CUSTOMER INTEGRATED SYSTEMATIC DESIGN

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I. INTRODUCTION

Systematic design can improve the product development process. We present an integrated set of structured methods developed in conjunction with industrial partners. In our approach, We interrogate the customer population for a product, and represent the demands of this group. Based on, a functional architecture is established, defining what the new product must do and how it must functionally interconnect. We then explore competitive products in the marketplace, and present methods for tearing down these products with the intent of establishing function -- how these products perform as they do. Competitive benchmarking of this type, in conjunction with customer needs and the functional architecture, is then used to create a customer-driven specification for the product through quality function deployment. From this specification, different technologies and components that meet this specification and functional model can be systematically explored and selected. With a preliminary concept selected, the functional model can be refined into a physically based parametric model that can be optimized to establish geometric and physical targets. This model is then detailed, and instantiated as the first alpha prototype of a new product. This systematic product development process has proven effective in both teaching and practice.

II. Task Clarification

The design of products begins and ends with the customer, emphasizing quality processes and artifacts throughout. Intertwined with a customer and quality focus are a number of technical and business concerns. We thus initiate the conceptual design process with task clarification: understanding the design task and mission, questioning the design efforts and organization, and investigating the business and technological market. Task clarification sets the foundation for solving a design task, where the foundation is continually revisited to find weak points and to seek structural integrity of a design team approach. In this sense, it is a *pervasive* activity that does not occur simply at the beginning of the process, but is employed throughout.

Mission Statement

A mission statement and technical clarification of the task are important first steps in the conceptual design process. They are intended to focus design efforts, define goals, provide a schedule, provide guidelines for the design process and to prevent conflicts within the design team and concurrent engineering organization.

A product's target market can be clarified through the development of a business case analysis. A number of financial assessment techniques exist at varying levels of detail. Two notable and generic techniques are the "Economics of Product Development Projects" in (Ulrich and Eppinger, 1995) and the Harvard business case method (Ronstadt, 1988; McNair, 1954). Application of the Harvard business case method is briefly described below, with context provided by a simple mechanical product: a finger nail clipper.

Finger nail clipper devices are widely used consumer products, with markets of the everyday consumer (primary), professional salons, and domestic pet manicurists. The mission is to design a finger nail clipper for comfortable use by either the left or right hand. A device solution, i.e., a new, generic, and hypothetical clipper design, is the objective, emphasizing the possibilities of reduced cost and higher reliability through compactness and fewer components.

Table 1. Cost scenario — generic, reduced part-count clipper.

Category	Projected Cost ($)	Cost per Product ($/clipper)
Labor Costs		
Small Clipper:		
Assembly	30,000	0.05
Handling	30,000	0.05
Large Clipper		
Assembly	9,000	0.06
Handling	7,500	0.05
Total	76,500	
Fabrication Costs		
Small Clipper:		
Materials	66,000	0.11
Piece-Parts	24,000	0.04
Tooling	24,000	0.04
Large Clipper		
Materials	21,000	0.14
Piece-Parts	9,000	0.06
Tooling	10,500	0.07
Total	154,500	
Engineering Costs:		
Avg. 10 weeks per product	187,000	0.25
Total Cost	418,000	

Issue	Analysis Result
Estimated Payback Period for Development Costs	6 months
Projected Savings for First 100,000 Products	$17,200
Projected Cost Savings for Next 650,000 Products	$111,800
Expected Average Cycle Time Savings for each 100,000 lot	38% of current work days

These possible benefits call for a "break-even" financial analysis for the clipper problem. This analysis answers the question: "is a hypothetical clipper concept with less materials (compactness) and fewer components feasible as a business venture?", and begins with a summary of the current costs for finger nail clipper development (as projected for from the current product). Because these costs continually change with new technology and market forces, actual-absolute cost values are not shown, but have been multiplied by a factor. The important issue is the relative cost of the current clipper operations versus a proposed, hypothesized solution. Table 1 lists the expected costs.

A comparison between the current and proposed generic clipper costs is carried out to determine the payback period and cost savings. Table 1 shows the results of the break-even analysis. The payback period is 6 months, with a potential savings of $129,000 for 750,000 products. Significant cycle time and cost savings may be achieved, the project should be carried to the next stage of conceptual design and prototype build.

III. Understanding and Satisfying the Customer

Now, having clarified what might make a technical and business opportunity, a firm should determine what features are in actual demand, before expending large resources to develop a new or revised product. Many new technology development initiatives are undertaken with no basis for market acceptance, other than management belief. If the developer thinks the technology is amazing and valuable, then everyone else should also. This is the *technologist's problem*, and is unfortunately very common in the engineering community. Akia Morita, founder of Sony Corporation, boasts "Our plan is to lead the public to new products rather than ask them what they want. The public does not know what is possible, we do." (Barabba and Zaltman, 1991). The result is products such as the Betamax. The fallacy inherent to such thinking is a prime market rejection of otherwise innovative products. They fail to satisfy the customer. While the fortunate technology-push approach can and does work, it is also clear that considering the customer's desires will pull product development into better directions and amplify success.

It is important to recognize that "the customer" is a statistical concept, there are numerous potential product buyers. Therefore, there are several tasks that must be completed to develop a statistically valid customer needs list. A short discussion is given below on different methods espoused to do each task, in addition to a detailed discussion of some preferred methods.

Methods to Gather the Voice of the Customer

Different techniques developed and applied to construct a customer needs list include: directly using the product, circulating questionnaires, holding focus group discussions, and conducting interviews. Urban and Hauser (1993) provide an excellent management science reference on customer requirements. Shiba (1995) also provides a TQM perspective.

The first method available to understand the customer is "to be the customer" and to use the product directly. Another customer need identification method is to circulate questionnaires. Another method is to hold discussions with multiple customers as a focus group. A final method often applied is to interview the customers. Both the interview and focus group approach can provide customer need information when the design team has limited intimate product knowledge as a customer. Griffin and Hauser (1993) found that conducting interviews is more effective in uncovering information per amount of effort. They also report that for consumer product sized design projects, properly interviewing 9 customers for one hour each provides over 90% of the customer needs, which experience also bears out. Interviews beyond the tenth subject tend to uncover very few new customer needs.

These propositions, however, assume the design team has placed a proper design scope over the customer interview activities. Typically the interviewer allows the interviewed subjects to begin and end where they feel is important. This scope may not be sufficient for the design teams' informational needs. To address this needs, a method is reviewed below for establishing customer use patterns, beginning with methods for uncovering customer needs.

Conducting Interviews

There are different approaches to interviewing. Using an interview sheet with canned questions does not work well for eliciting customer needs. It is much better to bring nothing other than the following single request:

"Walk me through a typical session using the product."

Then the customer should articulate what they are doing with every action. Typically the interview starts with the customer making their approach to the product in storage, before even using it. Where is it stored? How is it unpacked new from the box and assembled? Ideally, when the customer does any motion or thought processing, they should state what they are doing. This should be continued through the product use, followed by cleanup and re-storage. Some prompts that are useful to periodically pose during silent moments and general hints for customer interaction are given by Ulrich and Eppinger (1995).

A form for collecting customer data, developed both in industrial projects for clients and in academic design project courses, is shown in Fig. 1, completed for the fingernail clipper example. The first two columns are completed during the actual interviews. The first column documents any interviewer's prompts to the customer, what might have been said to get the response, if anything. The second column documents the raw data, what the customer said *in their words*. No interpretation should occur by the interviewer when filling these columns.

The latter columns are completed after the interview. The third and fourth columns are completed as soon as possible after the customer interview. The second column, containing customer statements, are interpreted into third column interpretations, in a structured *noun-verb* format (though not rigidly so). When making these interpretations, it is important to express them in terms of what the product must do, not how the product might do it. Also, positive, rather than negative phrasing should be used. This keeps the interpretations focused on the actual needs, not on how a product may not be satisfying them. Finally, one should not include "must" or "should" in the statement. Rather, these qualifications should be incorporated into subsequent importance ratings, which constitute the fourth column.

Customer Needs List Formation

Having formed multiple interpreted needs lists, the information must be compiled into a single interpreted Customer Needs List and their relative importance, to which the product will be designed. The needs list is the surrogate representation of the entire customer population for the design team.

Clipper Project				
Customer Data				
Customer:		Interviewer:	KNO	
Customer ID:	KNO5	Date:	9/3/95	
Willing to Follow Up?	No	Location:	Cambridge, MA	
Type of User:	Middle class, white, male, traveing			
Question/Prompt	**Customer Statement**	**Interpreted Need**	**Weight**	**Activity**
When usually use?	In the evening in hotel			
	Keep in my shaving bag	Reasonably Compact	Must	Store
How big is that?	About 3" x 2" x 6", and I have alot of			
	things in it, it is always full			
Size of things is important?	Very important. I look for the			
	smallest size of everything.			
	So I dig it out of my bag, and carry	Striking appearance	Nice	Prepare for filing
	it to the bed, where I usually clip	Lightweight	Nice	
	my nails.			
	Spin handle and rotate simultaneously	Easy to open file	Should	
Do you file?	Yes, I file at an angle, with a vertical	File at an angle	Must	Files nails
	and a angular motion			
	With file between thumb and index			
	finger, and clipper body in fist			
		Easy to close file	Should	Unprepare for filing
	Rotate file back in place			
		Easy to open clipper	Should	Prepare for clipping
	Rotate handle into position	Easy to hold clipper	Should	
	Grab in hand using thumb and			
	index finger, with tail up against			
	middle finger edge			
	Position nail to be cut on bottom	Easy to align clipper	Nice	Clipping
	blade	Low clipping squeeze force	Nice	
	Sqeeze finger and thumb to cut	Blade shape curved	Nice	
	Reposition blades and make a 2nd cut	Clips nails	Must	
	Reposition blades for final cut	Nail falls predictably	Nice	
	Catch cut nail			
	Toss in garbage	Dispose of nails		
	Rotate handle back	Easy to close clipper	Should	Return from clipping
	Spin handle to closed position			
	Put back in bag			

Fig. 1: Customer Need Collection Form, completed for the fingernail clipper example.

To carry out this compilation, the design team should copy each interpreted need onto an index card. Then, examining the index cards, the team places the first card on a large white board. Next, the second card is compared with the one on the board, and if it is different, it is put in a new column on the board. If however the second card statement concerns the same need as on the first card, the second card is placed under the first into a column. This process is repeated for all the hundreds of cards. This *affinity diagram* approach results in sorted customer need statements, one customer need per column, as shown in Fig. 2.

Rather than have the design team conduct the sorting, an alternative approach is to have a few customers conduct the sort. This prevents the customer data from being biased by the development team. Urban and Hauser (1993) provide details, but basically one has customers sort and parse the need statements, and this approach is believed a more complete, though more costly.

Customer Need Importance

Having represented the actual customer needs, numerical importance rankings must be established. A good approach to forming an importance ranking for a population is to send a questionnaire to a random customer sample, using the uncovered customer needs list and asking for importance on each need. This approach can provide a sound statistical sample (generally at least 100 randomly sampled customers) for ascertaining importance. Relative importance ratings need to be placed on the needs. Once this is established, the importance assigned to each customer need can be calculated by the average

$$\omega_{CR_i} = \frac{\sum_j \omega_{CR_i,j}}{\#\text{subjects}} \qquad \text{(Eq 1)}$$

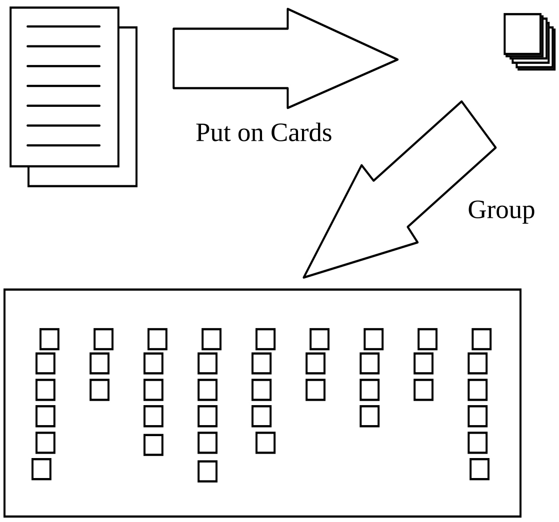

Fig. 2: Converting the set of interpreted needs into a customer needs list.

Clipper Project			
Customer Requirements			
Interviewer(s): KNO			
Date: 9-7-95			
5		Number of Customers	
0	5	Weighting Scale	
75%		Must Confidence	
Average Customer:			
		Male/Females, age 20-60, Middle Class	
		Not in the hair or nail industry	
		Customer Requirement	**WT**
•	Purchase		
	-	Cost	4
•	Transport in package		
•	Unpackage		
•	Chain Keys		
	-	Act as keychain	0
•	Store		
	-	Compact storage	4
	-	Non-snag storage	1
	-	Lightweight	2
	-	Striking appearance	3
•	Prepare to File/Pick		
	-	Easy to open file	2
•	Filing/Picking		
	-	Files nails	2
	-	Picks nails	must
	-	File rough	1
	-	File holds filed dust	0
	-	File has a picking tip	must
•	Return from Filing/Picking		
	-	Easy to close file	2
•	Prepare for clipping		
	-	Easy to open clipper	4
•	Clip nails		
	-	Easy to align clipper	2
	-	Easy to hold clipper	3
	-	Body contoured to hold	3
	-	Curved blade shape	3
	-	Wide handle	2
	-	Low squeeze force	1
	-	Blade can act as pusher	1
	-	Blade can act as a file	1
	-	clips nails	must
	-	clips toe nails	1
	-	clips hang nails	1
	-	sharp blade	1
	-	Nails fall predictably	1
	-	Stores cut nails	1
	-	Easy to clean	0
•	Return from clipping		
	-	Easy to close clipper	4
•	Throw away		

Fig. 3: Partial Customer Needs List.

where $\omega_{CR_i,j}$ is the numerical importance rating for the ith need assigned by the jth customer. The result of (Eq 1) can be linearly scaled to any other numerical range desired and the information contained will remain unchanged. The variance of (Eq 1) across the subject pool can also profitably serve as an uncertainty indicator to establish significant figures. As a working example, consider the redesign of a finger nail clipper. When redesigning this product, customer need importances were gathered as shown in Fig. 3. Other methods for determining importance are detailed by Urban and Hauser (1993).

In addition to customer needs, there are also other requirements that a product must satisfy, typically legislative or manufacturing. These can be represented as additional requirements in the customer needs list. Other non-customer requirements can be incorporated in the customer needs list as deemed appropriate. Alternatively, a specification sheet may be added for non-customer requirements, organizing the requirements according to topic. (Pahl and Beitz, 1991) and (Cross, 1994) provide detailed examples of how to create a specification sheet.

Customer Use Pattern Formation

Any non-trivial product has distinct activities that a user steps through when using the product. A product is purchased, transported, assembled out of packaging, stored away, removed for use, initialized, used in different ways in different environments, perhaps modified by the user, periodically cleaned or maintained, and disposed. For communication to the design team, these different customer use patterns should be captured and represented, as all can give rise to different product forms. Further, capturing the customer use patterns helps to ensure that each different activity has had customer needs gathered.

To form the possible use patterns, it is important to first capture the serial activity sequence for each customer. To do this, the last column of the customer data sheets, Fig. 1, is completed. Typically, a sequence of customer statements will have one associated activity. Activities differs from customer needs in that activities label what the customer is doing (not the product) when a group of needs are expressed about the product. Upon completing column 4 of the customer data sheets, the activity sequences are combined into a network *Activity Diagram*, as shown in Fig. 4. How typical any sequence is can be recorded by line width. The initial and final activity are also highlighted, scoping the customer requirement gathering activity. This can help system-engineer the environment within

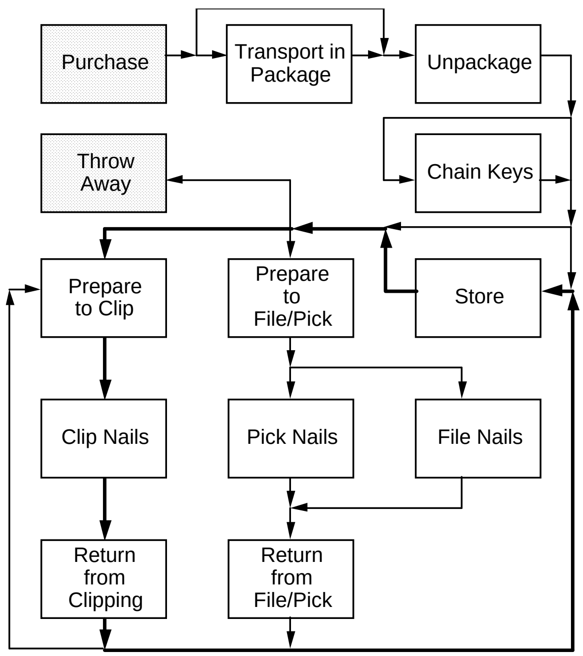

Fig. 4: Completed activity diagram for the finger nail clipper.

which the product is used, if that is a topic for a larger scope team.

The Activity Diagram can communicate to any new and different design team members what the customer does with the product. It helps ensure that a design team is aware of all customer lifecycle product needs. Note that the Activity Diagram can also be expanded upstream to capture sales, distribution and manufacturing activities. Similarly, downstream activities such as disposal can be represented.

IV. Functional Modeling

Having a representation of what the customer wants from the product, a model of how the product functions to satisfy the customer is needed. Functionally, all products *do something*. Products, therefore, accept “inputs” and operate to produce “outputs,” i.e., the desired performance. We can model any product, assembly, subassembly, or component as a *system*, with *inputs* and *outputs* that traverse a system boundary. The essence of such a model is the need-function-form definition of engineering design. In the sections below, we construct the necessary machinery for understanding and representing design function, according to a system perspective. This machinery will aid us in synthesizing form solutions, with greater breadth, less bias, and greater technical understanding than *ad hoc* approaches.

Phase 1 — Develop Process Descriptions as Activity Diagrams

Functional modeling includes developing a process description, here as represented with the Activity Diagram, and eventually forming a *function structure*. To start the function modeling process, an important tool is to specify the *process* by which the product being designed will be functionally implemented.

To see this, consider Fig. 4, which illustrates the Activity Diagram for the finger nail clipper design. To focus on product usage, the system boundary chosen includes all of the customer activities. Fig. 4 does not include manufacturing related activities such as packaging and transport, sales functions such as unpackaging, nor the disposal. Depending on the scope of the design task, it could have. This modeling boundary defines the product system, receiving inputs from and producing outputs to the user and environment.

Phase 2 — Formulate Subfunctions Through Task Listing and Black Box Modeling

Using the customer process description (Activity Diagram) and customer needs, a function structure for the product is next formulated, where a *function structure* is defined as an input-output model that maps energy, material, and signal flows to a transformed and desired state. Function structure modeling (Pahl and Beitz, 1984; Miles, 1972; Ullman, 1992; Shimomura, et al. 1995; Ulrich and Eppinger, 1995; Cross, 1994) has historically been used to create a form-independent product expression. We extend common function structure modeling to include a mapping of customer needs to subfunction sequences (called *task listing*), a method for aggregating subfunctions, and a comparison of a functional decomposition with customer needs.

The first step is to identify primary flows associated with the customer needs of the product activities. A *flow* is a physical phenomenon, i.e., material, energy, or signal (information), intrinsic to a product operation or subfunction. In the context of input-output modeling, a flow enters an operation or subfunction, is manipulated by the subfunction, and exits in a new state. For example, an operation may be to pressurize a fluid. Two critical flows for this operation are an energy to execute pressure change and the fluid material being operated upon.

Considering the finger nail clipper example, a subset of the customer needs are cost, compactness, files well, cuts well, is easy to open/close, easy hold, comfortable, and sharp cutting surface.

We now translate the customer needs to energy, material, or signal flows of the product when effects

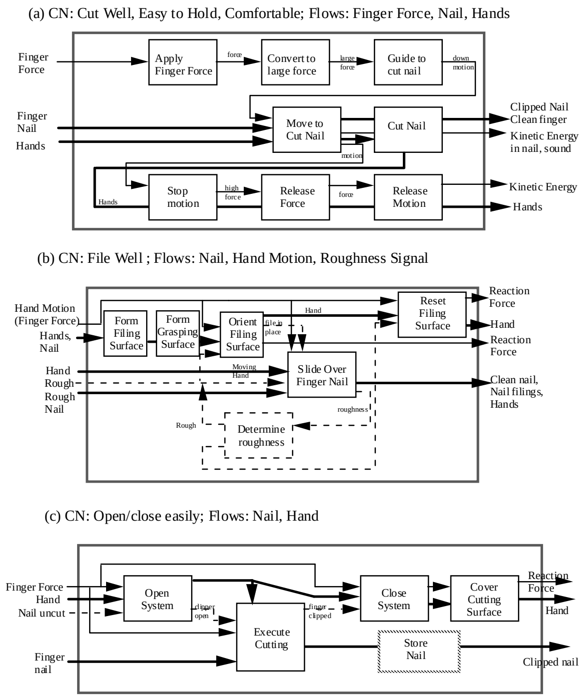

Fig. 5. Finger Nail Clipper Task Listing for Each Customer Need.

are exhibited or are expected to be exhibited during product use. Cost is not something that deals with what the product does. So we do not model "not inexpensive" functionally. Primary flows associated with "not compact" are the user's hands, the finger nail dimensions, and storage compartments, e.g., pants pockets, wallets, or purses. These flows are material in nature and capture capacity in terms of "volume." Primary flows for the remaining customer needs include:

- "Does not file well" — hand motion (energy), finger nail (material), finger nail roughness (signal).
- "Does not cut well" — generated cutting force (energy), finger force (energy), and finger nail (material).
- "Not easy open/close" — hand movements (energy) and hand (material).
- "Not easy to hold" — finger force (energy) and hand (material).
- "Not comfortable" — finger force (energy) and hand (material).
- "Not a sharp cutting surface" — generated cutting force (energy) and finger nail (material).

For each of the flows, the next step is to identify a sequence of subfunctions and specific user operations that when linked represent the product when interfacing with the customer during the customer activities. A subfunction, in this case, is an active verb paired with a noun that represents the causal reason behind a product behavior.

A useful approach for generating subfunctions is to trace the flow as it is transformed from it initial creation state to its final expected state when it leaves the product's system boundary. This approach may be executed by *play acting* the flow (becoming the flow) or brainstorming a hierarchy of functions that must process the flow.

For example, a customer need, expressed in the customers' voice, may exist for "Cuts nail well." A suitable flow for addressing this need is a *force* flow that ultimately acts on the nail material flow. Fig. 5 illustrates the task listing results for a subset of the customer needs and corresponding flows. Each function chain in the figure (a-c) represents a functional decomposition of the functions needed to "cut nail well." Customer needs directly lead to each of these function chains, a tactical advantage of the method.

Phase 3 — Aggregate Subfunctions into a Refined Function Structure

Each sequence of subfunctions for the full set of customer needs are aggregated (combined) to represent the functions of the entire product. This step is accomplished by appropriately connecting flows between each sequence and adding subfunctions that interact or provide control states.

Aggregation and refinement of the function structure ends based on two criteria: (1) are the subfunctions "atomic," i.e., can they be fulfilled by a *single, basic* solution principle that satisfies the function, and (2) is the level of detail sufficient to address the customer needs? The first criterion provides a basis for choosing the depth of functional analysis. For the finger nail clipper design effort, an aggregated function structure is shown in Fig. 6. Notice that subfunctions and flows are combined for overlapping or redundant functionality from Fig. 5. User functions are also listed outside of the system boundary for clarity.

Phase 4 — Validate the Functional Decomposition

Once the design team completes the subfunction aggregation, functional modeling and analysis comes to a closure through two verification steps. First, all major flows between the subfunctions are labeled and checked according to their state of transformation. By labeling the flows, validity and continuity is ensured, perhaps leading to the addition of further functional representations. Second, the customer needs list is reviewed, and the subfunction or sequence of subfunctions are identified that satisfy

Table 2: Validation of Subfunctions

Need	Validation (Applicable Subfunction(s))
Cost	N/A (Product does not do this)
Compact	Apply Finger Force, Form Filing Surface, Form Grasping Surface, Cut Nail
files well	Form Filing Surface, Form Grasping Surface, Orient Surface, Slide Over Nail
cuts well	Convert to Large Force, Cut Nail
easy open/close	Guide to Nail, Move to Cut Nail
easy hold	Apply Finger Force, Release Force, Release Motion
comfortable	Apply Finger Force
sharp cutting surface	Cut Nail

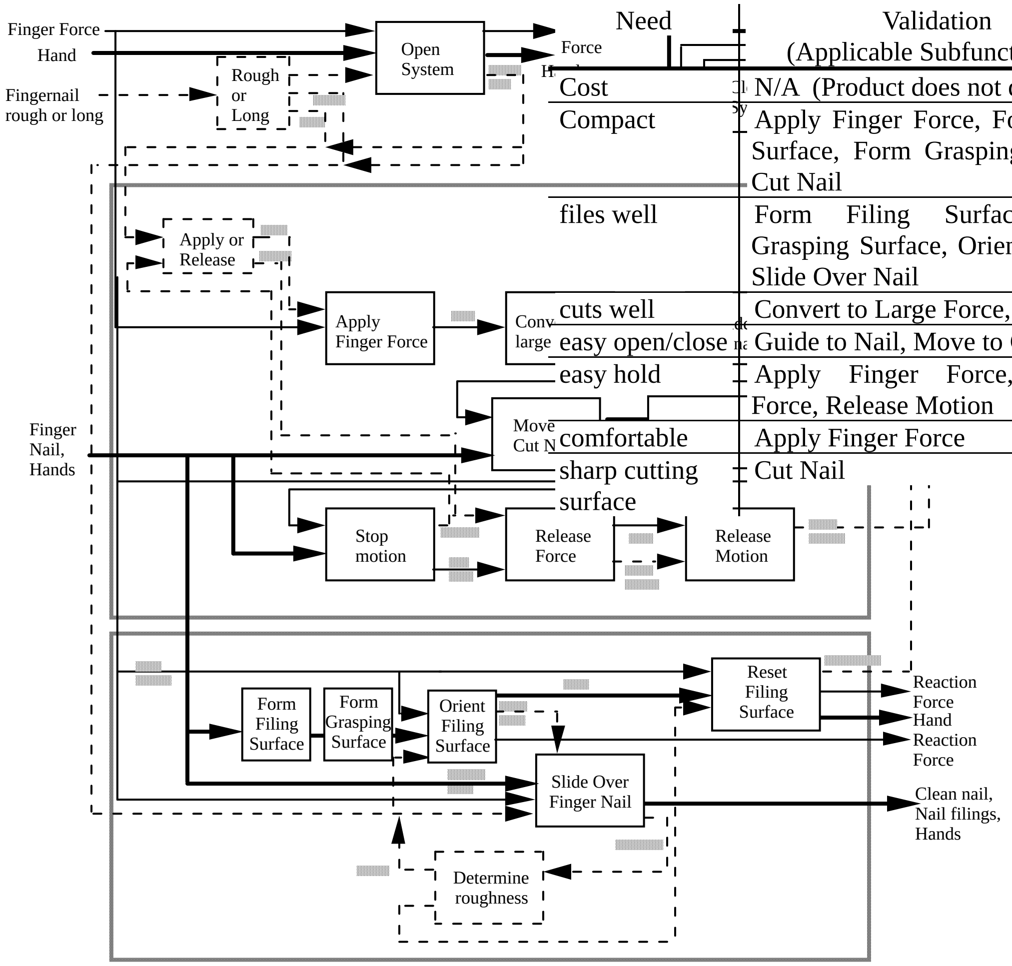

Fig. 6. Refined function structure for the finger nail clipper design task.

each customer need. Needs not covered by the function structure require further analysis, and subfunctions not satisfying a need require confirmation of their incorporation. This verification typically adds more subfunctions to the network, while simplifying or removing others that really do not apply. Consider the validation for the finger nail clipper task, as shown in Table 2.

The subfunctions listed for the validation combine to represent the customer need. For example, “compact” will ultimately be governed by the solution principles chosen for the “apply finger force” subfunction, etc. The size of these solution principles determines the overall compactness of the final finger nail clipper. This customer need will need to be balanced with “cuts well” and the “cut nail” subfunction since a minimum size will be needed to cut a nail.

V. Competitive Benchmarking

To remain competitive, a design team must compare any proposed concept with the competition. Typically a corporate group exists to tear down the competitor’s product, estimate costs, plot trends, make predictions on requirements, and work with the design teams. These efforts uncover the clever things that the competition has spent effort on, uncover the principles behind how they work, and predicts costs.

Ingle (1994) presents methods and an overview of a reverse engineering methodology at a large company. Thornton and Meeker (1995) present an approach and a case study from the computer industry. Camp (1989) presents a ten step approach to benchmarking company operational practices. We present a method here that is focused upon product design, using the customer demands and the product functions.

Form a List of Design Issues

First it must be clear what problems the design team is facing on the current project. If this is a new project, the technical form issues may be unknown, and so information about the customer market, competitors, and competitive products are worth investigating. If this is a redesign project, an investigation can ask of the previous design team:

- What was difficult for them?
- What design problem did they solve which they are proud of?
- What related technologies are they interested in?

The deliverable from this step is a list of keywords with explanations on topics to gather information.

Form a List of Related Products

Knowing the product function, one must examine the sales outlets for products which address these functions. For consumer products, sales outlets are typically retail stores. For the product, one must list all competitors and their different product models, and all related products in their portfolio. If the competitors have a family of products under a common product architecture (they use identical components for some aspects of each product, but different components for niche demands), one should detail this information, as it can indicate the competitor's preferred market segments.

This step should only be an identification of the competitors, as company names and product names. With a complete set of different products, vendors, and suppliers to examine, the list should be screened by highlighting the particular ones that appear most crucial for the design team to fully understand. This approach work feeds the next step, conducting a information search.

Conduct an Information Search

The importance of this step cannot be overstated. The wealth of information available about all business operations across the globe is amazing. Before starting any design activity, a team must understand the market demand for product features, and what the competition is doing to meet it. A design team should gather information on the products and related products, the functions they perform, and the targeted market segments. All keywords associated with these three categories should be used in informational searches.

Prepare for Product Tear Downs

From the previous efforts, a list of products that are worth spending time tearing apart and analyzing should be formed. This list should contain products that can provide technical solutions to design needs. Typically, this list includes the least expensive model on the market, the most expensive model, the most popular model, and models which have particular technical features.

Next, one must clarify the criteria on which data are required. Typically, these criteria include quantity of parts per product unit, dimensional measurement, maximum, minimum, and average material thickness, weight, material, etc.

Examine the Distribution

Important factors in the product development decision making process that must not be overlooked are the means used to acquire parts, contain them, ship, distribute, and market the product. These must also be examined as a part of the benchmarking process. The distribution packaging of the product should be examined and reported to the design team, often it can be quite expensive. Consumer installation instructions and procedures should be examined for costs and effectiveness.

Disassemble and Measure by Assemblies, and Form a Bill of Materials

Disassembly is the obvious step commonly pictured when thinking of reverse engineering. However, to be effective, this must be coordinated with measurements. One should take pictures and measurements on the whole assembly before disassembly, and similarly on each sub-assembly, down to individual components.

Part #		Part Name	Quantity	Finish	Function	Physical Parameters
A1	Arm Assembly					
	001	Actuator arm	1	Chrome	Transmit finger force	2", shaped
					Input from finger	.25" pivot
	002	Pin	1	Chrome	pivot	.13" round
A2	Cutter Assembly					
	003	Blade arms	2	Chrome	Cut nails	2.00 x .44 x .13
					Spring action	.13" blade gap
A3	File Assembly					
	004	File	1	Chrome	File nail	Scored
						1.50 x .25 x .06
	005	Pivot rivet	1	Chrome	Attach file	.19 rivet

Fig. 7. Reverse Engineering Bill-of-Material.

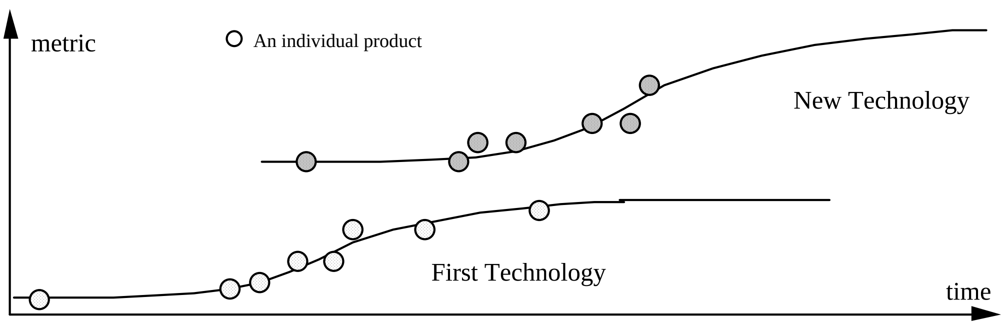

Fig. 8. Technological innovations plot as S-curves.

Complete a written form which details the product. A good format is shown in Fig. 7, where each column consists of the data analysis criteria. Also, the sequence of photos and an exploded view CAD drawing should be completed.

Plot Industry Trends

Having uncovered a wealth of information from such sources, the next problem is to arrange and transform it for clear understanding of implications for the design or redesign task.

The benchmarking of technical solutions is possible with a time history of product measurements. All technological innovations manifest themselves into the market along an "s-curve" timeline behavior, as shown in Fig. 8. For all of the different products in a market, one can plot each product's performance as a function of the time when each product was introduced. The metric values will naturally fall as an "s-curve" in time. First, the values are low and widely spaced: not much innovation is occurring in the market. Next, a rapid profusion of innovation occurs, and many products are launched in time. The lower leg of the "s" is forming. The new technology, however, eventually tops out, physical laws of the process dominate, and engineers cannot extract more performance. The slope of the "s" tops out again, and the curve becomes flatter.

These trends are critical for a competitive company to understand for their industry. If the market is becoming more competitive, the company must understand that to invest in product and process quality, or lose. One can tell this immediately as the point at which the lower leg of the "s" starts to form. If the market technology is topping out (the top of the "s"), the company should again know this to begin to investing in a new technology, to "jump" to the next s-curve, higher on the scale of the metric. Plotting trends provides all of this information. Clearly trending of competitive data is a necessary and culminating business consideration as a part of product benchmarking.

VI. Forming Quantitative Specifications

Having established the function structure and understood competitive product performance, each sub-function must now be associated to at least one line item in a product functional *Specification Sheet.* These are functional specifications of what the product must do, not necessarily form specifications for purchasing components. The specification list should include both the specifications and also an importance rank of each specification.

Approaches taken to forming specifications most often include Quality Function Deployment (Akao, 1990, Clausing, 1994). For the most part, these methods provide a means to verify and agree upon a proposed list of specifications, and a means to set target values on the variables. What these and other

Sub-Function	Specification
Open System	
	Opening force
	Opening gap
	Opening grip area
	Opening surface friction
Rough or Long	
	-
Apply or Release	
	-
Apply Finger Force	
	Fingerpoint surface friction
	Fingerpoint cupness
Convert to Large Force	
	Force gain
	Motion reduction
Guide to Cut Nail	
	Blade visibility
	Blade curvature
Move to Cut Nail	
	Open blade opening width
Cut Nail	
	Sharpness
	Hardness
	Flatness
Store Nail	
	Storage volume
Stop Motion	
	Click sound
	Stop compliance
Release Force	
	Expansion force
Release Motion	
	-
Form Filing Surface	
	Opening friction torque
	Finger opening surface area
	Finger opening friction
	Finger pushing area
	Open alignment force
Form Grasping Surface	
	Grip area
	Grip surface friction
Orient Filing Surface	
	Filed nail visibility
Slide Over Finger Nail	
	Filing surface area
	File roughness, Left to Right
	File roughness, Right to Left
Reset Filing Surface	
	Closed alignment force
Determine Roughness	
	-
Cover Cutting Surface	
	Closed blade opening width
Close System	
	Closed arm force

Fig. 9. Generating metrics for sub-functions, finger nail clipper example.

tools do not provide is a means to identify what variables should be used as specifications. How does one identify the measurable variables that are to be ensured?

Identifying Specification Metrics

To establish an initial set of engineering specifications, a design team should begin by listing each sub-function. Then to each sub-function, a relevant product subsystem is examined. From these sources, a means to "instrument" the product subsystem to measure the functional flows in and out of the sub-function should be considered. Depending on the product, this instrumentation can rely on engineering data acquisition, or can be as simple as touch, feel, or look. This depends on the comprehensive nature of the metric. A partial list for the finger nail clipper is shown in Fig. 9, with the process assumption of a mechanical cutting surface (a blade).

This approach generally produces better results than other approaches, in that the sub-functions are more quantified than customer needs. The approach still clearly relies on the creativity of the design team. On the other hand, the creativity is decomposed into two stages, conceiving of the function structure itself and conceiving of how the flows of each sub-function can be "instrumented" for measurement on the product sub-system. It is less a conceptual leap to generate measurable metrics for an independently generated set of sub-functions, each associated with a subsystem, than to generate measurable metrics for each customer need directly.

Next, the metrics generated must have target values assigned to each. This assignment is completed by examining the relevant customer needs associated to each metric. In general, establishing a target may require some calibration of the metric. For example, once it is understood that handle temperature is a good metric to represent comfort of the customer, it may be required to test different handle temperatures with the customers to determine the highest acceptable temperature value.

After these steps, a relevant hierarchical set of functional specifications is completed. It can be collected into a House of Quality matrix, for example, to verify and communicate how the customer needs are being met. The House of Quality can be used to document the product design targets of the different team members working in concert.

Forming Specification Importance Ranks

Finally, the importance of each specification can be calculated through the House of Quality. This calculation is carried out in the usual manner by inserting relationship values in the House of Quality matrix to relate customer needs with engineering specifications. Then a suitable algebra is used to combine these relationship ratings with the customer

		Open System	- Opening force	- Opening gap	- Opening grip area	- Opening surface friction	Rough or Long	-	Apply or Release	-	Apply Finger Force	- Fingerpoint surface friction	- Fingerpoint cupness	Convert to Large Force	- Force gain	- Motion reduction	Guide to Cut Nail	- Blade visibility	- Blade curvature	Move to Cut Nail	- Open blade opening width	Cut Nail	- Sharpness	- Hardness	- Finger squeeze area	- Flatness	Store Nail	- Storage volume	Stop Motion	- Click sound	- Stop compliance	Release Force	- Expansion force	Release Motion
Purchase																																		
- Cost	4																						2	O		2								
Transport in package																																		
Unpackage																																		
Chain Keys																																		
- Act as keychain	0																																	
Store																																		
- Compact storage	4				2											2												§						
- Non-snag storage	1																																	
- Lightweight	2														2									2							2			
- Striking appearance	3												2						2															
Prepare to File/Pick																																		
- Easy to open file	2																																	
Filing																																		
- Files nails	2																																	
- File rough	1																																	
Return from Filing/Picking																																		
- Easy to close file	2																																	
Prepare for clipping																																		
- Easy to open clipper	4		§	O	O	O																												
Clip nails																																		
- Easy to align clipper	2																	O	O		O													
- Easy to hold clipper	3											O																						
- Body contoured to hold	3												§																					
- Curved blade shape	3																																	
- Wide handle	2																								§									
- Low squeeze force	1														§																			
- Blade can act as pushe	1																	§																
- Blade can act as a file	1																																	
- clips nails	must														O								§	O										
- clips toe nails	1														O								§	O										
- clips hang nails	1																																	
- sharp blade	1																						§											
- Nails fall predictably	1																	§																
- Stores cut nails	1																										§							
- Easy to clean	0																		O		§													
Return from clipping																																		
- Easy to close clipper	4		§	O	O	O																												
Throw away																																		

		-	Form Filing Surface	- Opening friction torque	- Finger opening surface area	- Finger opening friction	- Finger pushing area	- Open alignment force	Form Grasping Surface	- Grip area	- Grip surface friction	Orient Filing Surface	- Filed nail visibility	Slide Over Finger Nail	- Filing surface area	- File roughness, Left to Right	- File roughness, Right to Left	Reset Filing Surface	- Closed alignment force	Determine Roughness	-	Cover Cutting Surface	- Closed blade opening width	Close System	- Closed arm force	Material FInish	Keychain	Weight	Material Cost
Purchase																													
- Cost	4																												⊙
Transport in package																													
Unpackage																													
Chain Keys																													
- Act as keychain	0																										§		
Store																													
- Compact storage	4				2		2			2					2								2						
- Non-snag storage	1																		O				§		§				
- Lightweight	2																											§	
- Striking appearance	3																									§			
Prepare to File/Pick																													
- Easy to open file	2			§	O	O	O	O											O										
Filing																													
- Files nails	2														O	§	O												
- File rough	1															§	O												
Return from Filing/Picking																													
- Easy to close file	2			§	O	O	O	O											O										
Prepare for clipping																													
- Easy to open clipper	4																												
Clip nails																													
- Easy to align clipper	2																												
- Easy to hold clipper	3																												
- Body contoured to hold	3																												
- Curved blade shape	3																												
- Wide handle	2																												
- Low squeeze force	1																												
- Blade can act as pushe	1																												
- Blade can act as a file	1											O		O	§	O													
- clips nails	must																												
- clips toe nails	1																												
- clips hang nails	1																												
- sharp blade	1																												
- Nails fall predictably	1																												
- Stores cut nails	1																												
- Easy to clean	0																												
Return from clipping																													
- Easy to close clipper	4																							2					
Throw away																													

Fig. 10. House of Quality for the finger nail clipper.

need importance ratings to establish importance ratings on the individual specifications.

The results for the finger nail clipper are shown and summarized in Fig. 10, the House of Quality matrix for the clipper. The numerically rated specifications become objectives that can be traded off in design decision making, with importance as indicated.

VII. Generating Design Configurations

Fig. 10 illustrates a crisp, quantitative specification for product design. Its roots are grounded in customer needs, and its structure is interwoven by the established product functionality. This specification, however, does not complete the conceptual design process. Form solutions must be generated for the decomposed subfunctions, combined into a finite set of concept variants, and then selected using the quantified specifications exemplified by Fig. 10.

Various methods for concept generation are documented in the literature (Pahl and Beitz, 1991; Ulrich and Eppinger, 1995; Ullman, 1992; Cross, 1992; Greenwood, 1982; French, 1985; Hubka, 1984; Pugh, 1991; Dixon and Poli, 1995; Altshuller, 1984). For the purpose of the finger nail clipper design, we seek to develop concepts according to a four step process: (1) generate as many solution principles to each of the subfunctions (Fig. 6) as possible, (2) qualitatively prune the number of solution principles using the criteria of Fig. 10, (3) combine the remaining solution principles into a number of feasible concept variants that satisfy the entire set of product functions, and (4) identify avenues for function sharing in each concept variant to reduce part count and complexity.

Figs. 11 and 12 illustrate a subset of the results from this three-step process. The morphological matrix contained in Fig. 11 shows a breadth of form solutions to the decomposed functions. In turn, Fig. 12 shows some possible combinations into concept variants. Because the concepts are generated directly from the functional specification, the likelihood of satisfying the customer needs is high, something that is not afforded by *ad hoc* approaches. Fig. 13 confirms this statement. A number of current finger nail clippers are shown in the figure. The concept generation, summarized in part by Figs. 11 and 12, covers these product ideas at a fundamental functional level. In fact, the “molded scissor” concept does not currently exist on the market, a potential product evolution.

VIII. Conclusions

Product concepts begin and end with the customer. A concise and quantified specification is an essential

Subfunction	Current	Solution Principles		
Opening				
Open clipper	Spin and flip			
Determine rough or Long				
Clip nail				
Determine apply or release				
Apply finger force	shaped top, bent bottom	shaped top and bottom	hand grip	finger holes
Convert to large force	pivot	linkage	concentrate it	pliers
Stop motion	teeth hit	peg		
Release force	spring of bent body	linear spring	coil spring	leaf spring
File nail				
Move file into place	pivot out file	file on arm	slide arm out	flip out file
Slide over nail				
Determine roughness				
Return file in place	pivot back file	(file on top arm)		
Closing				
Close clipper	Flip and spin			
Hold shut	spring of bent body			

Fig. 11. Partial morphological matrix (subset) for the finger nail clipper.

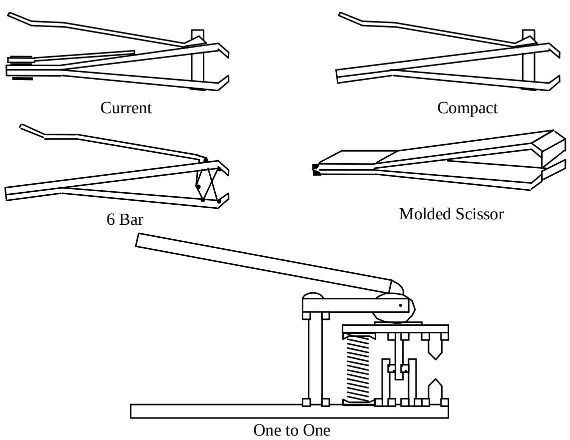

Fig. 12. Example concept variants (subset) for the finger nail clipper design.

element for developing suitable concepts. This chapter presents a systematic method for creating such a specification. We begin with the technical and business market, probing the design task for legitimacy. Customer needs analysis, functional decomposition, and competitive benchmarking are then presented as methods for directly mapping customer statements to functional requirements, in the context of competitors' products. Results of these methods lead to a House-of-Quality, forming the product specification and setting the playing field for concept generation.

A common design methodology criticism is that it is explanatory and thought provoking, but not relevant to actual practice. This criticism is becoming an antiquated view. We find leading industrial companies to be constantly seeking more structured approaches to their product development processes, especially in the era of concurrent development, intensive computing, and downsizing of workforces. An effective structured method allows not just one expert to understand and complete a task, but many others as well. In our opinion, concept design skills can be learned and fostered with structured methods.

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Fig. 19. Current finger nail clipper products on the market.

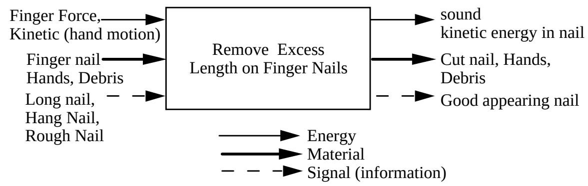

Fig. 9. Black box model of the finger nail clipper design task.