquid* and *stop liquid* into physical equations (Fig. 4) identifies that additional information is needed to complete the kinematic expression describing the valve closure specific to the water filter. However, the sub-function *stop liquid* identifies that information as rotational energy – the input flow to the sub-function. The physical equations developed for the sub-function chain feeding into *stop liquid* are also shown in Fig. 4. Combining the equations (in similar manner as block diagram algebra for control systems) creates the overall equation describing the performance parameter of operation time as:

$$\theta_{close} = h \cdot \left[\frac{r_1 r_3 r_5 r_7 r_9}{r_2 r_4 r_6 r_8 r_{10}} \right] \cdot \left[\frac{1}{R_{turbine,eff}} \right] \cdot \left[\frac{Q_{in} - Q_{out}}{A_{turbine}} \right] \qquad (1)$$

This equation parameterizes the design problem. Solving for h, the operation time, identifies design variables related to turbine dimensions ($A_{turbine}$, $R_{turbine,eff}$), the gear train connecting the turbine and valve (gear radii r_i) and the angle required to close the valve (θ_{close}). From this point analysis strategies can be directly applied. The equation model makes it easy to quickly see the interdependency of design parameters and try out various combinations of parameters to determine the best overall design.

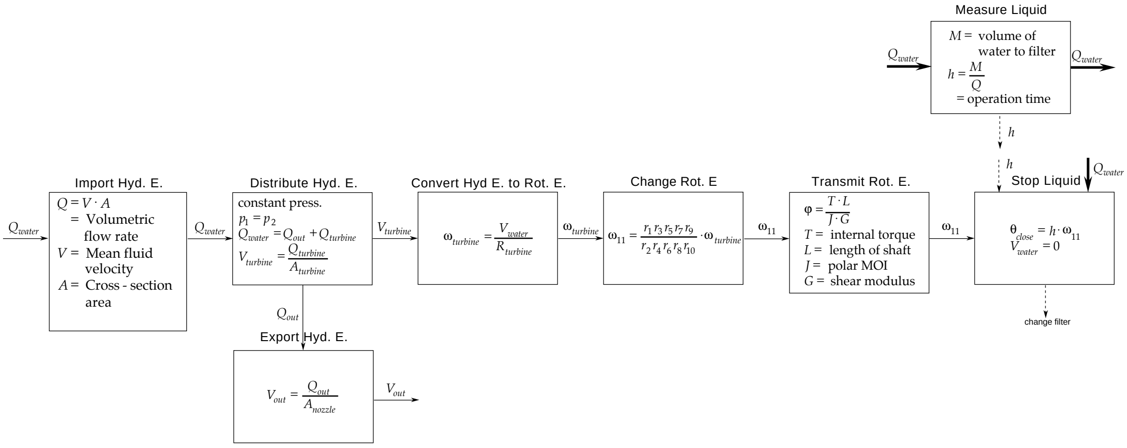


Figure 4. A physical equation model of the PUR water filter, derived from the overall functional model, used to develop the physical equation describing operation time performance.

While the equations in this example are derived from a specific product, *the individual sub-functions can be generalized and applied to any product with that functionality*. A possible implementation of this tool is a searchable matrix of sub-functions and physical equations set. If a sub-function description has a set of possible physical equations, then the designer would choose the best equation based on the form information available (a simple matrix entry is shown in Fig. 5).

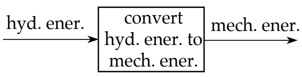
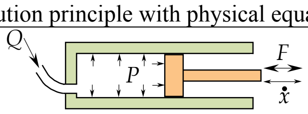
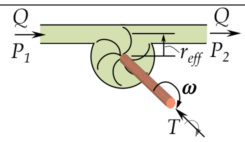
Sub-function description	Solution principle with physical equations	
	 $F = P \cdot A$ $\dot{x} = \frac{Q}{A}$ where F = translational force P = hydraulic pressure A = cross-sectional area of piston Q = volumetric flow rate $\dot{x}$ = translational velocity	 $T = (P_1 - P_2) A \cdot r$ $\omega = \frac{Q}{A} \cdot \frac{1}{r}$ (approximately) where T = torque ω = angular velocity

Figure 5. Two forms and physical equation sets correlated to the sub-function convert hydraulic energy to mechanical energy.

The similarities between the five products examined in this work are summarized in Fig. 6. The products share many functions in common and the common functions lead to similar physical equations describing performance. Similarities such as these are the key to making the concept of a designer's equation handbook feasible.

5 Conclusions

The previous detailed example has illustrated that it is both possible and useful to translate functional models into equations chains that relate back to customer performance parameters. In addition, given the functional likenesses between products, the concept of a handbook of equations catered to the methodology of design remains a feasible and valid goal.

Material Flows	Water filter	Juicer	Power paint roller	Air filter	Airplane	Airplane pump
Channel liquid		1				
Export liquid	1	1	1			
Guide liquid	1		1			
Import liquid	1		1			
Refine liquid	1		1			
Regulate liquid	1					
Store liquid		1	1			
Export gas				1	1	1
Guide gas				1		1
Import gas				1	1	1
Refine gas				1		
Separate gas					1	
Store gas					1	
Channel solid		2				
Connect solid				1		
Couple solid	1					1
Export solid	1	1	1	1		1
Guide solid	1			1		
Import solid	1	1	1	2		1
Secure solid	1					1
Separate solid		1				
Store solid	2	1	1	2		1
Supply solid				1		1
Import human	1	1	1	1	1	2
Export human	1	1	1	1	1	2

Energy Flows	Water filter	Juicer	Power paint roller	Air filter	Airplane	Airplane pump
Actuate e.e.		1	1	1		
Actuate p.e.					1	
Actuate rot. e.					1	
Convert e.e. to rot. e.		1	1	1		
Convert e.e. to static e.				1		
Convert e.e. to acoustic e.		1	1	1		
Convert hum. ener. to trans.e.					1	1
Convert hum. ener. to rot. e.	1					
Convert p.e. to trans. e.					1	
Convert rot. e. to p.e.				1		
Convert rot. e. to trans. e.		1	1		1	
Convert trans. e. to acoustic e.					1	
Convert trans. e. to p.e.			1			1
Convert trans. e. to rot. e.					1	
Export human ener.	1	1	1	1	1	1
Export p.e.			1	1		1
Export static e.				1		
Export trans. e.		1			1	
Import e.e.		1		1		
Import human ener.	1	1	1	1	1	1
Import p.e.					1	
Measure p.e.						1
Regulate trans. e.					1	
Store p.e.					1	
Supply e.e..			1			
Transmit rot. e.		1	1	1	1	
Transmit trans. e.					1	
Transmit weight	1	1	1	1	1	1

Figure 6. Matrix showing coincident sub-functions between products. The number indicates the frequency of occurrence for each sub-function in the product.

This example represented a very simplified case of the types of similarities that could occur among products. The results show that energy and signal flows lead to dynamic equations, and material flows lead to constraint equations that relate specifically to the product being described. In practice, energy flows tend to be the most transferable between products that may not seem similar at all. For instance, few ways exist to convert translational energy into rotational energy besides a cam system, whether for a pneumatically powered toy airplane or a car engine. Therefore, the general equation(s) for both systems will be the same. Where the difference lies will be in the basic assumptions and the scale of the variables used to complete the equations. In an effort to further evolve design methodology, this paper establishes the beginning of a handbook of reference equations that can be developed from a product's functional model.

6 Future work

The products analyzed in this experiment represent a specific subset of products with fluid flow characteristics. Future work in this field will expand and build on this research and include other product sets representing groups in heat transfer, structural engineering, electrical engineering, kinematics, pneumatics, and other classifications. Further research should be assembled into a singular reference to aid in the design and redesign of consumer products of all types.

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