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Product Evolution: A Reverse Engineering and Redesign Methodology

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Abstract. *New products drive business. To remain competitive, industry is continually searching for new methods to evolve their products. To address this need, we introduce a new reverse engineering and redesign methodology. We start by formulating the customer needs, followed by reverse engineering, creating a functional model through teardowns. The functional model leads to specifications that match the customer needs. Depending upon required redesign scope, new features are possibly conceived, or not. Next, models of the specifications are developed and optimized. The new product form is then built and further optimized using designed experiments. An electric wok redesign provides an illustration. The methodology has had a positive impact on results by using a systematic approach, both within design education and industrial applications.*

Keywords: Redesign; Design methods; Reverse engineering

1. Introduction: Background, Motivation and Related Work

In the literature, a number of descriptive and prescriptive design methodologies have been developed for general engineering design problems and engineering modeling (Pahl and Beitz, 1984; Pugh, 1991; Ullman, 1992; Ulrich and Eppinger, 1994; Asimow, 1962; Altschuller, 1984; Dixon and Finger, 1989; Clausing, 1994; Phadke, 1989). However, very few methodologies exist that focus on the class of problems known as redesign (adaptive, variant, etc.) (Sferro et al., 1993). As with original design, redesign problems include the process steps of ‘gathering customer needs’, ‘specification planning and development’, ‘benchmarking’, ‘concept generation’, ‘product embodiment’, ‘prototype construction and testing’ and ‘design for manufacturing’, but they also focus on an additional step, referred to here as ‘reverse engineering’ (Ingle, 1994). Reverse engineering initiates the redesign process, wherein a product is predicted, observed, disassembled, analyzed, tested, ‘experienced’, and documented in terms of its functionality, form, physical principles, manufacturability and assemblability. The intent of this process step is to fully understand and represent the current instantiation of a product. Based on the resulting representation and understanding, a product may be evolved, either at the subsystem, configuration, component or parametric level.

In this paper, a new reverse engineering and redesign methodology is presented. This methodology focuses on the process steps needed to understand and represent a current product. Extensions of contemporary techniques in engineering design are utilized at a number of stages in the redesign process to meet this goal. A number of new techniques are also developed to address the unique characteristics of product evolution. The specific use of the combined techniques provides a novel context for application in industry and engineering-design education. In this context, the primary target application for the methodology is developing a new product to enter an existing market. However, audiences ranging from academic instructors to applied engineers can use this material to question and consider alternative product development steps. By considering alternative steps and associated techniques, products may be viewed from new perspectives, perhaps leading to innovations ‘outside the current box’.

The next two sections describe our specific reverse-engineering and redesign methodology, with application to an electric wok product. Emphasis is placed on the salient and unique features of our methodology, with relevant literature providing supplemental details.

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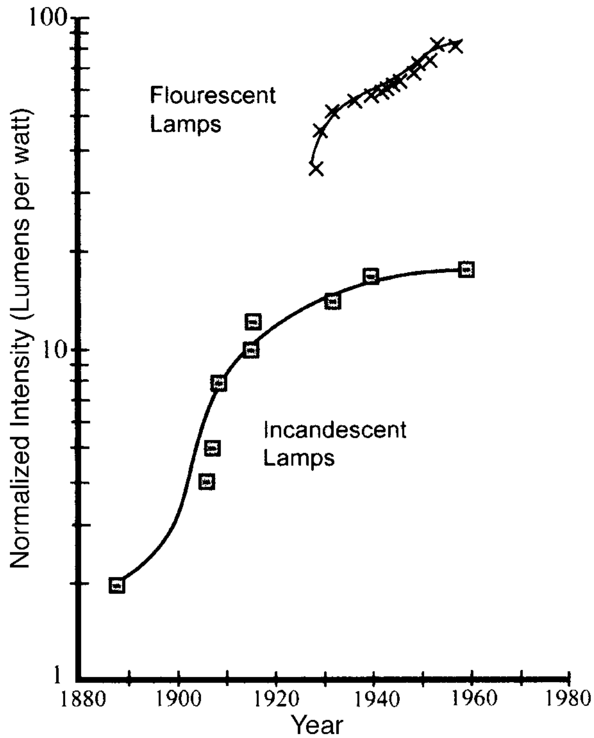

Fig. 1. Product evolution along S-curves (from Betz, 1993).

2. Reverse Engineering and Redesign

To motivate the need for a redesign methodology, consider an abstraction of product evolution in the marketplace, depicted in Fig. 1. As shown in the figure, one can determine a critical metric that is useful for evaluating a product and its market competition, and plot the value of performance for each product as a function of the time when each product was introduced. The metric values will naturally fall as an *S-curve* in time (Foster, 1986; Betz, 1993). At first, a new innovative product will enter a market domain as a new concept. The plotted curve will remain somewhat 'flat' for a certain period of time, representing the time for the competition to respond. 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 the engineers cannot extract more performance. The slope of the 'S' tops out again, and the curve becomes flatter.

Depending on the competitive environment, a product development team must redesign their product at two levels into the product's future. The first level is as described along an individual S-curve and includes parametric, variant and minor adaptive changes in the manufacturing, components, materials, geometry, assemblies, and subassemblies. These changes are a direct response to customer needs and feedback (Ashley, 1994). The second level, on the other hand, reflects a discontinuous jump in the product characteristics. Discontinuities of this type result from the introduction of new technologies, new production processes, or a fundamental change in product architecture.

The bottom line of product evolution with respect to S-curves is that all products must change (both nonlinearly along an S-curve and discontinuously between them) to remain competitive. We propose that a systematic methodology will lead to a better understanding of product evolution and how to execute effective change with reduced cycle time. The next subsection introduces the structure of such a methodology.

2.1. General Methodology

Figure 2 shows the general composition of our reverse engineering and redesign methodology. Three distinct phases embody the methodology: reverse engineering, modeling and analysis, and redesign. The intent of the first phase, reverse engineering, is twofold. First, a product is treated as a black box, experienced over its operating parameters, and studied with respect to customer needs and predicted and/or hypothesized functionality, product components, and physical principles. The second step of the reverse engineering phase is to experience the actual product in both function and form. This subphase includes the full disassembly of the product, design for manufacturing analysis, further functional analysis, and the generation of final design specifications.

The second stage of the methodology entails the development and execution of design models, analysis strategies, model calibration, and experimentation. The third and final stage of the methodology then initiates product redesign based on the results of the reverse engineering and modeling phases. Parametric redesign may be pursued using optimization analysis of the design models. Alternatively or in concert, adaptive redesign of product components and subassemblies may be pursued.

Beyond parametric or adaptive redesign, an original redesign effort may be needed to satisfy the customer needs. An original redesign, in this context, implies that a major conflict exists between the customer needs and the current product in the market. Because of this conflict, it is deemed that an entirely

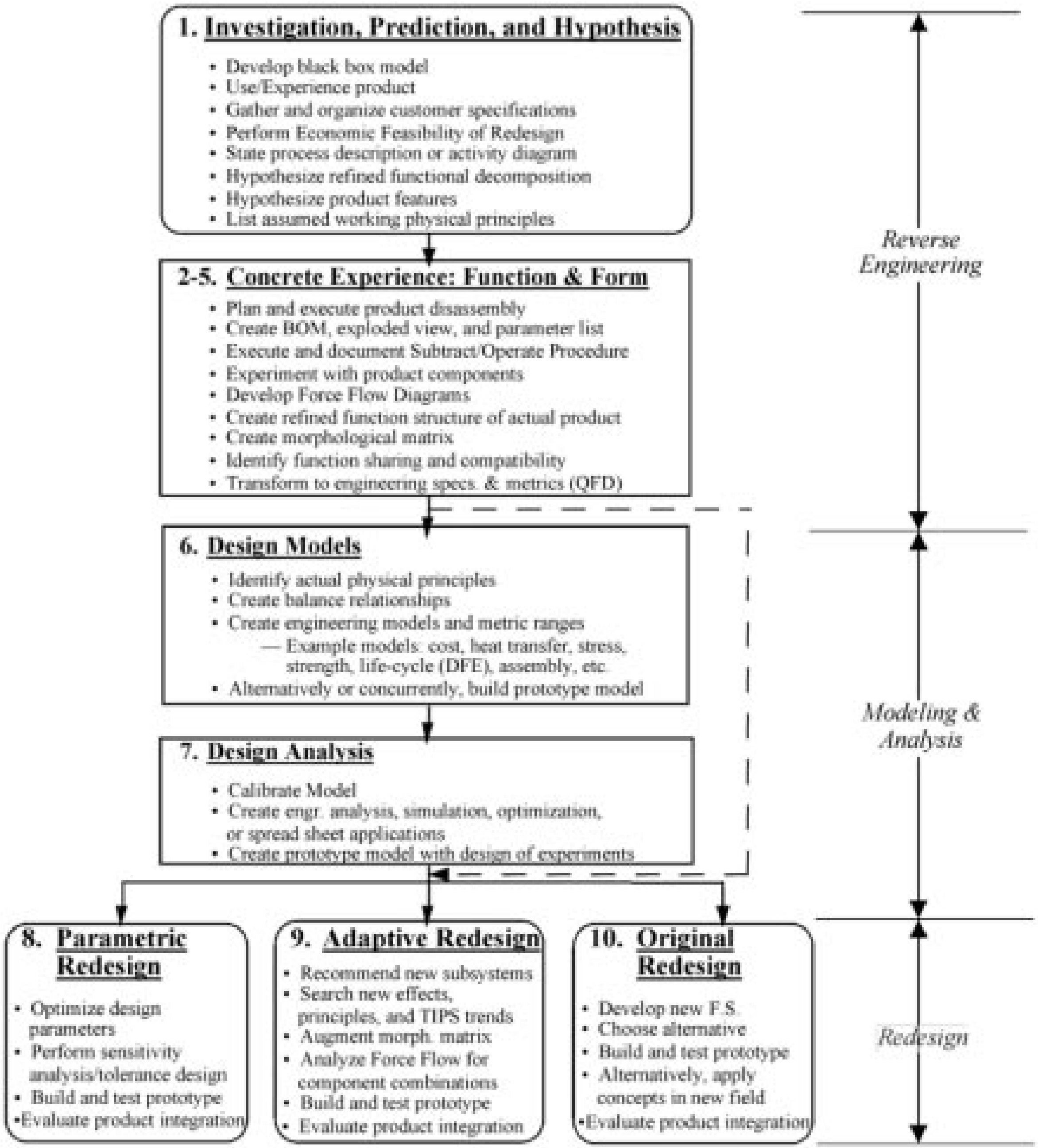

Fig. 2. Reverse engineering and redesign methodology.

new product concept is needed. Functional analyses from the reverse engineering phase will direct the redesign effort.

In sum, unbiased prediction, customer-driven design, analysis using basic principles, and hands-on experimentation are the philosophical underpinnings of this redesign methodology. The intent of the methodology is to be dynamic, depending on the needed evolution for a product. The dashed line in Fig. 2 shows the global dynamic nature of the methodology. For some product redesigns, it may be appropriate to perform adaptive or original changes before creating and optimizing a design model; similarly, the model development of phase two may lead to a better understanding of the product, bypassing parametric redesign and leading directly to adaptive. Alternatively, another product redesign may call for simple parametric modifications to produce dramatic S-curve response in quality and profit margin. The proposed methodology may be used for any of these scenarios or others.

The next section builds upon the methodology of Fig. 2. Explanations of the tools and techniques for each step in the methodology are provided. Without appropriate techniques, the methodology would be relegated to a philosophic goal without a foundation for actual use in the reality of industry or the university classroom.

3. Adaptive and Parametric Redesign: Applications to an Electric Wok

Based on the redesign methodology of Fig. 2, there are several tasks that must be completed to execute an effective redesign of a commercial product. We briefly introduce each task below. For continuity, however, only certain tasks are embellished and described in detail, following a particular theme of an electric wok example.

Step 1: Reverse Engineering: Investigation, Prediction, Hypothesis
Two primary goals are intrinsic to the first step of the methodology: (1) clarify the product domain, developing a rigorous statement of the customer needs, and (2) treat the product as a 'black box' and either hypothesize the 'internal' functions and product features (solution principles), or choose the design team's preferences for these items. Let's consider the salient features of this step, particularly black box modeling, customer need analysis, and predicting product function.

Task clarification: after stating an initial problem statement, a black box model is created, identifying the input and output flows of materials, energies, and signals and the global function of the product. These are documented in a single input-output block model. The intent here is to understand the overall product function, while maintaining, figuratively and literally, very little knowledge of the internal components of the product. By so doing, an 'unbiased' perception of possible product evolution is maintained, in addition to avoiding psychological inertia when generating concepts in later stages of the methodology.

Customer need analysis and diagnosis of product weaknesses: based on the problem statement and black-box model, customer needs are gathered and organized for the product. The voice of the customer is *the* essential task in forming a complete and usable product design specification. Several techniques exist to gather a list of customer needs. These techniques include: direct use of the product, circulating questionnaires, holding focus group discussions, and conducting interviews. A more complete discussion of the different methods is given in Urban and Hauser (1993).

For the purposes of our methodology, the task of gathering customer needs involves the subtasks of interviewing an appropriate sample size of customers. Typically, nine or more customers are interviewed for small consumer products (Griffin and Hauser, 1993), recording the customer statements in their words from prompted questions or from spontaneous statements (such as product likes, dislikes, and suggestions). These customer needs are interpreted into a noun-verb format, and then ranked according to importance. After completing customer need collection forms with this information, each interpreted need is copied onto an index card or post-it note, listing the need, importance rating, project title, and customer ID. The index cards are then grouped into collective customer need statements, and the relative importance of each group is assigned using the number of index cards per group, combined with the importance rating. The result of this technique, as documented fully for the wok example in Otto (1997), is a complete customer need list, with both primary and secondary needs and weightings. This customer need list is augmented with economic feasibility to determine the potential return on investment (Thornton and Meeker, 1995; Miller, 1995; Ulrich and Eppinger, 1994).

Functional prediction: assuming an adequate coverage of customer needs and economic viability, functional analysis begins the methodology's prediction tasks (Fig. 2). This analysis includes the development of a process description, or activity diagram, and the forming of a function structure, as summarized in Fig. 3. An important tool for analyzing the function of a product is to specify the 'process' by which the product being designed will be functionally implemented. A process or process description, in this sense, includes three phases: preparation, execution and conclusion (Hubka et al., 1988). Within each phase, high-level user *and* device functions are listed to show the full cycle of a product, from purchase to recycling or disposal. After listing the high-level functions in each phase, a number of product characteristics are chosen, including the product's system boundary, parallel and sequential paths through the function structure, process choices, and interactions between user and device functions. These choices are documented in a process description form.

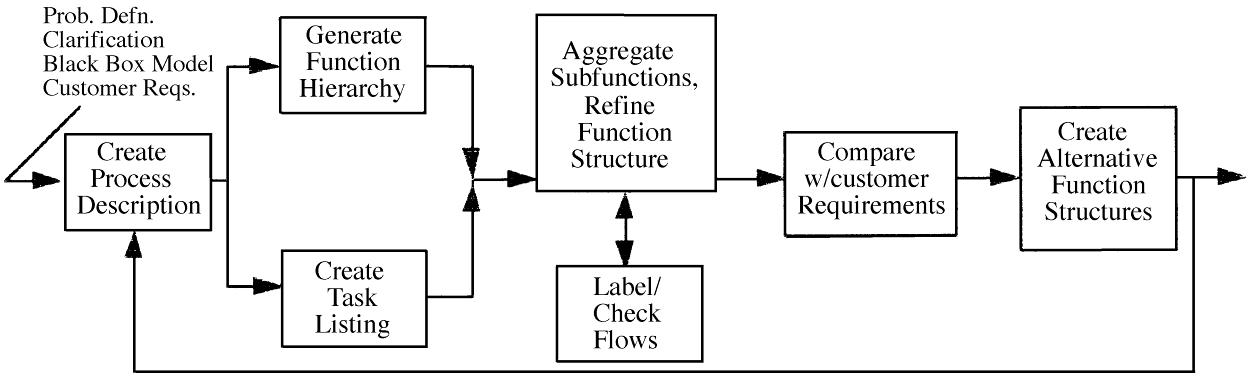

Fig. 3. Functional modeling and analysis process.

Using the process description and customer needs, a hypothesized function structure for the product is formulated (Fig. 3). Function structure modeling (Pahl and Beitz, 1984; Miles, 1972; Hubka et al., 1988; Ullman, 1993; Otto and Wood, 1997; Shimomura et al., 1995) has historically been used to create a form-independent expression of a product design. We extend common function structure modeling to include an approach for mapping customer needs to subfunction sequences (called task listing), a method for aggregating subfunctions, and a comparison of a functional decomposition with customer needs.

Functional modeling: the first step is to identify major flows associated with the customer needs of the product activities. A *flow* is a physical phenomenon intrinsic to a product operation or subfunction. For example, an operation may be to convert electricity for heating food in a wok. Three critical flows for this operation are an input electrical energy, the heat energy produced from the conversion, and food material being operated upon. Stone and Wood (1998) summarize common flows used in functional modeling.

For each of the flows, the next step (Fig. 3) is to identify a sequence of subfunctions that when linked represent the hypothesized product functions or customer activities when interfacing with the product. A subfunction, in this case, is an active verb paired with a noun that represents a product operation. Little and Wood (1997) provides lists of appropriate verbs and nouns to use in functional analysis.

For example, two important customer needs, expressed in the customer's voice, may exist for an electric-wok product as 'heats and cools quickly' and 'temperature uniform across inner surface'. A suitable flow for addressing this need is an energy flow of heat that ultimately acts to heat a material flow of food. A sequence of subfunctions for the energy flow may be of the form: convert electricity to radiation, heat container, conduct heat, sense heat, regulate heat, heat food, insulate from environment, etc.

Once the design team completes the function structure, functional modeling comes to a closure through a verification step. This verification entails a review of the customer needs list, where the subfunction or sequence of subfunctions are identified that satisfy each customer need. Needs not covered by the function structure require further analysis and added functionality; sub-functions not satisfying a need require confirmation of their incorporation.

A predicted process description and function structure provide a sound basis for critically analyzing an actual product and for seeking avenues to improve quality. The customer needs are related to a form-independent functional model of the product. Two additional hypothesis tasks are now needed for completion: directly matching the customer needs with product features and working physical principles. Between these two matchings, a design team can determine which product features or principles offer the best opportunity for redesign.

In summary, the first step of the redesign methodology provides us with the necessary investigation, hypotheses, and predictions for a successful product evolution. While this information is only the preface to the redesign task, if properly wielded, it should give us insights that far exceed our expectations and the resources needed to gather and document the product state. Let's consider the electric wok application to illustrate example results.

Wok redesign application – Step 1: this redesign project was initiated through the perception of a need: the inadequacy of current electric woks to satisfy the demands of the young urban dweller desiring to

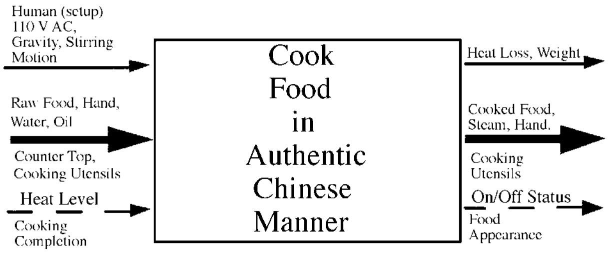

Fig. 4. Wok black box model.

Fig. 5. Six quart electrical wok.

conveniently cook authentic Chinese food (Fig. 4). The original product is a six-quart Electric Wok, shown in Fig. 5.

A competitive product is a traditional wok, used over a gas flame and heated by convective and radiative modes of heat transfer. Heating occurs uniformly across the entire wok surface, rather than in a concentrated ring. This method thus lends itself to uniformly cooking the food placed within it.

Beginning with the black box model in Fig. 4, a set of customers were interviewed as they used the wok in normal cooking operations. Interview sheets were used to document the customers' stated strengths and weaknesses of the product, especially compared with a traditional wok. These sheets were then organized into a cumulative customer need list, recording the aggregate importance ratings as evaluated by the customers. Important customer needs include: temperature – 'temperature uniform across the inner surface', 'heat and cool quickly', 'maintain uniform temperature in time', etc.; size – 'compact wok for countertop and storage'; cleanable – 'prevent food from sticking' and 'allow the removal of cooking surface from heating unit', etc. Figure 6 summarizes the critical customer needs diagnosed from the current product. (Otto, 1996) provides the detailed approach and analysis that supports this list. In the following sections, we build on these customer needs and focus on the key threads of 'uniform temperature' and 'heats quickly' to illustrate the methodology at a sufficient level of detail.

Step 2: Reverse Engineering: Product Teardown and Experimentation

Concrete experience now becomes the emphasis of the redesign methodology. The current product architecture must be understood in detail, and, most importantly, the customer needs must be compared with the current product's functionality, solution principles and choices of design parameters. While this is generally understood when working to redesign an existing product, a development team needs to execute a complete teardown approach when they have no product in the market and are using a competitive product as a baseline. Also, for education purposes, students can apply this approach to dissect, deduce and understand how a product was designed. Overall, repeating this approach, on several competitive products provides a comparison that ultimately leads to avenues for product evolution.

Product teardown: product disassembly (or teardown) initiates the second step of reverse engineering. A plan is incrementally developed for the disassembly activity, listing the order of disassembly, component or assembly to be removed, tool usage, access direction, orientation of product (to prevent components from falling out) and any expected permanent deformation caused by the disassembly. In its entirety, the plan provides a means for assessing the assemblability of the product, as well as a means for returning the product to its original form. It should be noted, however, that the disassembly plan may not correspond to the same order the product was originally assembled. It just provides one possible arrangement for evaluation.

The disassembly is systematically executed, labeling each component as it is removed. Distinct

	Customer Need	Weight	Fix	Current
I.	Cleanable			
	A. Non-stick surface	5	N	6
	B. Washable	4	Y	2
	C. Detachable from the heating unit	3	Y	0
	D. Instructions	1	N	0
II.	Aesthetics			
	A. Aesthetically pleasing	4	N	4
	B. Can be used to serve	3	N	6
III.	Cooking Shape			
	A. Flat bottom for frying	3	-	-
	B. Small, rounded bottom for stir-fry	7	Y	3
	C. No ridges on inner surface	5	Y	2
IV.	Size			
	A. Compact for easy manipulation/small storage	8	Y	2
	B. Lightweight	7	Y	8
V.	Stability			
	A. Able to stand on own	7	N	8
	B. Doesn't slide on table top	2	Y	3
	C. Enable rapid heat removal when cooking	2	Y	0
	D. Rest for spatula	1	N	0
VI.	Temperature			
	A. Heats and cools quickly	6	N	8
	B. Temperature uniform across inner surface	7	Y	2
	C. Steady-state temperature uniform	4	Y	3
	D. Capable of high temperature	1	N	8
	E. Heat contained in wok	2	N	9
VII.	Capacity			
	A. Large volume capacity	4	Y	8
VIII.	Manipulation			
	A. Easy to handle	7	Y	3
	B. Long extension cord	6	N	1
	C. Handles remain cool/don't get hot	3	Y	8
	D. Contents can be poured out	4	Y	3
	E. Removable cord	1	N	10
IX.	Cost			
	A. Cost	7	N	6
X.	Temperature Control			
	A. Temperature switch readable	2	Y	2
	B. Off switch included	2	Y	0
	C. Temperature indicator	3	Y	0
	D. Temperature controls remain cool/don't get hot	2	N	7
XI.	Impact			
	A. Impact resistant	1	Y	4

Fig. 6. Electric cooking wok: Customer needs list w/diagnosis of weaknesses.

Part #	Quantity	Part Description	Part Color	Function	Physical Parameters
A1 Lid Assembly					
001	1	Cover	Red (top)	Minimize oil splattering	Stamped .030" alum.
			Silver(bot)	Steaming	
002		Cover knob	Black	Lift support for wok lid	Plastic
				Temperature insulating	
A2 Bowl Assembly					
003	1	Wok bowl	Black	Holds food	14" diameter
				Distributes heat	.080" aluminum
				Handles attached	Hard anodized surface
				Heating assembly attached	Rolled edge
				Provides non-stick surface	Flat, circular bottom
				Contain liquid	Raised ridge along
				Non-stick	bottom's perimeter
004	2	Handles	Black	Lift support for wok	Plastic
				Temperature insulating	
005	1	Wok stand	Black	Encases heating elements	Plastic
				Provides support for bowl	8" circular diameter
				Provide friction anti-skid	4 short legs
				Temperature settings label	
				Cord connection support	
006	2	Connector prongs	Steel	Elec. connect wok to cord	.13" diameter round
				Provide Electrical shield	.50" long, threaded
007	4	PEM studs	Steel	Connect bowl to stand &	2 short (1" from
				heating elements	bottom of bowl)
008	1	Metal Plate	Aluminum	Contain heating assembly	Aluminum
				for safety	Embossed lettering
				Provide customer informatn	
A3 Electrical Heating Assembly					
009	1	Electrical Cord	Black	Provides connection from	2' long
				wok to electrical outlet	
010	1	Thermostat	Mtl/Cmc	Provide on-off electrical	Bimetallic strip
				regulation based upon temp.	
011	1	Heating Coil	Black	Converts elec. energy to	1000 W Cadmium Wire
				radiation and convective	6" diameter ring
				heat	.38" loops
012	1	String	White	Holds heating coil in place	
013	3	Insulated Wires	White	Connect heating element to	Steel20 Gauge hard wire
				bimetallic strips	Wrapped in thread insltn
A4 Electrical Heating Support					
014	1	Radiation Shield	Metallic	Shields thermostat from	.01" millboard
				radiant heat	fireproofing Sheet
					3.5" diam. ring
015	12	Coil Supports	Off-white	Hold heating coil in place	Ceramic
				Electrically insulate coil	
016	1	Element housing	Aluminum	Provide attachment of	.030" aluminum
				coil supports	.75" U-channel ring
				Reflect radiation into bowl	4" mid-diameter
017	1	Spacer	Silver	Provides support for heating	Aluminum
				assembly attachment	Elliptical shape
018	1	Slotted spacer	Dark gray	Holds bimetallic strip in	Indented, angled shape
				place	2.60" on longest side
019	1	Square spacer	Light gray	Presses down against backs	3.80" x 4.25"
				of coil supports	Square shape
				Registration holes for assmbly	2.80" diam. circle
					cut through center

Fig. 7. Wok bill of materials and exploded view.

assemblies or sub-assemblies are also noted to understand the product architecture. As the product tear down progresses, a *Bill-Of-Materials* (BOM) and an exploded view (Fig. 7) are constructed to investigate the abstract and concrete features of the product. This BOM and exploded view should list all assemblies, sub-assemblies and parts in the order they were originally assembled. These results make DFA cost analysis easier.

In concert with product tear down, a novel *Subtract-and-Operate* (SOP) procedure is executed to study the functional dependence of each product component (Lefever and Wood, 1996; Lefever, 1995). A summary of the procedure for an assembly or subassembly of a product is given below:

- Disassemble (subtract) one component of the assembly.
- Operate the system through its full range.
- Analyze effect through visual inspection or measurements.
- Deduce the component's subfunction; compare to BOM.
- Replace component; repeat for all parts in assembly.

Using this procedure, construction of a SOP table occurs, listing the part number, part description, and determined effect of removal. Through this procedure, a more refined understanding of component functionality may be obtained; likewise, for those components that are recorded as having 'no effect on degrees-of-freedom' when subtracted, redundant functionality exists in the product, implying that part reduction may be directly pursued. Table 1 shows the SOP deduced functionality for the electric wok, as well as identified components that represent avenues for simplification (Type 1 and 2 degree of freedom redundancies in the table).

Table 1. Electrical wok SOP effects table

Assembly/ Part No.	Part Description	Effect of Removal	Degree-of-Freedom Type	Deduced Subfunction(s) & Affected Customer Needs
A1	Lid Assembly			
001	Cover	Heat radiates to environment; Food splatters		Insulate Energy Flow Contain Food
002	Cover knob	No effect	2	Import Hand
A2	Bowl Assembly			
003	Wok bowl	Food falls into base; Food directly in contact with coils		Contain food, Conduct Heat, Direct Food, Heat Food, Enable Cleaning
004	Handles & Handle Caps	Burn hands	2 (handles) 1 (caps)	Import Hand Insulate Hand Transmit Weight
005	Wok stand	Bowl cannot be oriented/ stabilized; Heat element is exposed; Temp. settings not visible	2 (each redundant foot)	Orient Cooking, Transmit Loads, Distribute Loads, Insulate Heat, Indicate Temperature Setting, Prevent Skidding
006	Connector prongs	Cannot turn on/off; Electricity doesn't flow; Exposes electricity	1 (second prong)	Actuate On/Off Transmit Energy Protect from Shock
007	PEM studs	Bowl is not connected to base	1 (>1 stud)	Transmit Loads
008	Metal Plate	Exposed coils; Safety info. not displayed		Insulate Heat Indicate Visual Safety Signals
A3	Heating Assembly			
009	Electrical Cord	No connection to source		Connect to Energy Transmit Energy
010	Thermostat	Temperature very high, continuously		Regulate Power/Temp. Sense Heat
011	Heating Coil	Open circuit; Wok doesn't heat		Convert Electrical Energy to Radiation
012	String	Heating coil is not held in place		Transmit Loads
013	Insulated Wires	Temp. rise continuously; No temp. sensing		Transmit EE to Sensing
A4	Electrical Heating Support			
014	Radiation Shield	Thermostat heats up; Heat is lower in bowl		Shield Temp. Control Direct Heat
015	Coil Supports	Heating coil misaligned; Housing heats up	2 (>1 support)	Insulate Heat Direct Heat
016	Element housing	Heating element is free floating; Bowl does not heat well		Direct Heat/Radiation (Heat Container)
...	...	...	...	...

Experimentation: the final task of the second step is to experiment with the overall product, its assemblies, and its components. Step 1 of the redesign methodology generates a complete list of customer needs, in addition to predicted product features and physical principles. These data, in conjunction with the BOM, are now used to direct the choice of physical parameters that must be recorded for the product. For example, for the electric wok customer needs of 'uniform temperature' and 'heat quickly', the tear-down process reveals a heating coil, controller, coil supports, spacers, and a wok bowl. Temperature distributions of the bowl (spatially and in time), geometry of components, and material properties of the coil, bowl, and supports are needed to further understand the meaning of the customer needs. Recognition of these physical parameters may not occur at this stage of the redesign, but instead during the forming of engineering metrics (Step 5), or the construction of design models (Step 6). In either case, the design team iterates back to the experimentation task to obtain the required data. Results of the task, independent of when it is executed, are recorded on an updated BOM.

Wok application – Step 2: the wok tear down revealed the cause of the failure to deliver a uniform temperature distribution across the bowl. The electric elements were housed within a narrow circular channel, concentrating the heat transfer. The non-uniform heating characteristics in time were revealed to stem from a bimetallic temperature controller, which also was the design driver for the poor power control interface.

Step 3: Reverse Engineering: Functional Analysis
Product disassembly provides detailed information regarding component function, assemblability, physical parameters, manufacturing processes, and an intuitive understanding of the product as a consequence of the various hands-on experiences. These results must now be abstracted to the level of the customer needs statements, developed in Step 1. By so doing, the design team may identify and rank areas of focus for product improvement.

Functional analysis is the key instrument for building the abstraction. Two primary tasks enable functional analysis of the actual product. The first task is to develop energy flow diagrams of the product and/or separate product assemblies (Lefever and Wood, 1996; Lefever, 1995). Energy flow diagrams are graphical aids that represent the transfer of energy through a product's components.

Actual product function: after or in concert with force flow analysis, a function structure for the actual product is formulated. This task entails the same approach as described in Step 1 (Fig. 3), except, in this case, subfunctions are not predicted; they are derived from the actual components in the product. This time we have the benefit of tearing apart the actual product. We believe this two step approach helps a design team understand different physical principles by which the product could operate. Using the flows for each customer need, as developed in Step 1, a useful approach to generating subfunctions for the actual product is to examine the exploded view and BOM from Step 2. Each flow is traced through the product, recording the subfunction(s) for a component as it is encountered by the flow. This process creates a subfunction chain for each flow. The next step is to connect the parallel flow chains together as a network, adding subfunctions and flows for components that link flow chains. The result of this process is the desired function structure.

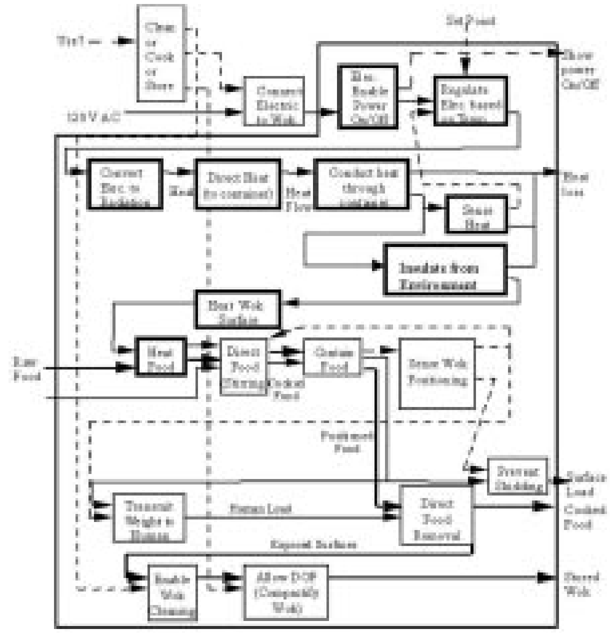

Fig. 8. Wok function structure – actual product.

Wok application – Step 3: a function structure was developed by first associating flows to each customer need. This process produced three primary flows: flow of food through the wok, flow of electricity, and heat flow. These flows were then expanded into sequences of subfunctions as the flows traced through the wok. They were then aggregated in the structure (Fig. 8). For the customer needs of 'uniform temperature' and 'heats quickly', the key function chain from Fig. 8 maps the electrical energy input to the heating of the food material. The nine functions associated with these flows (highlighted in Fig. 8) provide a high-level model for the customer needs. They are also targets for generating adaptive concepts for evolving the wok.

Step 4: Reverse Engineering: Constraint Propagation
Product disassembly and functional analysis, as completed in Steps 2 and 3, yield detailed design data for product evolution. With these data, improvements in design function, parameter choices, etc. may be approached knowledgeably for assemblies, subassemblies, or components. However, constraints between product components must also be well understood. With such understanding, the ramifications and propagation of design changes may be properly forecasted.

Function	Current Wok	Possible Solutions				
1. Connect to Wok	Plug	Direct				
2. Switch Electric Power on/off	Plug	**Flip Switch**	"Off" Setting	IC Control		
3. Regulate Electricity	Thermostat on/off	P-Control at Center	PD-Control Thermocouple	**Open Loop P-Control Power**		
4. Convert Electricity to Radiation	**Heating Coil**	Halogen Heat Lamp	Washable Coil	Silicon Rubber Pad + Coil	Inductive Coil & Plate	Ceramic Disk
5. Channel Heat to Bottom of Container	Square U-Ring	Parabolic U-Ring	**Dish-Shape**			
6. Heat Bottom of Container	Exposed Ring on Bottom	Larger Ring	**Circle**			
7. Conduct Heat	Change Mat'l Geometry	**Thicker Bowl**	**Different Mat'l**			
8. Sense Heat	Thermostat at Center	Thermocouple	Thermistor	IC Sensor	**Dimmer Switch (Power)**	
9. Prevent Skid	**4 Dimple Pt. Contact**	3 Dimple Pt. Contact	Rubber Pad	Flat Bottom (No Legs)		
10. Transmit to User	Short tabs	**Full Handle**				
11. Clean Wok	Attached Base; Handwash	Detachable Bowl				
12. Compactify Wok	None	**Base Attachmt. Fits Inside Bowl**	Detachable Handle	Pivot Handle		

Fig. 9. Wok morphological matrix.

Morphological analysis: the first task in this step is to create a morphological matrix (Pahl and Beitz, 1984; Ulrich and Eppinger, 1994) of the solution principles (components) for the significant functions. Each row of the matrix corresponds to a subfunction from Step 3, and each column represents a solution principle.

Function sharing and compatibility: subsequently, function sharing and compatibility analysis comprise the second task for understanding the product configuration (Lefever and Wood, 1996). The design team may identify function sharing of the product components simply by scanning the morphological matrix for components that are listed for more than one subfunction. Through such identification, it is possible to plan for design changes without violating functional requirements. Likewise, *compatibility* of the produce components may be analyzed by dissecting each critical product interface, between components, to identify its degrees-of-freedom, access directions, relative motion with other components, tribological properties, and tolerances (size and geometric). A matrix listing each component versus these data may be constructed to document the analysis.

Wok application – Step 4: a morphological matrix was developed for the electric wok (Fig. 9). (Note: results are also included here from Step 9.). Likewise, a function-sharing and compatibility analysis for the wok (customer needs: uniform temperature and heats quickly) shows that the heating coil, element housing (reflector), and wok bowl perform six of the nine functions of the highlighted chain in Fig. 8. It also shows the size, shape, or material properties of these components are coupled to each other (especially due to the inset ring to attach the coil to the bowl). Parametric or adaptive redesigns to satisfy the customer needs will thus require a change in the interface between the components.

Step 5: Reverse Engineering: Forming Engineering Specifications

The last step of reverse engineering entails the forming of specifications, benchmarking, and choosing the product systems that will be evolved. The intent of the first task is to define quantitative targets for the product (Otto, 1995). Having established organized customer needs and a function structure for the product, each subfunction must be associated to at least one line item in a product Specification Sheet (House of Quality), where each specification item must be quantifiable and measurable.

To establish an initial set of engineering specifications, a design team should start by listing each subfunction as rows of a matrix. For each subfunction, a means to measure the input and output flows should be conceived. These measures should be listed for each subfunction row as the metrics for the subfunction. For example, a subfunction exists to

Table 2. Abbreviated House of Quality data for an electric wok

Customer Need	Sub-function(s) (to be measured)	Metric(s)		Benchmark (Consumer Reports, 1997)	Target	
Uniform Temperature on Inner Surface	Regulate Electricity (w.r.t. temp.)	Steady State Temp. Error (time) [°F]	Set Point Temp Error (space) [°F]	• Maxim EW-50: Excellent • West Bend 79525: Fair (50°F) • Joyce Chen Wok 22–9940: Excellent	5°F	5°F
	Heat food	Temperature Variation Across Surface [°F]		• Maxim EW-50: Excellent • West Bend 79525: Fair (55°F) • Joyce Chen Wok 22–9940: Excellent	Excellent: 5–10°F	
Heats Quickly	Heat food	Temperature Rise Time [sec.]		• Maxim EW-50: Excellent • West Bend 79525: Fair (>2 min.) • Joyce Chen Wok 22–9940: Excellent	Excellent: 1 min.	

'regulate temperature' of an electric wok (Fig. 8). Possible measurements include steady state temperature error, set point temperature error, and temperature variation across the material (wok bowl).

Next, the generated metrics must have target values assigned to each. This subtask is accomplished by examining the relevant customer needs and performing benchmarks with related products or technologies. After these tasks, the results should be collected into a House of Quality matrix, creating the necessary importance rankings and relationship matrices. The result of this process is the forming of quantified specifications with direct links to customer needs (Hauser and Clausing, 1985; Otto, 1995).

Quantified specifications provide clear goals for evolving the current product. In turn, a complete House of Quality, with this information, may be used to choose, preliminarily, which components of the product should be evolved first. A question exists, however, concerning the type of redesign activity to pursue. Should parametric redesign be attempted first, or is adaptive redesign required, followed by parametric efforts? This question may be straightforward to answer when obvious component deficiencies exist in a product; however, in many cases, an answer may not be easily forthcoming. For example, in the redesign of an electric wok for quick heating and uniform temperature profile, an engineering specification may exist to reduce the temperature distribution across the entire heating surface from 55°F to 10°F. Such a large reduction in temperature variation may seem to imply that a technology change is needed in the wok. A simple mathematical model based on heat transfer may show, however, that changes in material properties, thermal mass, etc. can easily meet the desired specification. Thus, creating a parametric model of the current product is a needed step in the evolution process, as presented in the next section.

Wok application – Step 5: a full House of Quality (specification) was developed for the electric wok. Space limitations prevent a full listing of the results; however, Table 2 shows abbreviated House of Quality data for the customer needs of 'uniform temperature' and 'heats quickly'.

Step 6: Modeling and Analysis: Model Development Virtual and physical modeling of a product will provide in-depth insights into its operation and possible improvements that may be achieved parametrically. Three tasks are needed to develop a virtual or mathematical model. Beginning with each important customer need or engineering metric from the House of Quality, the critical product components should be listed. The governing physical principles and associated modeling assumptions must then be identified for each component, or the group of components as a whole. For example, for an electric wok, the customer need of 'uniform temperature' is important. Components affecting uniform temperature (spatially) are the heating element, the electrical energy input, the wok bowl, the radiation reflector (housing), supports, and the food. The choices for the governing physical principles might be conduction, convection, and radiation assuming steady state and lumped masses.

High-level model: after identifying the physical principles and assumptions for each customer need, a balance relationship is created to document a high-level physical model. As in Step 1, a fishbone diagram, or a failure modes and effects diagram (Clausing, 1994), may be used to document the balance relationship, where the 'effect' in the diagram is the customer need, and the 'causes' are the physical principles. The ultimate goal is to refine the 'causes' to the level of physical parameters.

Balance relationships: the last task in formulating mathematical models for the product is to convert the balance relationships into a set of mathematical equations. Basic engineering principles may be used to choose the appropriate scaling law relationships (Miller, 1995). Parameter ranges from the product's bill-of-materials should be used to augment the mathematical relationships with appropriate parameter values. If such parameter values are unavailable, the 'Experiment with Product Components' task of Step 2 should be executed.

Physical prototype models: in some cases, cycle-time, economic, or product-complexity considerations may prevent the development of a mathematical model. The creation of a physical prototype can be used as an alternative modeling approach. Prototype models should be designed in such circumstances. The intent here is to create a bench-top or other experiment (not an entire product prototype) for a customer need, focusing on the effected product components and variables. For instance, a customer need may exist for an electric wok lid handle to 'fit comfortably in the user's hand during operation'. A mathematical model of this need is not directly apparent; however, physical prototypes that vary shape, size, and texture of the handle may be designed for analysis and testing.

Wok application – Step 6: mass, steady-state temperature uniformity, temperature rise time, and

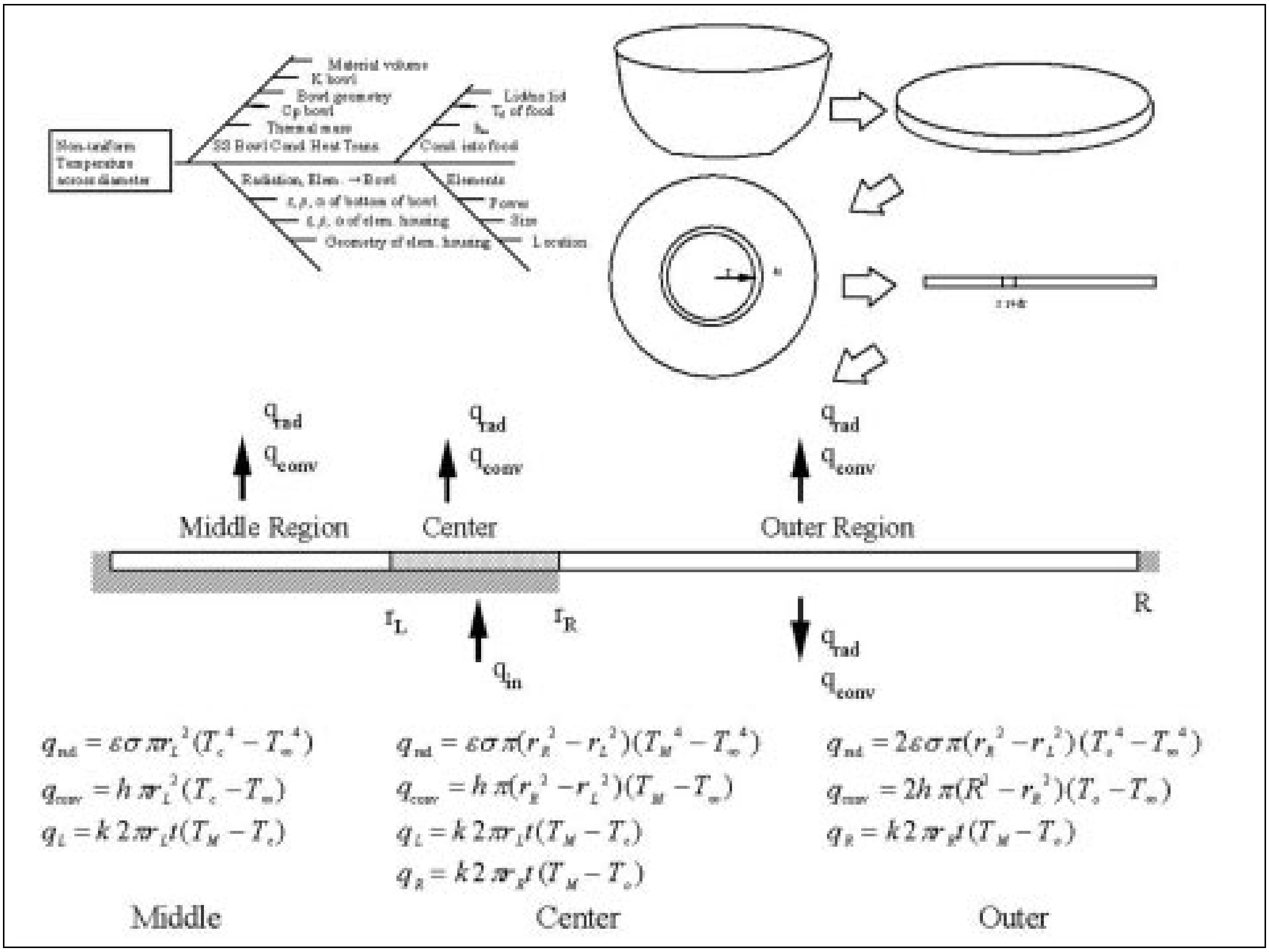

Fig. 10. Wok heat transfer model.

volume equations were derived for the electric wok, in addition to handle temperature and weight. An example high-level model and spatial and balance relationship for steady-state temperature uniformity are shown in Fig. 10.

Step 7: Modeling and Analysis: Analysis Strategies
Models are developed for each of the important customer needs in Step 6. The next step is to develop analysis strategies for solving the models. The first task for developing such strategies is to calibrate the model for each customer need.

Model calibration and formulation: model calibration entails the 'matching' of the model to the actual performance of the product. Two update procedures are usually required for calibration: either changing estimates of model parameters, or adding terms to the model to capture important physical effects. Once the model is calibrated, it must be converted into a form that is conducive for solution. Example formulations include objective functions and constraints for optimization or constraint propagation, simultaneous equations for spreadsheets, state space equations for simulation, or combinations of these.

Physical prototypes: an alternative approach to the virtual model formulations is the creation of a physical prototype strategy. In this case, design of experiments must be developed, including the number of control factors, identification of noise factors, choice of response(s), number of experiments, and the experimental matrix. For statistical validity, it is also important to choose the number of replicates, the in-between tests for residual analysis, blocking, and the random run order for the tests.

Wok application – Step 7: based on the model from Step 6, experiments were executed to determine wok time constants and heat transfer coefficients. These experiments included temperature measurements with thermocouples attached to the inner surface of the bowl (consistent with the specification metrics, Table 1). Figure 11 shows example experimental results at a 10–20% power level. The results were used to calibrate the metric equations and to solve an optimization formulation:

$\|\|T\|\|$	(temp. variation)
$t_r \leqslant t_t$	(rise time)
$\|T(t_r) - T_{ss}\| \leqslant \mathscr{E}$	(temp. at SS)
$\dot{T}(t) + f(t) = 0$	(transients)
$W \leqslant W_\tau$	(weight)
$T_c \geqslant T_{\tau c}$	(min. center T)
$T_h \leqslant T_{\tau h}$	(max. handle T)

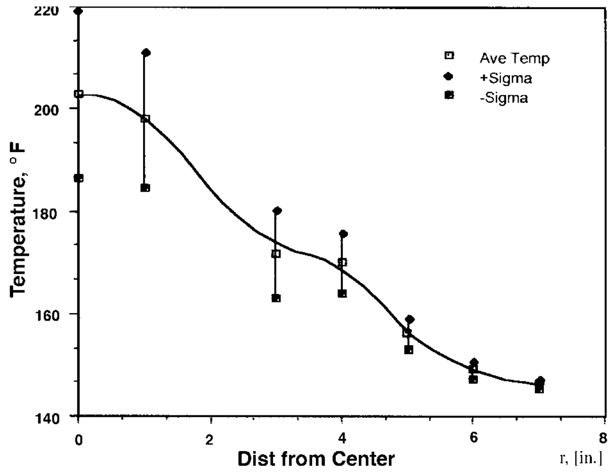

Fig. 11. Wok calibration.

Steps 8–10: Redesign: Parametric or Adaptive
The data from Steps 1–7 provide the design team with immeasurable knowledge and capability. Customer needs are gathered and organized. Product function is predicted, experienced and abstracted. Physical principles are hypothesized, tested, and modeled. Engineering specifications are quantified and ranked. The design team must now employ these data in a successful redesign effort, i.e. parametric, adaptive, and/or original.

Parametric redesign: parametric redesign requires a model of the original product or a model of a new product configuration following adaptive redesign. The model should be calibrated and reformulated according to the chosen solution technique. Optimization, spread sheets, and/or simulation is then applied to obtain new product parameters. Verification of the results then commences using sensitivity analysis or tolerance analysis, such as statistical tolerance stackup (Ullman, 1992) or Taguchi tolerance design (Phadke, 1989). If satisfactory results are obtained from the parametric redesign, fabrication and experimental testing of a beta prototype commences to verify the recommended design improvements.

Adaptive redesign: in the case of adaptive redesign, the design team seeks to create alternative solution principles to chosen product subsystems, replace subfunctions of the product, or add new subfunctions to the product.

The first task, then, is to update the functional description of the product, by either comparing the predicted function structure to the actual, or by simply adding new functions prescribed by the customer needs. Based on the new function structure, adaptive solutions may be obtained in a number of ways. For example, the morphological matrix of Step 4 may be expanded to include a wide variety of solution principles for the important subfunctions. Brain storming techniques and discursive bias are directly applicable for augmenting the morphological matrix. Alternatively, or in concert, the Theory of Inventive Problem Solving (TIPS) may be applied (Altschuller, 1984). This theory employs documented physical effects (over 1000), design principles (40), and prevailing trends in technology (eight so-called laws of evolution) to seek alternative solutions. For example, the customer needs, functional models, and specification of an electric wok might show a conflict between ‘washable’ and ‘safety’ (doesn’t burn or heat parts excessively). Separating the base and bowl in time and space (exposed heating element when bowl is attached vs. covered element when bowl is removed for washing) is a possible solution suggested by the TIPS’ principles. Alternatively, TIPS recommends covering the heating elements with a radiative-transparent material that does not retain heat as it transmits radiation.

No matter what adaptive redesign technique is employed, new solution principles result. These solutions must be verified with the function sharing and compatibility analysis of Step 4 of the methodology, and checked against current patents. In addition, modeling and testing of a physical prototype must occur to verify the design changes, usually after a design model is executed.

Product integration: as shown in Fig. 2, the final task in the reverse and redesign methodology (prior to detail design and beta prototyping) is to perform a product integration of the new concepts developed from the parametric and adaptive redesign steps. This task, at a fundamental level, entails a decision process of whether or not to implement the individual concept ideas into the product. Many factors must be considered to perform this analysis: importance level of the customer need, compatibility of the concept with other being considered, how well the design concept satisfies the target values, the current performance of competitors’ products, the capability of the company to fabricate the new concept within the current manufacturing process, and the cost impact of the new concept on the product. A Pugh chart, trade-off table or detailed performance/cost analysis is needed to execute this decision process.

Wok application – Steps 8–9: the model developed in Steps 6 and 7 was used to perform a parametric redesign of the wok bowl and heating element. This model was solved using the EXCEL Solver, resulting in a new bowl geometry (increased thickness for a greater thermal mass), greater aspect ratio from the heating element, modified handle geometry that remains cool, etc. Figure 12 shows a result of running the optimization. Notice that for a bowl thickness of 0.0035 m, the uniformity of temperature (spatially in

Constants								
Boltzmann Constant		W/m^2 K^·	5.7E-08	5.7E-08	5.7E-08	5.7E-08	5.7E-08	5.7E-08
Temp Environ	T inf	°C	25	25	25	25	25	25
Bowl Conductivity	k	W/m°C	200	200	200	200	200	200
Convection Coeff	h	W/m^2	4.40	4.40	4.4	4.40	4.40	4.40
Wok Radius	Xmax	m	0.18	0.18	0.18	0.18	0.18	0.18
Wok Height	Ymax	m	0.09	0.09	0.09	0.09	0.09	0.09
	Rmax	m	0.20	0.20	0.20	0.20	0.20	0.20
Density	rho	kg/m^3	2800	2800	2800	2800	2800	2800
Emissivity	eps		0.80	0.80	0.8	0.80	0.80	0.80
Heat Capacity	c_p	J/kgm^3	100	100	100	100	100	100
Wattage	q_in	W	1000	1000	1000	1000	1000	1000
	Duty Cycle		12%	12%	12%	12%	12%	12%
Handle Conductivi	k_h	W/m°C	20	20	20	20	20	20
Handle Convect Cl	h_h	W/m^2	4.40	4.40	4.40	4.40	4.40	4.40
Design Variables								
Thickness	t	m	0.0030	0.0033	0.0035	0.0040	0.0100	0.0500
r_L	r_L	m	0.05	0.05	0.05	0.05	0.05	0.05
r_R	r_R	m	0.13	0.13	0.13	0.13	0.13	0.13
Handle								
	L	m	0.16	0.16	0.16	0.16	0.16	0.16
	s	m	0.03	0.03	0.03	0.03	0.03	0.03
Performance Metrics								
Temp Rise Time	t_r	min	3.00	3.25	3.50	4.00	10.00	49.60
Steady State Temperatures								
Center	T_c	°F	217	214	213	209	192	180
Mid	T_m	°F	225	221	219	215	194	181
Outer	T_o	°F	159	160	161	163	171	176
Steady State Temperature Errors								
	|| T_ij ||	°F	33	31	29	26	12	2
Weight								
Bowl	W	kg	1.07	1.18	1.25	1.43	3.56	17.81
Handle Temperature								
	T_h	°F	125	126	126	128	133	137

Fig. 12. Example optimization results for the parametric analysis.

Fig. 13. Wok DOE experiments.

the heating area, from center to mid-point) decreased to 6°F, satisfying the target value shown in Table 1. A designed experiment was subsequently performed about the new model optimum (Fig. 13).

In addition to the parametric redesign, adaptive concepts were chosen based on the morphological concepts developed in Fig. 9. A Pugh chart was developed to determine the preferred choices of these concepts, based on the specifications and House of Quality in Step 5. Preferred choices of concepts are highlighted in Fig. 9.

Based on the results of parametric and adaptive redesign, product integration of the new concepts was considered. Table 3 shows an abbreviated trade-off table for the new wok concepts, focusing only on the customer needs of ‘uniform temperature’ and ‘heat quickly’. Concepts were discarded if they did not significantly increase the product performance, if they increased cost significantly, or if they raised new customer need issues, such as reliability, etc.

The final alpha prototype for the redesigned wok (Fig. 14) represents the result of the product integration shown in Table 3. It includes many advances: a removable bowl for washing, a large handle, an on/off switch, removable cord, simple/visible power control, uniform power control in time, compactable volume for storage, and a wide view radiant surface. *No electric wok on the market yet incorporates all of these customer-requested features.*

Fig. 14. Final alpha prototype.

Table 3. Abbreviated product integration trade-offs

Concept	Customer Need	Customer Need Rating (Fig. 6)	Significant % Toward Targets (Table 1)	Capability	Cost	Integrate Y/N)?
Thicker Bowl (Parametric)	Uniform Temp.	7,/4, Y/Y	Y	Y	Low	Y
Bowl shape (Parametric)	Uniform Temp.	7,/4, Y/Y	Y	Y	Low	Y
New Bowl Mat’l, (Parametric)	Uniform Temp. Heat Quickly	7,/4, Y/Y 6, Y	Y	Y	Low	Y
Ceramic Heating Element (Adaptive)	Uniform Temp.	7,/4, Y/Y	N	Y	Medium	N
Pirex Heating System (Adaptive)	Uniform Temp.	7,/4, Y/Y	Y	Y	High	N
Power Controller: Dimmer Switch (Adaptive)	Uniform Temp.	7,/4, Y/Y	Y	Y	None	Y
Dish-Shaped Reflector (Parametric & Adaptive)	Uniform Temp. Heat Quickly	7,/4, Y/Y 6, Y	Y	Y	Low	Y
. . .						

4. Conclusions: Introspection of Design Education and Industry

This paper presents a novel redesign methodology, compared with related literature, such as the work of Sheppard and Tsai (1992), Brereton and Leifer (1993) and Gabriele (1994). It is based on a ten-step process with three primary phases. Each phase provides a clear set of tasks to seek new product configurations, combining contemporary design techniques with new applications and extensions developed by the authors. These tasks provide a unique forum for significantly evolving all types of consumer products, as illustrated by the electric wok example. Over the last four years, the methodology has been applied to over 150 products at MIT and UT (Otto et al., 1998; Jenson et al., 1998).

4.1. Design Education

We have conducted these methods both on industrial applications and taught these techniques for five years running at MIT, UT and the United States Air Force Academy: MIT as a single class project graduate course, and UT/USAFA as a two-person project freshman course, a 3–5 person project sophomore course, a five-person project senior course, and a single-person project graduate course. In general, we find the exercise of a structured design process has many benefits, including concrete experiences with hands-on products; applications of contemporary technologies; realistic and fruitful applications of applied mathematics and science principles; concept generation from function to morphological matrices to new effects, studies of systematic experimentation; exploration of the boundaries of design methodology, and decision making for real product development.

At MIT, the instruction focuses on exploring the strengths and deficiencies of various structured design methods that have been developed in the community, as detailed above. The student population includes a large fraction of persons returning to graduate school after having worked in industry. They find that, for the most part, they did not have a full appreciation for the theory and power behind many of the methods. Many are surprised at the quality and comprehensive nature of results that the methods provide, and become believers in a systems approach to a well posed design process.

At UT, the results are much the same as at MIT. The most popular project in the freshman-level introductory course to mechanical engineering is the reverse engineering of a children's toy or simple mechanical device. Students resonate with the opportunity to learn the basics of design and apply principles from their freshman physics and mathematics courses. Senior-level students express their desire for even more hands-on experiences. They also make it clear that the redesign of a consumer product is a great forum for learning design methodology and for preparing for their capstone design class that focuses on design projects sponsored by industry.

4.2. Industrial Relevance

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.

These observations have led to most companies developing internal product development processes, which they also tend to guard as proprietary knowledge. Our experience is that, for the most part, there is little intellectually unique within these processes. Yet, as our industrial partners have remarked, product development remains the key market battleground, and simply the high stakes involved lead companies to these measures of guarding structured design methods.

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