Chapter 1-C: Conceptual and Configuration Design of Products and Assemblies

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"I want to know God's thoughts...the rest are details."
— Einstein

Section I. Product Development — A Perspective of Exponential Competition

Competitive design of new products is the key battleground that companies must master to remain in business. It is a set of activities that involves more than engineering, it is fraught with risks and opportunities, and it requires effective judgment over technology, the market, and time. A study of recent business decisions gives insight to these claims:

- To avoid losing market share, all U.S. commercial airplane manufacturers have offered contracts to deliver aircraft at prices that are below current cost (Wall Street Journal, 1995). The companies are betting they can remain profitable through improvement of their products and processes.
- In the early 1980's, Sony offered an improved magnetic videotape recording technology, the Betamax system. While technologically offering better magnetic media performance, it did not satisfy the customers, who rather were more concerned with low cost, large selection of entertainment, and standardization.
- In 1996, both Ford and Toyota launched new family sedans. Three years earlier, each had torn down each other's car. Ford decided to increase the options in its Taurus, matching Toyota's earlier Camry, while Toyota decided to decrease the options in its Camry, matching Ford's earlier Taurus.

To avoid such pitfalls, there is clearly a need to apply statistically sound measurement methods of a product's intended customer population. It is equally important to functionally architect what is required to meet the customer demands, applying rigorous methods for incorporating the best technologies.

To address this need, we present here an integrated set of structured methods, as outlined in Fig. 1, developed in conjunction with a host of industrial partners. We start with the customer population for the product, and develop a representation of the feature demands of this group. Based on this representation, a functional architecture is established for the new product, defining what it 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, known as quality function deployment. From this specification, different technologies and components can be systematically explored and selected through functional models. 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 may then be detailed, and instantiated as the first alpha prototype of a new product.

As shown in Fig. 1, our approach focuses on conceptual and configuration design of products and assemblies. The process begins with a design task and generates a functional model that culminates in a product specification. Later chapters build upon the functional model and specification to execute the product development process to fruition.

Section II. Task Clarification: What Avenues Exist for Market/Technical Improvements? What Development Path Should Be Pursued?

Conceptual and configuration design of products, as depicted by the global process in Fig. 1, 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 and Technical Questioning

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 (goals must be stated before they can be met)
- provide schedule for tasks (define time-lines for task completion)
- provide guidelines for the design process and to prevent conflicts within the design team and concurrent engineering organization

The first step in task clarification is usually to gather additional information. In so doing, the following questions need to be asked and answered, not once but continually through the life cycle of the design process:

- What is the problem really about?
- What implicit expectations and desires are involved?
- Are the stated customer needs, functional requirements, and constraints truly appropriate?
- What avenues are open for creative design?
- What avenues are limited or not open for creative design? Limitations on scope?
- What characteristics / properties must the product have?
- What characteristics / properties must the product not have?
- What aspects of the design task can and should be **quantified** (now!!)?
- Do any biases exist with the chosen task statement or terminology? Has the design task been posed at the appropriate level of abstraction?
- What are the technical and technological conflicts inherent in the design task? (Altshuller, 1984)

It is surprising how often failing to take time at the front end of a project to really "understand" what the problem is causes a great deal of time (and money) to be wasted later in the design process. To obtain this understanding, the design of any product or service must begin with a complete understanding of the customers' needs, as discussed in Section III. It does no good to create a product that can not, or will not be used. It is equally important to ask and answer, on a continual basis, the technical questions given above. By so doing, vitality of the design will always be questioned and, hopefully, maintained.

The tangible result of this questioning procedure is a clear statement of the design team's mission. Fig. 2 shows an example template for a mission statement (Ulrich and Eppinger, 1995). This template should not be used as a mere statement of "parenthood;" instead it should be used as a "passport," "calling card," and "banner," stating the design team's intentions. When interviewing customers, meeting with potential suppliers, or carrying out design reviews, the calling card should be the lead item of discussion, clarifying and equalizing the playing field of negotiation, debate, and probing questioning.

Business Case Analysis: Understanding the Financial Market

Technical questioning is only one-side of the proverbial design coin. Understanding the business market represents the other side, especially to complete the mission statement of Fig. 2. During any conceptual and configuration design effort, a product's market must 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; Ratliff, *et al.*, 1993). By example, this section presents the Harvard business case method to understand the potential impact of a product development through fabrication. A summary of the Harvard business case methodology is shown in Table 1. Application of the methodology 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. For the purposes of this section, let's assume that our corporation seeks to improve its current product offering in the primary finger nail clipper market, a complimentary product to our finger nail polish product line. The mission, following Fig. 2, is to design a finger nail clipper for comfortable use by either the left or right hand. It is assumed that comfort, cost, reliability (consistently remove nails with a simple finger force throughout the product's life), and stowage compactness are the driving market needs (to be confirmed or revised through customer interviews). The corporation also seeks only a 30% gross margin, since the goal is to compliment and increase the market share of finger nail polish.

A number of solutions exist for addressing both the technical and process issues associated with a finger nail clipper product development. A business (financial) case may be derived for each of the possible solutions. However, the intent during the early stages of conceptual and configuration design is not to study all possible alternatives in detail, but to determine if a minimal benefit to the business will be realized by improving the clipper problem, i.e., comfort, cost, reliability, and compactness. As such, we concentrate here on steps five and six of the Harvard business case method (Table 1), where only one generic alternative is considered. A device solution, i.e., a new, generic, and hypothetical clipper design, is the alternative considered, emphasizing the possibilities of reduced cost and higher reliability through compactness and fewer components.

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 in this section. The actual costs have been multiplied by a random factor. The important issue is the relative cost of the current clipper operations versus a proposed, hypothesized solution.

The current costs for clipper development are listed in Table 2. These cost projections are based on 750,000 clippers, with a product distribution of 80% small clippers, for finger nails, and 20% large clippers, for toe nails. The average cost for this distribution is $0.31 per product for fabrication, $0.17 for labor, and $0.23 for engineering time.

For the purpose of comparison, the adopted concept for this analysis is a "generic," hypothesized clipper with reduced parts. It is assumed that there exists suitable component and fabrication technology for this concept. Such a device would require less materials, piece-parts, assembly, and labor; however, tool costs would potentially increase due to higher precision in the cutter alignment. Based on this new fixture concept, Table 3 lists the expected costs for 750,000 products (same distribution of small and large clippers and, as with the current costs, multiplied by a random factor). One-time development (engineering) costs account for $187,000 (increase in tooling design), and projected on-going fabrication and engineering costs account for $231,000 ($154.5k fabrication + $76.5k labor), compared with current product on-going costs of $352,500.

The necessary information is developed for a break-even analysis. A comparison between the current and proposed generic clipper costs is carried out to determine the payback period and cost savings. Table 4 shows the results of the break-even analysis. The payback period is 6 months, with a potential savings of $121,500 for 750,000 products. These results are extremely encouraging. Significant cycle time and cost savings may be achieved for the business if suitable finger nail clipper concept can be developed. Because of these potential savings, the project should be carried to the next stage of conceptual design and prototype build.

Implications

While only a subset of the Harvard business case method is illustrated above, the potential impacts are impressive. A "go/no-go" decision may be made early in the product development process, provided that financial information exists for the current market and that projected costs may be readily assumed for hypothesized concepts. Such decisions should be made in parallel with technical and industrial design clarifications. Also, they should continually be reviewed and updated as new information becomes available, especially as concrete product configurations are derived.

An important caveat of the Harvard Business Case approach is the existence of past financial information for a product family or the existence of analogous product data. While a business case should be developed before or during concept generation, cost data are needed to predict a product's potential return on investment. If an entirely new product or family of products is under development, cost data may not exist directly. The Harvard Business Case methodology still applies in this case, where data are obtained from a similar or analogous product, or very rough estimates of preliminary product layouts.

Section III. The Organizing Backbone of Product Design: Understanding and Satisfying the Customer

Now, having clarified what might make a technical and business opportunity, a firm should determine if there is 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 Total Quality Management perspective.

The first method available to understand the customer is "to be the customer" and to use the product directly. Here a design teams goes to the locations where their or their competitor's product is used, and completes the customer's tasks with the product. If the customer tasks can be easily understood and undertaken by the design team, and the design team is small, then this approach is effective. It is costly, though, for projects with either large design teams or highly skilled customer tasks that require training. Further, it does not directly address documenting the customer needs, which will still require an effort similar to that discussed here.

Another customer need identification method is to circulate questionnaires. A criteria list is developed that a design team believes is relevant to the customers' concerns, and the customers rank the product on these criteria. Alternatively, the design team forms a question list for the customers to answer. In either case, the team examines the responses provided, and from this examination forms a customer needs list. The problem here is that the design team will hear back what it has already determined to be important. The customers only provide answers to the posed questions, which are not necessarily the same as what are most important to the customer.

Another method is to hold discussions with multiple customers as a focus group. Here, a moderator facilitates a session with a group of customers who examine, use, and discuss the product. Usually this is done in the design team's environment, typically a room with a two-way mirror so that the design team can observe the customers during the session. This session can be video or audio taped for later examination.

A final method often applied is to interview the customers. Here, an interviewer discusses the product with a single customer, one at a time. This is typically done in the customer's environment where the product is used by the customer. The customer is observed and questioned with the product. Again, the interview can be video or audio taped for later examination.

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. Assuming a homogeneous market segment, interviews beyond the tenth subject tend to uncover very few new customer needs. Exceptions exist for this approach when multiple segments exist. More interviews would need to be conducted to discover the unique customer needs per segment. Overall, however, interviews should stop when little new information is being with respect to 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 in an *ad hoc* manner. 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? What must they do to attain it from storage and prepare it for use? Ideally, when the customer does any motion or thought processing at all, the customer 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 include (Ulrich and Eppinger, 1995):

- What do you like about the existing product?
- What do you dislike about the existing product?

- What issues do you consider when purchasing the product?
- What improvements would you make to the product?

In cases where a business entity is contemplating the development of a new product (e.g., a new technology with no existing products on the market), the above questions work well as a starting point. Because the customer can not walk through an actual product's use, analogous devices should be used, even a blob of clay, so that customer can manipulate a substance when describing their desires. In this case or when a product is being evolved, some general hints for effective customer interaction include (Ulrich and Eppinger, 1995):

- *Go with the flow*. Do not try to stick to any interview guide, including this one.
- *Use visual stimuli and props*. Bring any tangentially related product, and ask about it.
- *Suppress preconceived notions about the product technology*. The customers will make assumptions about the technology, but the interviewer should avoid biasing the discussion with any assumptions about how the product will be designed or used. It leads to speculation, not facts.
- *Have the customer demonstrate*. It usually unveils new information.
- *Be alert for surprises and latent needs*. One should pursue any surprise answer with follow-up questions. This usually uncovers latent needs - ones that the customer does not know they have and are hard to find.
- *Watch for non-verbal information*. Words cannot communicate all product sensations. Each should be explained.

A form for collecting customer data, developed both in industrial projects for clients and in academic design project courses, is shown in Fig. 3, 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.

Subjective importance is generally not modeled directly in current interview methods. To address this deficiency, the following has been proposed (Otto, 1995). In the fourth column, the customer's subjective need importance is interpreted linguistically using five ordered ratings,

MUST,
GOOD,
SHOULD, (Eq 1)
NICE,
NOT.

A *MUST* is used when a customer absolutely must have this feature, generally when it is the determining criteria in purchasing the product. *MUST* ratings will act as constraints. The *NOT* rating is for needs that the customer expressed only because it was observed that the product could do it, but that the customer also never use and do not care about. Note that more rating levels can be used for a more refined resolution, depending on the subjects' abilities.

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.

To carry out this compilation, the design team should copy each interpreted need onto an index card, as shown in Fig. 4. 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. 5.

Rather than have the design team conduct the sorting, an alternative approach is to have a few customers carry out this activity. This prevents the customer data from being biased by the development team. A common approach is to provide each customer sorter with a small index card stack that each sorts as above. Next, a matrix is created with each interpreted need statement down each row and column. The matrix is filled by each entry (i,j) containing the number of times interpreted need i appears in a stack with interpreted need j. With this filled matrix, a statistical hierarchical cluster analysis is performed, thereby converting the matrix into a tree structure, where each interpreted need statement is arranged next to interpreted need statements or clusters that are “closest.” The development team then parses the tree into a two or three level structure with exemplar labels for the branches. Urban and Hauser (1993) provide details, but basically this approach is believed a more complete way to parse the need statements, though more costly.

Customer Need Importance

Having represented the actual customer needs, numerical importance rankings must be established. A design team should take care, however, as the typical customer population will be multi-modal, with segments that have different importance weightings. Multi-modal populations present systems-level choices on the product option variety to offer. Architecting a product family to meet such demands remains active research (Ulrich 1995; Fisher *et al*. 1995).

A traditional approach to forming customer importance ratings is to first compare the number of subjects who mention a need to the total number of subjects, using the original small set of customers with no further questionnaire activity. For example,

$$\omega_{CR_i} = \frac{\#\,\text{times mentioned}}{\#\,\text{subjects}} \quad \text{(Eq 2)}$$

where ω_{CR_i} is the ith interpreted customer need importance rank. This ranking is flawed, as it includes a measure of need obviousness, as opposed to need importance. A need may not be important but may be very obvious, and so every subject mentions it. Because of this concern, the design team typically reviews the different statements in column 2 of the customer response sheets (Fig. 4) to raise and lower the result from (Eq 2). This approach is less than quantitative, takes excessive time, and is hard to justify.

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.

We believe, however, that any statistical importance determination must incorporate two phases. First, a decision must be made as to whether the customer need is a *hard constraint* that must be satisfied, or an *objective* that can be traded off versus the other customer needs, and so carries a degree of relative importance. The former must be separated from the latter and accounted for differently by the design team. The latter can then be profitably modeled with importance weightings (or more generally preferences or utilities) in a second phase. To separate out any customer needs that are hard constraints that must be met, each need is examined one at a time, and the number of *MUST* responses compared to the total number of subjects. Clearly, if every subject flags the need as a *MUST*, than that need must be satisfied. But if only a fraction of the subjects indicate the product must satisfy a need, a decision must be made over what fraction should be used before interpreting the customer need as a constraint.

To answer this question, statistical outlier analysis (John, 1990) can be applied to determine when a "few" *MUST*s are outlier responses not worth flagging. We define a *MUST-confidence percentage level* C_{MUST} as the desired customer response percentage about the median needed to switch the customer need from an objective to a constraint. C_{MUST} is bounded between zero and one. Note that though C_{MUST} is a confidence percentage level, the approach here does *not* presume normally distributed data. Confidence intervals have not been mentioned, only confidence percentages. Often engineers feel comfortable with $C_{\mathrm{MUST}} = 0.999$, corresponding to 3 confidence intervals when operating with normally distributed data. Such a value of C_{MUST} is excessive here, as it can create a very constrained design space for the design team. It will force many customer needs to carries infinite importance as *MUST*s.

To establish an explicit method for establishing whether a customer need is a constraint or not, consider tabulating the importance responses into categories from (Eq 1). One can calculate the subject number needed to provide *MUST* responses to cause the customer need to be flagged as a *MUST*. This approach can be implemented as test for a need to be flagged a *MUST* by

$$(1 - C_{\mathrm{MUST}})(N-1) < N_{\mathrm{MUST}\,i} \qquad \text{(Eq 3)}$$

where N is the total number of subjects, and $N_{\mathrm{MUST}i}$ is the subject count who provided a *MUST* response on the ith need. If $N_{\mathrm{MUST}i}$ is less than the left hand side of (Eq 3), then the need becomes a constraint with a *MUST* importance rating. This test proves very simple to implement and use.

Having separated the customer needs into *MUST* and non-*MUST* categories, relative importance ratings can now be placed on the non-*MUST* needs in the traditional way. As one approach, first convert the subjective importance ratings into numerical equivalents. A typical transformation used is

$$\begin{array}{lc} \text{MUST} & 9 \\ \text{GOOD} & 7 \\ \text{SHOULD} & 5 \\ \text{NICE} & 3 \\ \text{not mentioned} & 0 \end{array} \quad \text{or} \quad \begin{array}{lc} \text{MUST} & 1.0 \\ \text{GOOD} & 0.7 \\ \text{SHOULD} & 0.5 \\ \text{NICE} & 0.3 \\ \text{not mentioned} & 0.0 \end{array} \qquad \text{(Eq 4)}$$

This mapping is always a subjective interpretation-conversion that a design team must agree upon to convert linguistic customer expressions into numbers. This subjectivity is a customer modeling issue that will always arise with any approach. Once the mapping (Eq 4) is established, the importance assigned to each customer need can be calculated by the average

$$\omega_{CR_i} = \frac{\sum_j \omega_{CR_i,j}}{\#\text{subjects}} \qquad \text{(Eq 5)}$$

where $\omega_{CR_i,j}$ is the numerical importance rating for the ith need assigned by the jth customer using (Eq 4). The result of (Eq 5) can be linearly scaled to any other numerical range desired and the information contained will remain unchanged. The variance of (Eq 5) 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 needs were gathered as shown in Fig. 6.

Other methods for determining importance are detailed by Urban and Hauser (1993). These include an anchored measure approach, whereby the customer respondent first determines the most important need, which is assigned a "10." Then each lower importance need is ranked relative to that need. Another approach is to maintain a constant sum, say "100", to which the respondent must force the importance ranks' sum to equal. This method can work in small needs sets, but can become confusing and suffer from the customer not accurately ranking low priority needs, especially in hierarchical need structures. Some believe all of these direct approaches suffer from scaling problems: the customers think they know what they want, but they do not purchase accordingly. Therefore, a revealed preference approach is advocated, where the design team describes different product features as numbers, then asks for purchasing preferences on entire products (not features), and then regression fits importance coefficients from the products to the features. Hauser and Griffin (1993) report poor results with the revealed preference approach.

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. 3, 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 activities are transcribed onto index cards and combined into a network *Activity Diagram* using another affinity exercise, as shown in Fig. 7. The number of cards for each activity can indicate how typical each is, which can be recorded by the line width connecting the activities. The initial and final activity are also highlighted, scoping the customer requirement gathering activity. This can help system-engineer the environment within which the product is used, if that is a topic for a larger scope team.

The important uses of the resulting Activity Diagram are two-fold. First, 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. Incorporating such lifecycle and manufacturing concerns remains an active research area.

The second important result of the exercise is that the activity list creates a useful categorization for the Customer Needs List, Fig. 6. Typically, the customer needs are grouped into more abstract categories based upon the design team or customer interpretation. This is usually arbitrary. Experience has shown that the activities list provides a more meaningful interpreted customer needs grouping. To each activity, the new customer needs introduced in that activity are listed under it, as shown in Fig. 6. This provides a clearer understanding of the customer needs' context, and may help alleviate the need for a customer sort.

Customer Need Summary

The customer need gathering effort is complete, and so must be summarized into a document that the design team can reference. A form for presenting the interpreted needs is given in Fig. 6. Among other items, the header information contains a brief, typical customer description. The customer description should be a very brief target market description. This description should have been given to the product development team from management originally or through the mission statement, but it should also be refined now based upon the customer needs. An example for a fingernail clipper is

Male/Female, age 20-60
Carries clipper on the run
Not in the beauty industry

Basically, the customer description includes the core demographic description applied when selecting customers to interview, and any relevant product particular information. This information is particularly important for segmented customer populations.

When tabulating the customer needs down the chart, again they are listed by activity. The activities are arranged in serial order, with parallel activities ordered by importance. Within each activity group, the customer needs should be similarly arranged. The numerical importance rating for each need should also be included in the second column. Customer needs which are *MUST*s should have this indicated in the second column. The scale (0 to 1, 1 to 10, etc.) and normalization (relative to most important goal, relative to a sum, etc.) should also be indicated on the top of the form, if there is no company standard. (Eq 5) reflects a relative scale as compared to the most important goal.

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. Typically all have *MUST* constraint importances, since indeed they must be met for the product to be legally sold or physically produced. 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.

Section IV. Functional Decomposition: Modeling, Analysis, and Structure

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.

Why Functional Decomposition?

While methods to carry out market studies or to gather customer needs are widely accepted, methods to generate concepts are typically allocated to the whims of the design team. The transition from customer needs to concrete solutions is seen more as an art than a science or method (Dixon, 1995). In fact for many consumer products, our experience has shown a tendency to seek form solutions directly based on the previous experience of the design team members.

With ever shrinking cycle times and budgets, and with ever expanding demands for quality, this approach has a number of limitations. Most notably, the links between customer needs and design concepts are, at best, indirect or implicit. They exist only in the minds of the designers. As such, customer needs are relegated to the criteria for evaluating concepts, not the direct catalysts for generating concepts.

Over the last twenty years, new methods for engineering design have emerged that focus first on mapping customer needs to functional descriptions, or mapping these descriptions to sets of technologies that satisfy the underlying functional requirements (Pahl and Beitz, 1991; Cross, 1994; Ullman, 1992; Hubka, 1984; Ulrich, 1995). When combined, these methods have a number of intrinsic advantages:

- Concentration is on “what” has to be achieved by a new concept or redesign, and not “how” it is to be achieved. By so doing, a component- and form-independent expression of the design task may be achieved to comprehensively search for solutions.
- Creativity is enhanced by the ability to decompose problems and manipulate partial solutions (Ullman, 1992). By first decomposing a design task into its functional elements, solutions to each element are more apparent due to the reduction of complexity and extraneous information.

- Functions or sets of functions may be derived or generated directly from customer needs. These functions define clear boundaries to associate assemblies or subassemblies of the final design solutions. These boundaries provide a basis for allocating resources to concurrent engineering efforts and for seeking modular concepts.
- Functional modeling provides a natural forum for abstracting a design task. Many levels of functional abstractions may be created, from a very high level single function statement to alternative detailed functional statements for a design's subsystems.
- By mapping customer needs first to function and then to form, more solutions may be systematically generated to solve the design problem. "If one generates one idea it will probably be a poor idea; if one generates twenty ideas, one good idea might exist for further development" (Ullman, 1992).
- Needs mapped to function and then to form promote set-based concurrent engineering processes (Sobek and Ward, 1996). Feasible regions of technology may be explicitly defined based on functional requirements, not implicitly. Trade-offs may also be explored in parallel among a wide array of radical and known solutions since a common functional description is driving the design effort directly from the voice of the customer.

Fig. 1 illustrates the role of functional decomposition in conceptual design process. The next section describes a systematic approach for establishing functionality of a new design or redesign. The finger nail clipper provides a running example to clarify the approach.

Establishing Functionality and Product Architecture

The previous section provides us with a clear statement of the customer needs, organized to establish priorities for the design efforts. Functional modeling begins the systematic process of transforming these needs to a clear specification of the design task. It also initiates the conceptual design phase, wherein a breadth of solutions are sought.

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*, as summarized in Fig. 8. To start the function modeling process, an important tool 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; Otto, 1996; Otto and Wood, 1996). Within each phase, we network high-level user activities to show the full lifecycle of a product, from purchase to recycling or disposal. By listing the high-level activities in each phase, a number of product characteristics are chosen, including the product's system boundary, parallel (independent) and sequential paths of functional, process choices, and interactions between user and device functions. These choices are documented by the Activity Diagram, and so can be more fully considered.

To see this, consider Fig. 7, 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. 7 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. Parallel and sequential activities are given by the Activity Diagram structure. Parallel customer activities will likely lead to parallel product or device functions (since they are needed as such by the customer), providing implicit subsystems or assemblies for each parallel path. Besides the system boundary and parallel paths, the Activity Diagram clearly shows a number of choices of what will be the customer process, and clearly that will influence the final design. For example, the activities of "picking" and "filing" are process choices for improving the customer's finger nail appearance through mechanical contact. Chemical "soaking" process choices or others might be chosen as alternatives. They would lead to different activities, functional descriptions, and, ultimately, product architectures and components.

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 (Fig. 8), 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; Hubka, et al. 1988; Ullman, 1993; 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 (Fig. 8).

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. A list of some common energy flows are given in Table 5 (Hundal, 1990; Little, 1997).

Considering the finger nail clipper example, a subset of the customer needs are given as:

Need	Effect	Importance
cost	Not inexpensive	4
compact	Not compact	4
files well	Does not file well	2
cuts well	Does not cut well	must
easy open/close	Not easy open/close	4
easy hold	Not easy to hold	3
comfortable	Not comfortable	3
sharp cutting surface	Not a sharp surface	3

We now translate the customer needs to energy, material, or signal flows of the product when effects are exhibited or are expected to be exhibited during product use. Cost is not something that deals with dynamic use of the product. 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).

To document the mapping of customer needs to flows, a "black-box" model of the product is developed. A black box model lists all input and output flows for the primary, high-level function of the design task, stated in an active verb-noun phrase. Fig. 9 illustrates a black box model for the finger nail clipper task. This model must now be refined and decomposed to identify the basic product or device functions that will satisfy the overall function and needs.

For each of the flows, the next step (Fig. 8) 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. An operation is a specific action by the user needed to complete the function structure, typically a switch selection decision making node. Miles (1972), Hundal (1990), Little (1996), and Ullman (1992) provide lists of appropriate verbs and nouns to use in functional analysis, where Table 6 summarizes typical classes of engineering functions (as defined in Table 7). 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. Through play acting these flows, a subfunction sequence may be of the form: capture force, apply force, transform to larger force, transmit force as motion, guide motion, cut material, stop motion, release force, dampen reaction to force, etc.

Returning to the finger nail design task, Fig. 10 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, e.g., a sub-function of "control motion in 3D" should obviously be refined to control in three rotations and translations since a single, basic form solution in finger nail clipper technology does not provide 3D control. On the other hand, the second criterion assures that time is not wasted refining a function structure to the level of miscellaneous and secondary product components, such as fastening.

For the finger nail clipper design effort, an aggregated function structure is shown in Fig. 11. Notice that subfunctions and flows are combined for overlapping or redundant functionality from Fig. 10. 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. Table 8 lists the pertinent questions, checks, guidelines, and actions implemented at this stage. Second, the customer needs list is reviewed, and the subfunction or sequence of subfunctions are identified that satisfy each customer need. Needs not covered by the function structure require further analysis, and sub-functions 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 following validation for the finger nail clipper task:

Need	Effect	Validation (Applicable Subfunction(s))
cost	Not inexpensive	N/A (Criterion for evaluating design concepts)
compact	Not compact	Apply Finger Force, Form Filing Surface, Form Grasping Surface, Cut Nail
files well	Does not file well	Form Filing Surface, Form Grasping Surface, Orient Surface, Slide Over Nail
cuts well	Does not cut well	Convert to Large Force, Cut Nail
easy open/close	Not easy open/close	Guide to Nail, Move to Cut Nail
easy hold	Not easy to hold	Apply Finger Force, Release Force, Release Motion
comfortable	Not comfortable	Apply Finger Force
sharp cutting surface	Not a sharp surface	Cut Nail

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.

Phase 5 — Establish and Identify Product Architecture and Assemblies

With the functional decomposition verified, it is now important to identify product assemblies that can be addressed by individual designers or cross-functional design teams. The key elements of this phase are to define collection of functions (chunks) that will form assemblies in the product and to clarify the interactions and interfaces between these chunks. By so doing, a product team will have a basis for choosing between *modular* and *integral* architectures (Ulrich and Eppinger, 1995; Cutherell, 1996). They will also have a basis to choose parallel design tasks for the product development, where only the interaction and interface information need be shared continuously among the subteams.

A simple process for establishing the product architecture and assemblies includes the following steps:

- *Using the functional decomposition of a product, cluster the subfunctions or elements in the function structure.* Dashed boxes around the clusters of subfunctions and a title will serve as an appropriate representation. These clusters are chosen by identifying parallel subfunction chains (each parallel track is a candidate cluster), subfunction chains that have common energy types as flows, and subfunction chains that only have simple interactions between each other.

- *Create a rough spatial layout (block diagram with a reference frame) for the product.* This layout is meant to show the relative position of each cluster to understand spatial interactions and clarify interfaces.

- *Define Interactions, Interfaces, and Performance Characteristics between each cluster*. Given that interfaces are the boundaries between clusters, four types of interactions exist as flows across interfaces: spatial (geometry), energy, information, and material interactions. These interactions represent what must be shared across interfaces within the performance requirements.

Fig. 11 shows the application of the first of these steps to the finger nail product. Three primary assemblies are identified: the base, force amplifier, and file. Important interactions include the hand flow of the user, attachments to allow relative motion for opening and closing activities, etc. These assemblies may now be designed relatively independently, if a modular architecture is chosen. Reference (Cutherell, 1996) studies further examples, including spatial layouts. In particular, an HP1200C printer product is studied with respect to its basic architecture.

Summary

Functional decomposition provides an abstract, yet direct, method for translating customer needs to a functional specification of a design task. Fig. 8 illustrates a systematic five phase process for executing a functional decomposition. Using the results of the method, quantitative specifications may be formulated for customer needs, based on the applicable subfunctions. The next sections describe an approach for creating such a quantitative specification, based, in part, on competitive benchmarking. In addition, a designer is tactically situated for generating and then combining concepts for each subfunction (Fig. 1), a far simpler task compared to the complexity and potential enormity of an overall design problem without decomposition.

Section V. Competitive Benchmarking: Know Your Enemy to Know Yourself

To remain competitive, a design team must compare any proposed concept with the competition (Fig. 1). 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.

An overview of an effective benchmarking process is given in Fig. 12. A functional product teardown is far more than disassembly of a product to see how it is put together. One must analyze the systems, and transform this analysis into information which can be used as a part of the new concept, configuration, or redesign. (Note: Benchmarking is a dynamic activity. It may be more appropriate to benchmark products before customer needs analysis and functional decomposition. Alternatively, a team may not wish to bias these initial analyses, but update the results with the benchmarking data.)

Related Work

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 Competitive or 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,
- the targeted market segments.

All keywords associated with these three categories should be formed from Step 2 (Fig. 12), and used in informational searches.

Sources of information are varied and as common as the library. Most business persons are perfectly happy to discuss the market and non-competitive business units. Though most will not provide strategic information about their own companies, many people are happy to tell all about their competitors. Suppliers will usually discuss their customers, if it appears you might provide an additional sale. The key is to always be open and honest about your questioning for information. Once people understand you are designing or redesigning a new product, they naturally want to get involved with new orders, and will help you up to the point they legally can. Pursuit of information beyond that point is unethical, and not necessary. Most people are happy to share information, and so simple honesty and a friendly attitude can get you a long way.

Public sources of information include the library and electronic wire services. University libraries are filled with technical engineering modeling references. Also, librarians have expertise in uncovering obtuse references with limited initial information. Particular references of interest include:

- Thomas Register of Companies. This is a "yellow pages" for manufacturing related businesses. The Thomas Register lists vendors by product.
- Market Share Reporter. Published every year by International Thomson Publishers, this book summarizes the market research of Gale Research Inc. It comprises market research reports from the periodicals literature. It includes corporate market shares, institutional shares (not-for-profits), and brand market shares.
- U.S. Dept. of Commerce and NIST. This U.S. government branch provides, among other things, national labor rates for all major countries. This proves very useful for determining competitors' manufacturing costs.

As another source, professional market survey companies now provide their results in on-line databases (World Wide Web) that can be searched using keywords, for a small fee. In the U.S., these include:

- Lexis/Nexis. These two databases are the most comprehensive full text on-line news and business information source. Lexis provides legal information, and Nexis focuses upon business. Both comprise a database that provides abstracts and full text from public news sources including newspapers, magazines, wire services, newsletters, journals, company and industry analyst reports, and broadcast transcripts.
- Dialog Information Services Databases. Dialog is the world's largest on-line information research service containing millions of documents. These include databases with simple abstracts as well as the full article text. For the most part, the articles come from business journals and include information on company histories, competitive intelligence, new product development efforts, sales and earnings forecasts, market share projections, R&D expenditures, financial activities, demographics, socio-economic activities, government regulations, and events that impact the business environment.

There are other sources of information about competitive products. Most major manufacturers have a presence on the world wide web. Much information can be gathered simply and at no cost, particularly technical information. Material properties of industrial brand plastics and metals, for example, are easily found. This resource will only grow, and topical search engines are readily available.

After examining trade journals and uncovering which competitors have bragged about new innovations, gathering the patents on these new innovations also explains much. Patent searches based upon company names are difficult, however, since typically companies "bury" their patents by filing under the individual names of designers. Uncovering the individual patents is usually by refined topical searches. Therefore absolutely as much information as possible should be supplied to the person searching the patents.

Vendors of OEM components also are a valuable source of information. Cost quotes using the competition's ordering quantities is effective at uncovering OEM part costs. Usually one can also obtain unsolicited information about the competition. Persons in the industry can provide good pointers on non-obvious cost, technical, and market drivers. Particular overseas labor rates, shipping rates, reliability of supply from geographic areas, etc., are all "inside knowledge" that might be uncovered from other public sources only when one knows what to look for. University faculty specializing in a technical area that is exercised by the product can also provide invaluable assistance in design, or simply as consultants to participate as design reviewers. All of these and other sources must be leveraged to determine as much as possible about what customers want, what competitors are supplying, and what the dynamics of the market are.

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 measurements
- Maximum, minimum, and average material thicknesses
- Weight
- Material
- Color/Finish
- Manufacturing process, including sufficient information for a Design for Manufacturing analysis
- Primary function
- Other notes

Next, one should identify all tools that will be required to complete teardown. Also, identify all sensors and test equipment required. Camera? Videotape (of product operating)? Multi-meter? Hardness tester? Optical sensor? Flow meter? etc. Typically, one documents this information into a written or electronic report, similar to professional laboratory experiments.

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

Disassembly is the obvious step commonly pictured when thinking of reverse engineering. However, to be effective, this must be coordinated with measurements. First, take pictures and measurements on the whole assembly before disassembly. Then,

- Take apart the assembly.
- Take pictures in an exploded view.
- Take measurements on the parts and assemblies to complete the data sheets.

Form a Bill of Materials

Complete a written form which details the product. A good format is shown in Fig. 13, where each column consists of the data analysis criteria of Step 5 (Fig. 12). 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. This process should include:

- Categorization of the market
- Categorization of Technical solutions
- Benchmarking of Technical solutions
- Benchmarking of competitors

The market categorization is typically by socio-economic status and percentage of the market.

The technical solution categorization is more difficult, and should be categorized by the function structure modeling. This often poses difficulty, however, since the competitors may include functionality you choose not to. The function structure modeling could be completed for all of the competitive products, and provide a means to list all known technical solutions to particular sub-functions.

The benchmarking of technical solutions and companies is more readily completed, but requires a time history of product measurements. All technological innovations manifest themselves into the market along an “s-curve” timeline behavior, as shown in Fig. 14. That is, consider examining any important product metric, for example, clock speed for microprocessors. For all of the different products (microprocessors) in the market, one can plot each product’s metric value (clock speed) 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.

Section VI. Forming Quantitative Specifications: Quantitative Consensus

Introduction

Having established the function structure/architecture and understood competitive product performance (Fig. 1), 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.

Related Work

Approaches taken to forming specifications most often include Total Quality Management methods (Ishikawa, 1992, Clausing, 1994, Shiba, 1995), and in particular Quality Function Deployment (Akao, 1990) and the House of Quality (Hauser and Clausing, 1988). 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 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?

Many researchers and practicing engineers have developed methods for forming specifications. Ulrich and Eppinger (1995) provide an excellent chapter where they discuss forming product specifications and using the House of Quality. Hauser and Clausing (1988) also provide a popular article on the House of Quality. Akao (1990) provides a text on Quality Function Deployment complete with case studies. Alternatively, Urban and Hauser (1993) also present several methods for selecting among different variables to find those which make most sense to use for specifications. Yet, in all of these methods, the approach for generating variables on which to make specifications is simply to be creative. We review here methods to generate and track specification variables.

Specifications

First, what is meant by an engineering *specification* must be precisely established. Typical definitions state that a specification is a dependent evaluation including both a *metric* and a *value* (Ulrich and Eppinger, 1995). A metric is the quantity of discussion. The value is a target for the metric, and can be a particular number, a range, or an inequality.

These statements clearly have meaning when operating with numerically real-valued metrics. It is not the case that all specifications must be real-valued, however. A specification can be generated using a collection of colors, smells, or other sets of elements that are hard to quantify. In general, every specification that is made will always have an associated informal subjective interpretation by each design team member. All design team members interpret the metric target values into a subjective connotative meaning from past experience.

To be valid, a specification must have the following three characteristics that all team members implicitly or explicitly agree upon. The specification must come from a set of possible different elements (or values), and these elements must collectively be *comprehensive* and *measurable*. A set is comprehensive if, by knowing the value, the extent of achievement of the associated informal reason for setting the specification can be interpreted by members of the design team. For example, if a numerical specification of "20" for machinability is not agreed upon or understood by the design team, it is not a good specification of machinability. The specification must be grounded with understood points (Otto, 1995), such as associating "50" with 1020 steel.

A specification must also be measurable. Formal definitions of measurability exist (Otto, 1995), but essentially the design team must be able to at least partially order the set of values, otherwise the set is no more formal than a person's subjective connotations. It must be understood that "30" is better than or equal to "20", for example. This is not an issue with quantitative numbers, but is with non-numeric datasets.

Identifying Specification Metrics

To establish an initial set of engineering specifications, a design team should begin by listing each subfunction. Then to each subfunction, a relevant product subsystem (either architectural assembly or physical subsystem of a redesign) 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. 15, 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 need importance ratings to establish importance ratings on the individual specifications.

The first step is to create the mapping from the customer needs to the specifications. In a typical House of Quality manner, the relationships are captured by a set of symbols:

$$(\odot, \mathrm{O}, \Delta, \text{' '}). \qquad \text{(Eq 6)}$$

There is always a question concerning how to make these assignments. In this development, the problem is more complex with the additional *MUST* constraints. When some of the customer needs have *MUST* ratings and others do not, how should these be propagated through symbols (Eq 6) onto a importance rating for any particular specification?

To answer this question, the following interpretation is proposed when making causality assignments to relate the customer needs to the specifications. One considers each specification one at a time, and then for a given specification considers each customer need. One assigns a ⊙, O, or Δ based upon the following subjective rules:

⊙ indicates that attaining the target on this one specification will totally cover the customer need,

O indicates that attaining this specification will cause at least half satisfaction of the customer need, (Eq 7)

Δ indicates that attaining the target on this specification will cause less than half satisfaction of the customer need,

' ' A blank indicates that attaining the target on this specification will do nothing towards causing satisfaction of the customer need.

This interpretation of the assignments creates least misunderstanding. The linguistic values of "half" and "nothing" used define both the subjective weighting criteria and the level of resolution that the design team must take care to agree upon. Doing so establishes the mapping (Eq 7).

The next step is to map the *MUST* importance ratings on the customer needs into *MUST* importance assignments on the specifications. The specifications with *MUST* ratings then act as functional constraints for the design team — they must be met.

It is not immediately clear what an appropriate overall algebra is for mapping the customer importance ratings (Eq 3) and (Eq 5) through the causality assignments (Eq 7) into importance ratings on the specifications. In particular, the means to combine *MUST* and non-*MUST* importances is not obvious. On the other hand, it is clear that if a *MUST* customer need has a ⊙ relationship with a specification using (Eq 7), then that specification deserves a *MUST* rating. Also, for the remaining specifications that map from that covered *MUST* customer need, the *MUST* on that covered customer need is not required to be treated as a *MUST*, since it is "covered" with a specification. That covered customer need can be assigned the highest numerical importance rating in (Eq 5) for use in determining the remaining non-*MUST* specification importances.

Given these insights, experience shows that the best approach is to insist that every customer need *MUST* constraint have at least one $\odot$ entry in its mappings to the specifications. Then that specification can serve as a direct proxy measurement for the *MUST* customer need.

If there is no such specification that can directly $\odot$-map the *MUST* customer need constraint, it is an indication to the design team that the specification list needs re-examination. If the condition persists, the team must agree upon the set of specifications that predominantly map to the customer need constraint. All of these specification must then be assigned *MUST* importance ratings. An excessive number of *MUST* assignments, though, places excessive demands of a design team.

Once the specifications that act as constraints are identified, the subsequent specifications can be assigned numerical importance ratings. This process is usually a simple exercise of multiplication and addition. The causality values (Eq 7) are given numerical equivalents, typically

$$\begin{array}{c} \odot = 9 \\ \mathrm{O} = 5 \\ \Delta = 3 \\ '\ ' = 0 \end{array} \quad \text{or} \quad \begin{array}{c} \odot = 1.0 \\ \mathrm{O} = 0.5 \\ \Delta = 0.3 \\ '\ ' = 0.0 \end{array} . \qquad \text{(Eq 8)}$$

Any *MUST* customer needs are assigned the maximum importance value, typically 5 out of 5 or 1.0 out of 1.0. Then the numerical importance of each specification is determined through a weighted sum across the needs

$$\omega_i = \sum_j T_{ij}\,\omega_{CRj} \;,$$

where T_{ij} is given by (Eq 8). The results can then be linearly normalized to any selected scale.

The results for the finger nail clipper are shown and summarized in Fig. 16, the House of Quality matrix for the clipper. Note the propagation of the *MUST* importance assignments onto the engineering specifications. These can now be readily modeled into hard constraints for the design team. The other numerically rated specifications become objectives that can be traded off in design decision making, with importance as indicated.

Section VII. Preview — Generating Design Configurations and Form Concepts

Fig. 16 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 (Fig. 1). 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. 16. Subsequent chapters/articles in this handbook document detailed methods for executing these tasks. As a preview, however, let's consider the finger nail example, and generate solutions that may be derived as a direct consequence of our systematic approach.

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. 11) as possible, (2) qualitatively prune the number of solution principles using the criteria of Fig. 16, (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. 17 and 18 illustrate a subset of the results from this four-step process. The morphological matrix contained in Fig. 17 shows a breadth of form solutions to the decomposed functions. In turn, Fig. 18 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. 19 confirms this statement. A number of current finger nail clippers are shown in the figure. The concept generation, summarized in part by Figs. 17 and 18, covers these product ideas at a fundamental functional level. In fact, the "molded scissors" concept does not currently exist on the market, a potential product evolution following the business case of Table 4.

Section VIII. Product Applications

Fig. 1 illustrates, at a high level, the entire product development process. The finger nail clipper design task is used throughout this chapter to focus attention on conceptual and configuration design. As such, it provides a broad list of customer needs and functional issues, while maintaining a level of familiarity and simplicity.

Building upon this example, this section presents two brief product applications. The first application, referred to as "batter up," concentrates on original design (Faulkner, *et al.*, 1995). It carves out a new market, initiating the first data point on an s-curve innovation. Alternatively, the second alternative, an electric wok consumer product, represents a redesign task, wherein a market is already established. The focus of this example is to create a conceptual framework for product evolution and improvement.

Batter Up! Application

Leisure and recreation are vital for people's physical and mental health. "Evidence indicates that what an individual does during leisure time significantly affects illness, disease, and even longevity" (Wankel, 1994, p. 29). Persons with disabilities in primary and secondary education need recreational opportunities and skills as part of their educational development so they can carry skills into adulthood and into life in their communities (Auxter, 1993). This general need leads to the mission statement "to design a device and/or process that will enhance the recreational activities of students with severe mental and physical disabilities."

After initial clarification and high-level customer interviews at Rosedale School in the Austin Independent School District (Faulkner, *et al.*, 1995), the mission statement is refined to "the design of a product that would enhance tee ball for the students, while maintaining their integration in the community." The primary market for the device is educational institutions as an assistive technology. Initial business case analysis demands that the product cost less than $100 as a one-off device produced by the institutions.

Customer needs analysis (10 customers) for this application gives the results shown in Table 9. The final product must adapt for changing skill levels for educational development, and it must guide the bat to consistently hit the ball, providing the primary function for integrating the students into community activities. Beyond these "musts," critical needs for a successful product include the ability to adjust the height of the ball for persons in wheel chairs and persons of various sizes, assure that the student uses the device independently (not hand-over-hand), provide auditory stimulation for cause-effect learning, and reduce the size for storage and transportation (separation of function in time and space). It must also be "Easy to build/duplicate" since the institutions will be fabricating the device themselves.

Through the specification of a process description and task listing of these customer needs, the black box model and refined function structure are shown in Fig. 20. The system boundary for this functional analysis includes only the operational phase tee ball. Notice in the function structure the convergence of both an external energy source and the human energy from the user. These energy flows, in addition to guidance functions, provide the primary means of satisfying the operational needs of students with disabilities.

A House-of-Quality for the "Batter Up!" includes measurements of the volume, mass, and number of piece parts. In addition, the length of bat grips, operating noise, range of bat height, range of handle movement, and range of bat speeds provide a quantified specification of the functions in Fig. 20.

This specification leads to concept generation of a tee ball assistive technology. Table 10 shows a partial morphological analysis of the main functions in the function structure. Solution principles are listed discursively according to energy domain. A wide variety of mechanical and electro-mechanical solutions are shown for the application, especially for the external energy source. These solution principles lead to a number of concept variants. Fig. 21 illustrates the selected concept. This concept, based on a pneumatic energy source and a guide line, was produced from basic hardware supplies to satisfy the fabrication requirements of wood shops in secondary school systems. After prototype testing, this successful concept was installed in the Austin Independent School District as a regular recreational activity.

Electric Wok Application

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 conveniently cook authentic Chinese food (Pan and Otto, 1995; Otto and Wood, 1996). The original product is a six quart Electric Wok, shown in Fig. 22.

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.

Important customer needs, gathered and organized using interviews and importance ratings, 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. Table 11 provides the list of customer needs and priorities, including background information that supports this list.

Task listing is applied to the customer needs and activities listed in Table 11. An example of the flow of electric energy, related to the cooking and temperature control activities and needs, is illustrated in Fig. 23. The resulting function chain for each of the customer needs leads to the aggregated function structure and black box model shown in Fig. 24. In turn, an analysis of the subfunctions leads to the quantified specification shown in Fig. 25. This specification and functional modeling provides the basis for concept generation, concept selection, design modeling and analysis, and design-of-experiments prototyping (these topics are covered in subsequent chapters).

Table 12 shows a partial morphological matrix for the electric wok redesign. Solution principles are listed for the critical subfunctions from the customer needs analysis. Through combinations of principles, concept selection, and design analysis, this matrix leads to the alpha prototype shown in Fig. 26. The final alpha prototype for the redesigned wok 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.*

Section IX. Closure: The Conceptual and Configuration Design Process

Product concepts begin and end with the customer. A concise and quantified specification is an essential 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. Later chapters continue this theme with conceptual design of parts and creativity.

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, documenting all decisions for subsequent redesign. In our opinion, conceptual design skills can be learned and fostered with structured methods. We encourage the reader to seriously formulate their systematic methodology, similar to those presented in this handbook. We predict that the rewards of doing so will be endless and dramatic, overcoming the psychological and bureaucratic inertia that tends to infiltrate our business lives.

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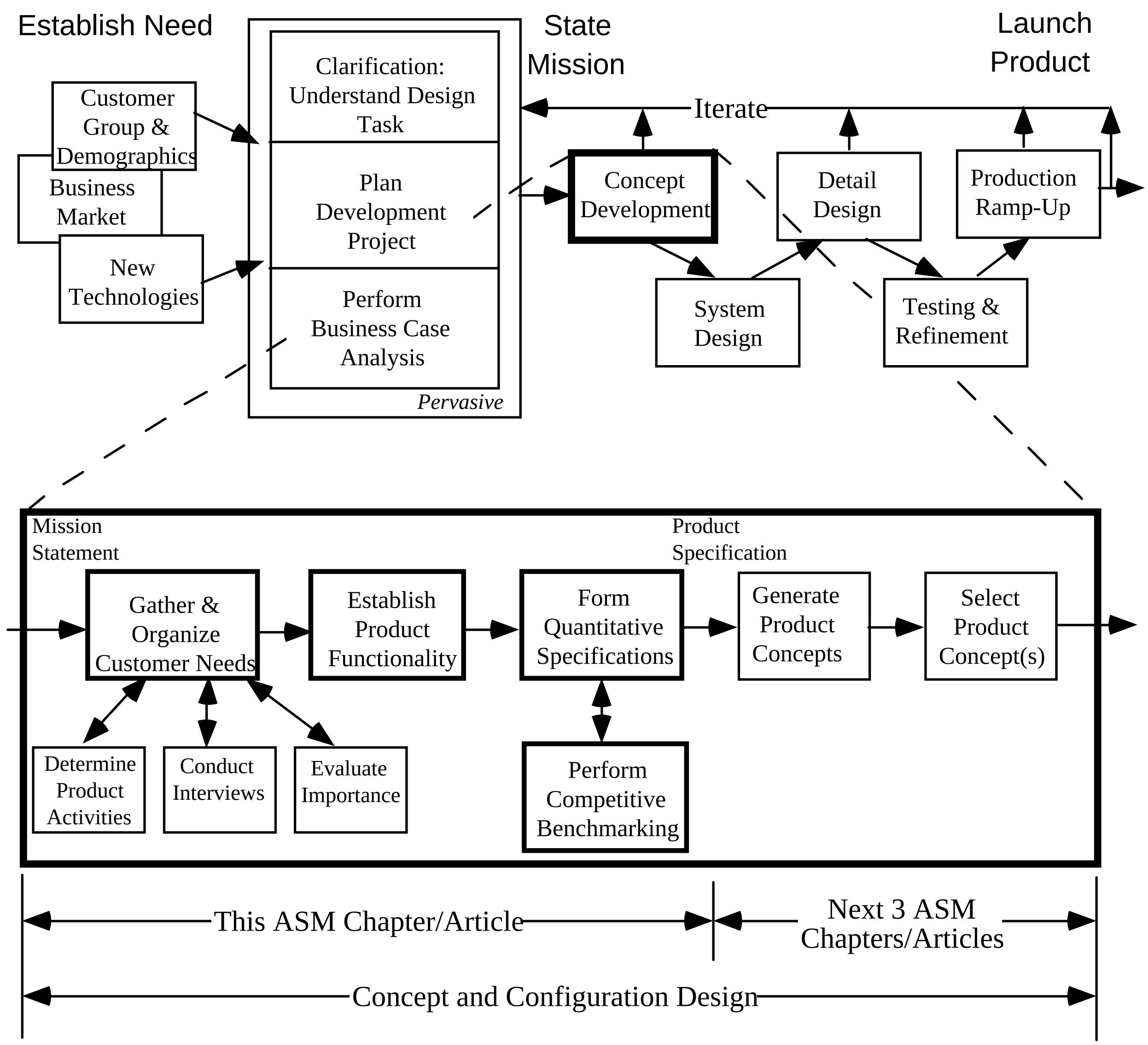

Fig. 1. The Concept and Configuration Development Process.

Mission Statement: XXXX Product	
Product Description	one concise and focused sentence
Key Business or Humanitarian Goals	• schedule • gross margin/profit or break-even point • market share • advancement of human needs
Primary Market	• brief phrase of market sector/group
Secondary Market	• list of secondary markets, currently or perceived
Assumptions	• key assumptions or uncontrolled factors, to be confirmed by customer(s)
Stakeholders	• 1-5 word statements of customer sets
Avenues for Creative Design	• identify key areas for innovation
Scope Limitations	• list of limitations that will reign back the design team from "solving the world"

Fig. 2. Mission statement template.

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

Fig. 4: Recording a customer need.

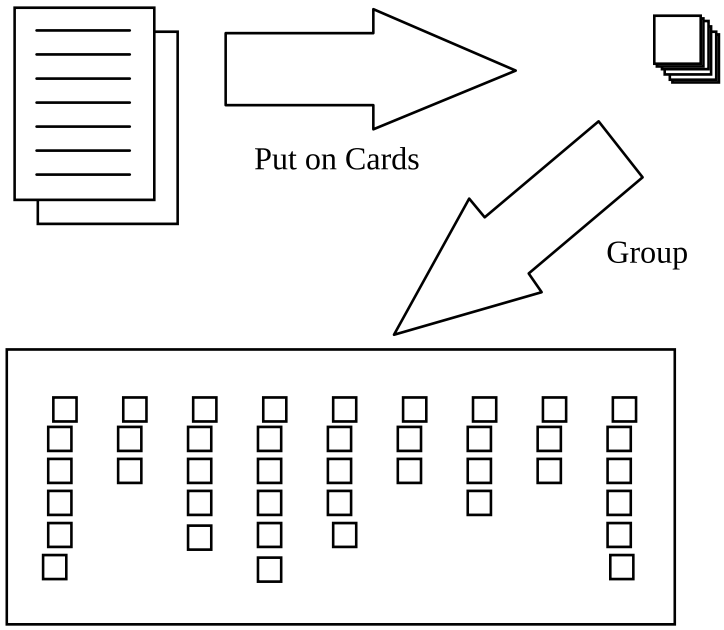

Fig. 5: Converting the set of interpreted needs into a customer needs list.

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. 6: Partial Customer Needs List.

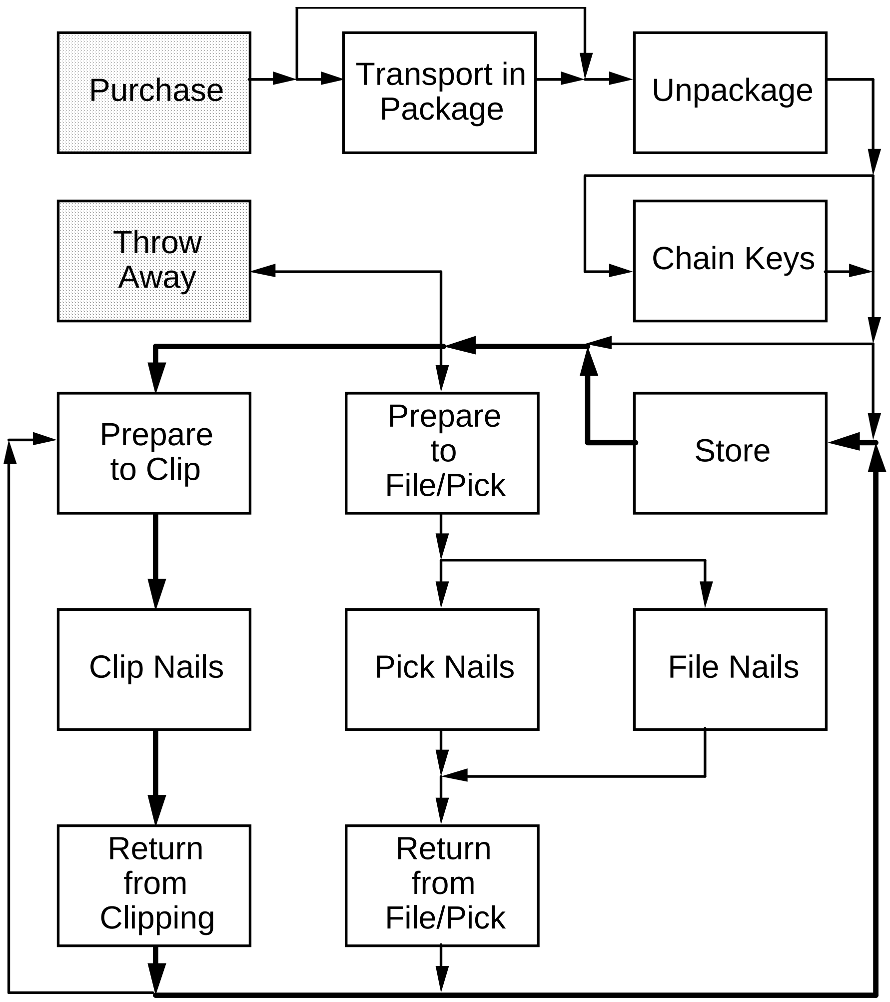

Fig. 7: Completed activity diagram for the finger nail clipper.

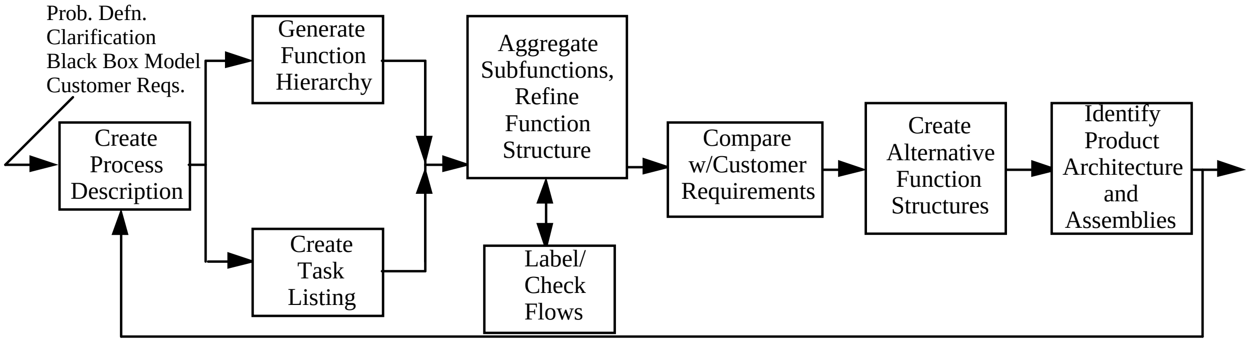

Fig. 8. Function modeling and analysis process.

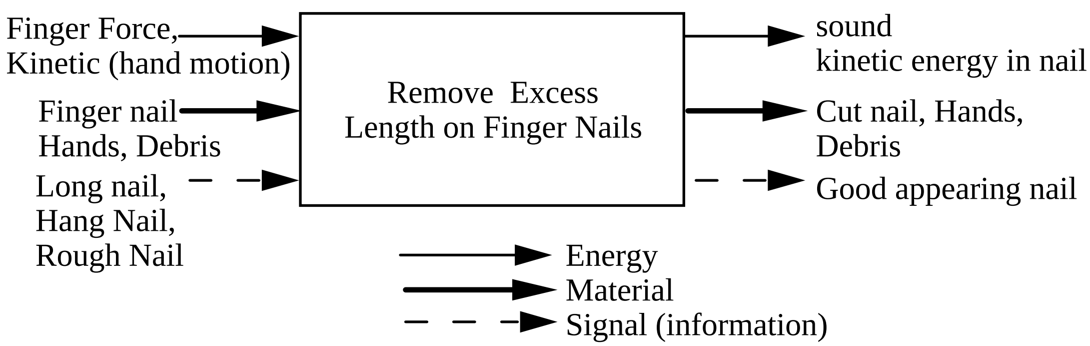

Fig. 9. Black box model of the finger nail clipper design task.

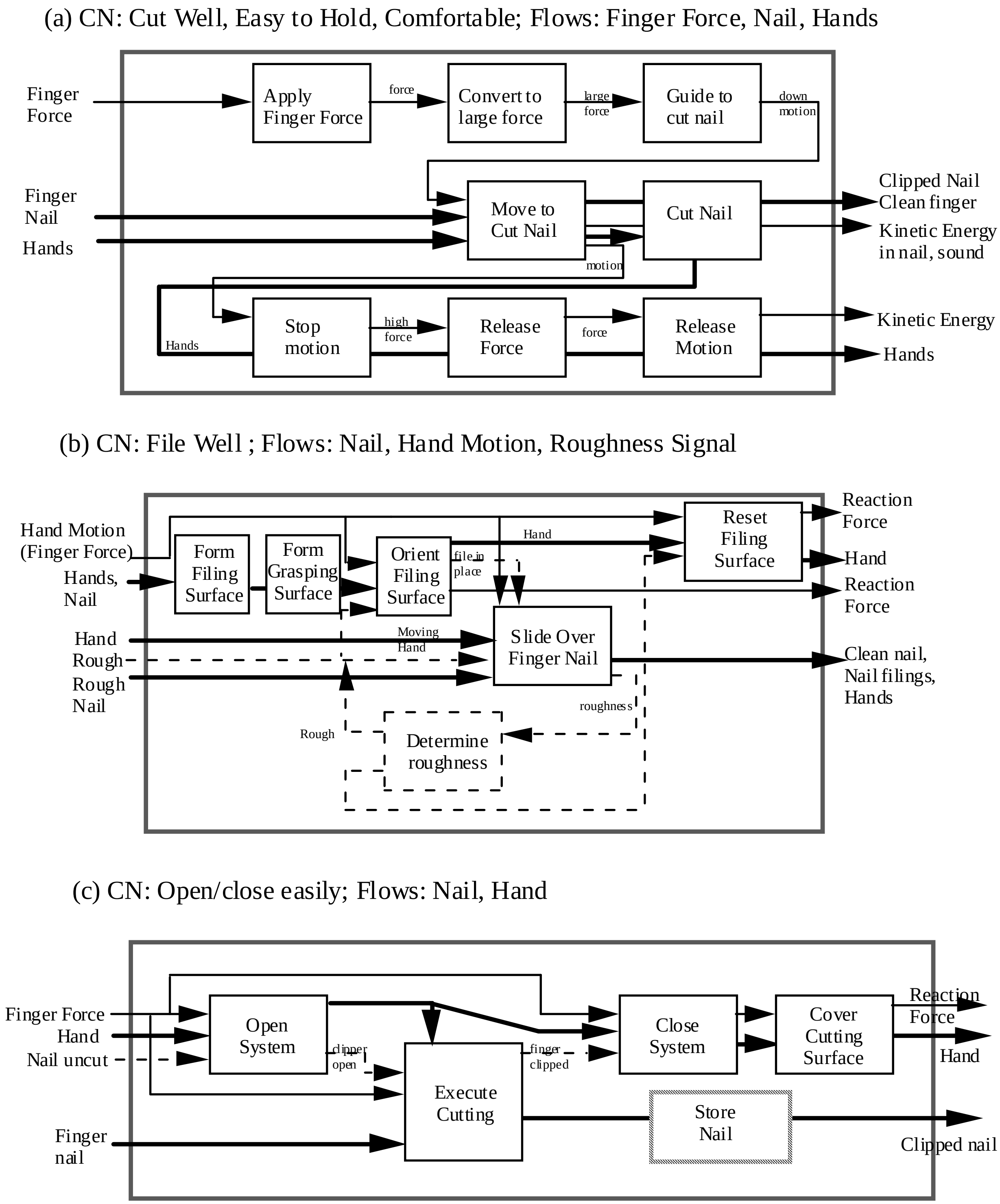

Fig. 10. Finger Nail Clipper Task Listing for Each Customer Need.

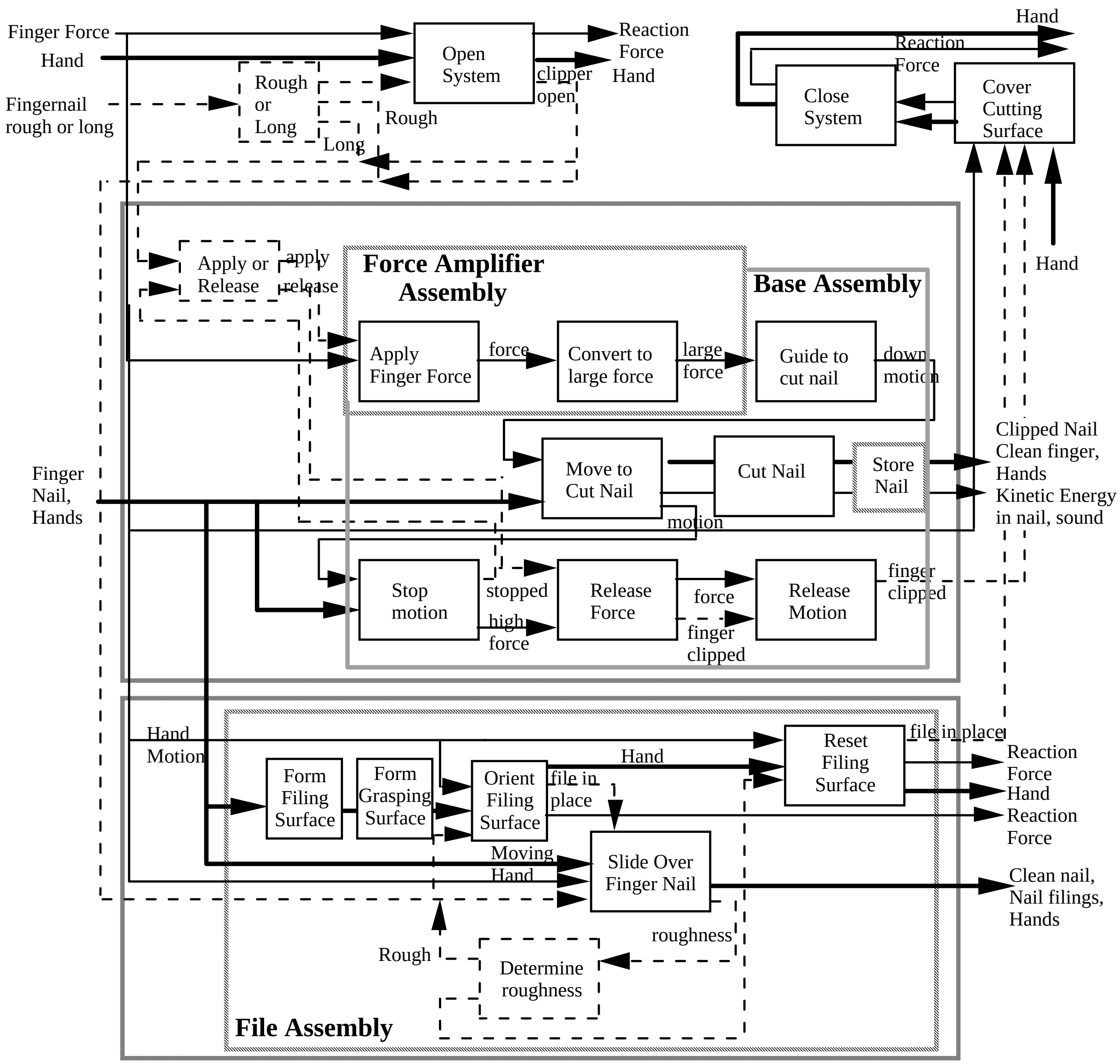

Fig. 11. Refined function structure for the finger nail clipper design task.

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. 13. Reverse Engineering Bill-of-Materials.

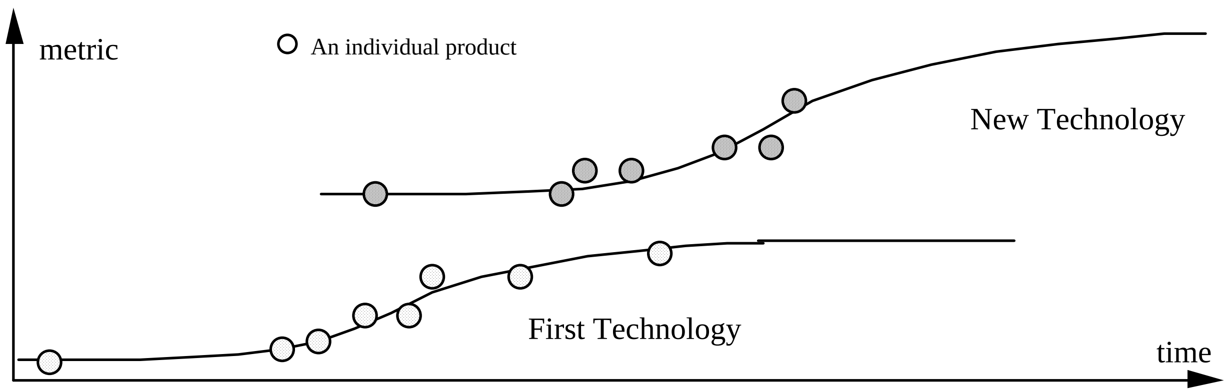

Fig. 14. Technological innovations plot as S-curves.

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

	Purchase	- Cost	Transport in package	Unpackage	Chain Keys	- Act as keychain	Store	- Compact storage	- Non-snag storage	- Lightweight	- Striking appearance	Prepare to File/Pick	- Easy to open file	Filing	- Files nails	- File rough	Return from Filing/Picking	- Easy to close file	Prepare for clipping	- Easy to open clipper	Clip nails	- Easy to align clipper	- Easy to hold clipper	- Body contoured to hold	- Curved blade shape	- Wide handle	- Low squeeze force	- Blade can act as pusher	- Blade can act as a file	- clips nails	- clips toe nails	- clips hang nails	- sharp blade	- Nails fall predictably	- Stores cut nails	- Easy to clean	Return from clipping	- Easy to close clipper	Throw away
		4				0		4	1	2	3		2		2	1		2		4		2	3	3	3	2	1	1	1	must	1	1	1	1	1	0		4	
Material Cost		⊙																																					
Weight										⊙																													
Keychain						⊙																																	
Material Finish											⊙																												
- Closed arm force									⊙																													2	
Close System																																							
- Closed blade opening width								2	⊙																														
Cover Cutting Surface																																							
Determine Roughness																																							
- Closed alignment force									O				O					O																					
Reset Filing Surface																																							
- File roughness, Right to Left															O	O													O										
- File roughness, Left to Right															⊙	⊙													⊙										
- Filing surface area								2							O														O										
Slide Over Finger Nail																																							
- Filed nail visibility																													O										
Orient Filing Surface																																							
- Grip surface friction																																							
- Grip area								2																															
Form Grasping Surface																																							
- Open alignment force													O					O																					
- Finger pushing area								2					O					O																					
- Finger opening friction													O					O																					
- Finger opening surface area								2					O					O																					
- Opening friction torque													⊙					⊙																					
Form Filing Surface																																							
Release Motion																																							
- Expansion force																																							
Release Force																																							
- Stop compliance										2																													
- Click sound																																							
Stop Motion																																							
- Storage volume								⊙																															
Store Nail																																			⊙				
- Flatness		2																																					
- Finger squeeze area																										⊙													
- Hardness		O								2																				O	O								
- Sharpness		2																												⊙	⊙		⊙						
Cut Nail																																							
- Open blade opening width																						O														⊙			
Move to Cut Nail																																							
- Blade curvature											2											O														O			
- Blade visibility																						O						⊙						⊙					
Guide to Cut Nail																																							
- Motion reduction								2																															
- Force gain										2																	⊙			O	O								
Convert to Large Force																																							
- Fingerpoint cupness											2													⊙															
- Fingerpoint surface friction																							O																
Apply Finger Force																																							
Apply or Release																																							
Rough or Long																																							
- Opening surface friction																				O																		O	
- Opening grip area								2												O																		O	
- Opening gap																				O																		O	
- Opening force																				⊙																		⊙	
Open System																																							

Fig. 16. House of Quality for the finger nail clipper.

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

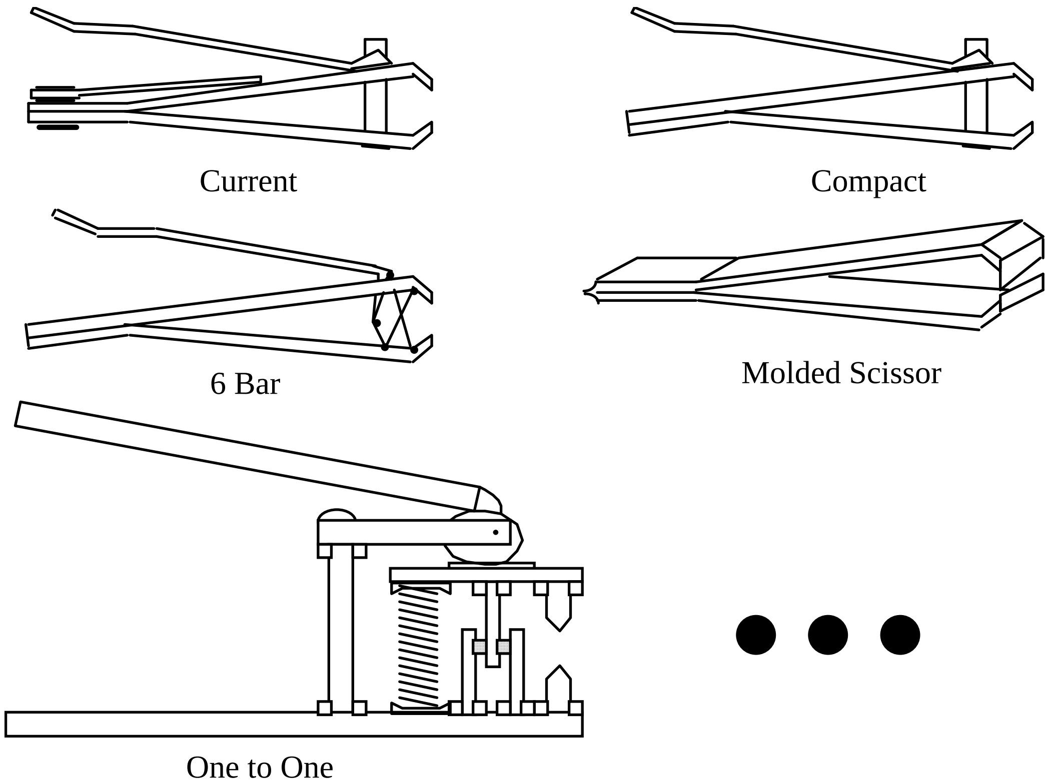

Fig. 18. Example concept variants (subset) for the finger nail clipper design.

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

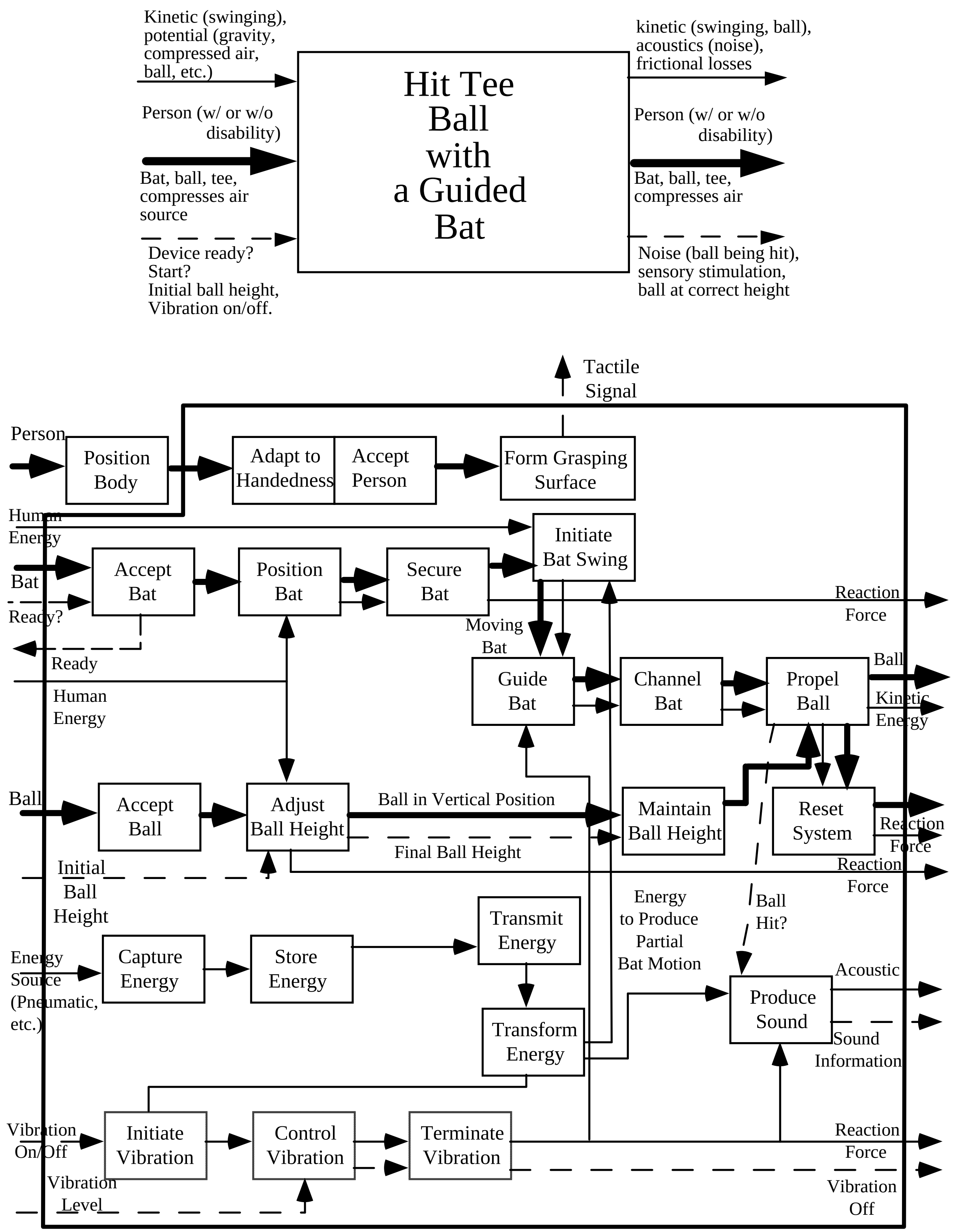

Fig. 20. Black box model and refined function structure — Batter Up! Application.

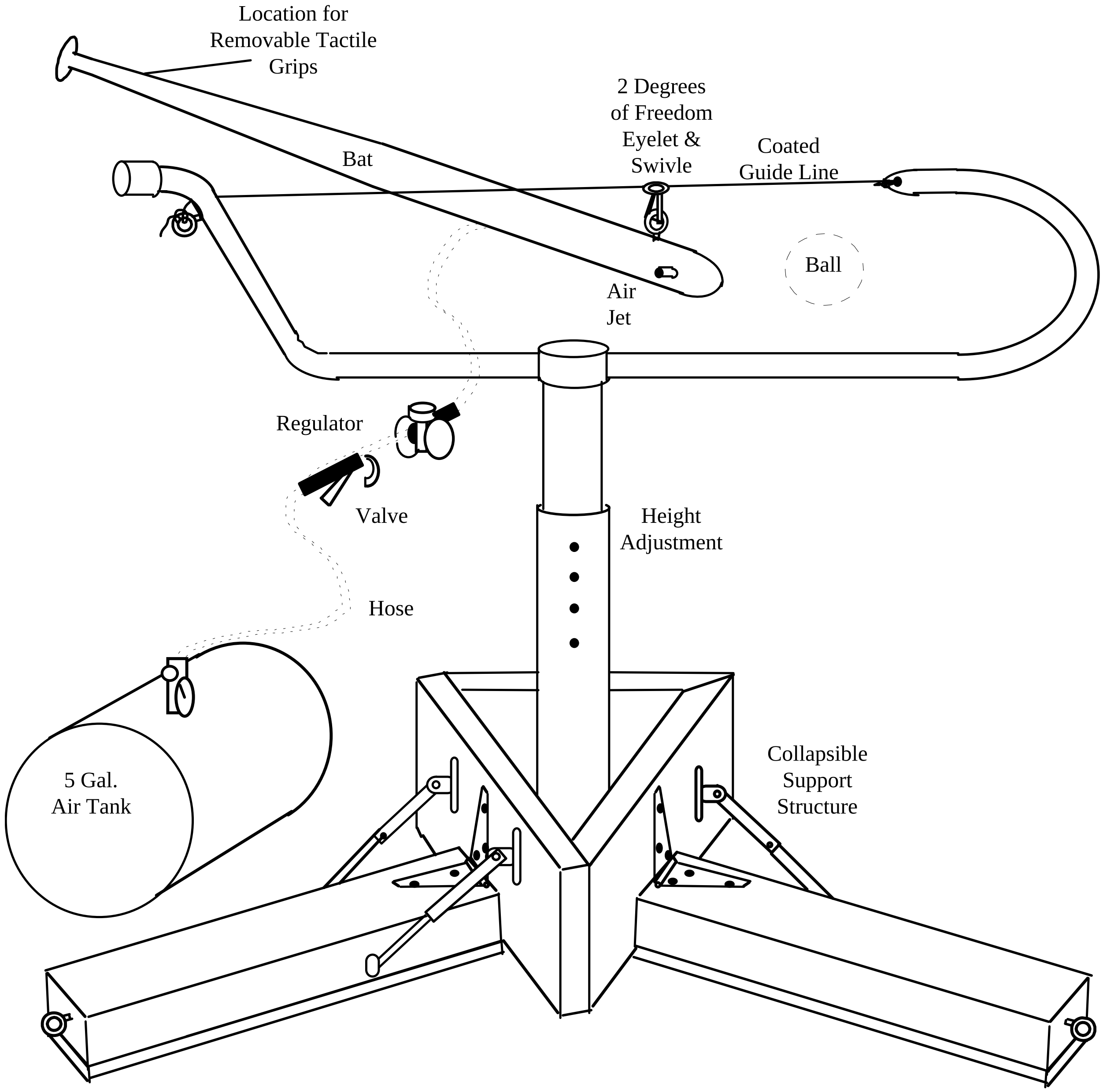

Fig. 21. Selected Design Concept for Beta Functional Prototype — Batter Up! Application.

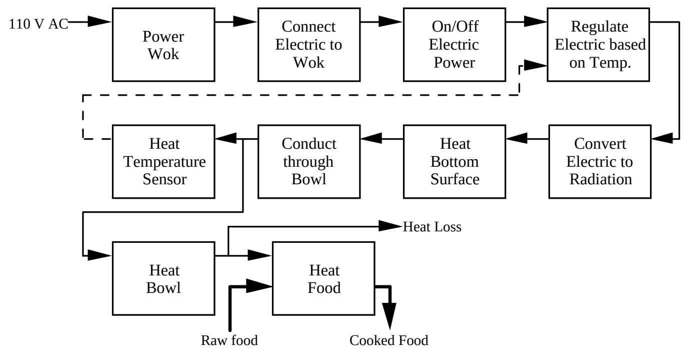

Fig. 23. Task listing of the electric energy flow — Electric Wok Redesign.

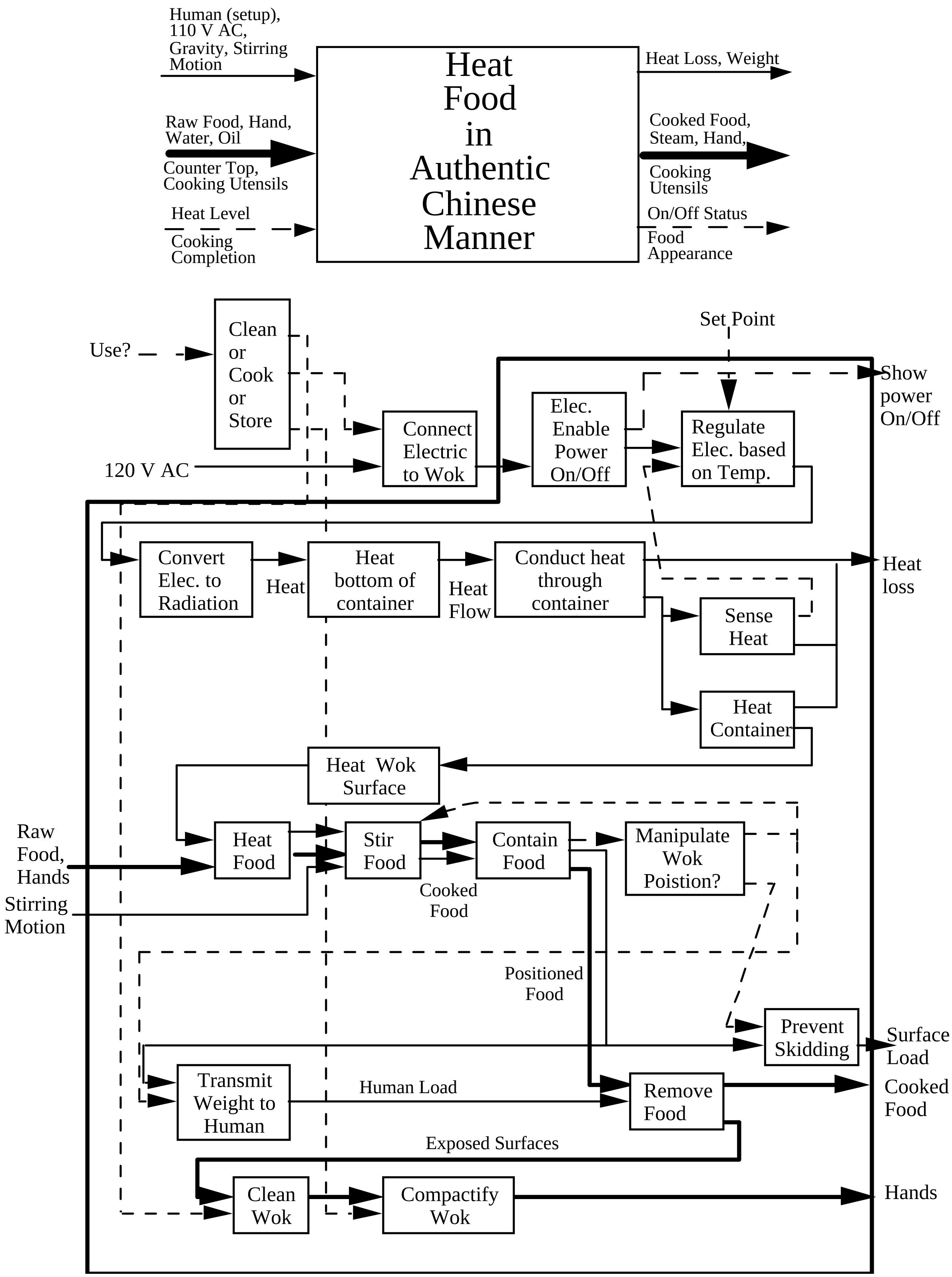

Fig. 24. Black box model and function structure — Electric Wok Redesign.

Sub-Function	Metrics
Transport wok	Weight Diameter
Store wok	Compacted diameter Compacted height
Support wok	Foot pad maximum temperature Foot pad pressure Foot print
Non-skid support	Tipping force Sliding force
Transmit weight to human	Handle shape Handle maximum temperature
On/Off electric power	Switch provided Switch visibility angle
Regulate electric based on temperature	Steady state temperature error Set point temperature error
Heat food	Temperature variation across the surface Temperature rise time

		Specifications																	
		Weight	Height	Diameter	Bowl shape	Bowl volume	Compacted diameter	Compacted height	Foot pad pressure	Foot print	Tipping force	Sliding force	Handle shape	Handle maximum T	Switch provided	Switch visibility angle	Steady state T error	T variation across surface	T rise time
	WT.	9.0	9.0	9.0	MUST	3.0	5.0	5.0	3.0	3.0	5.0	3.0	MUST	5.0	3.0	5.0	3.0	MUST	5.0
Return to kitchen storage																			
- Compact to manipulate	8	5	5	9									5						
- Heat contained in wok	2													9					5
Store in kitchen																			
- Compact for storage	8						9	9											
Transport to serving room																			
- Aesthetically pleasing	4																		
- Doesn't slide	2										5	9							
Turn on																			
- Heats and cools quickly	6																		9
- Switch readable	2																		
- Off switch included	2														9	9			
Add raw food																			
- Large volume capacity	4		5	5		9													
- Temperature indicator	3															9			
Cook food																			
- Flat bottom for frying	3				9														
- Small, rounded bottom	MUST				9														
- No ridges	5				9														
- Able to stand on own	7								5	5	9								
- Detachable heating unit	2	5											5	5					
- Bowl T uniform	MUST																	9	
- Steady-state T uniform	4																9		
- Handles remain cool	3													9					
Remove cooked food																			
- Contents can be poured	4				9														
- Easy to handle	MUST	5	5	5									9						

Fig. 25. Quantified specification — Electric Wok Redesign.

Table 1. Summary of the Harvard Business Case Method.

Process Step	Description
1. Problem Statement	What market problem are you addressing, fixing, improving, making more efficient, etc.? This should be limited to ONE sentence, two at the most. Only one problem can be addressed. If the problem is complex, with many interrelated subproblems, the problem should be clarified and refined to the basic (atomic) or kernel problems.
2. Assumptions:	Discuss any limiting assumptions made in preparing the business case proposal, such as product costs, direction of the industry/department, etc. This step provides a clear statement of the scope of work.
3. Major Factors:	List, briefly, major factors of the environment which affect the decision. This may be the state of the business (capital constraint) critical business needs or directions (strategies), etc.
4. Minor Factors:	List, briefly, factors that should be considered, but are perceived as not significantly impacting the problem
5. Alternatives:	List concrete or hypothesized alternatives (minimum of three) to address the problem or opportunity defined by the problem statement, assumptions, and major factors. Two or three sentences should be sufficient. Under each alternative list the advantages and disadvantages of each.
6. Discussion of Alternatives:	Review each of the alternatives with respect to the stated problem, assumptions, major and minor factors. Compare alternatives and discuss the relative merits of each (in terms of cost savings/avoidance, cycle time reduction, increase in quality, and head count reduction). From this discussion, a clear leader among the alternatives, i.e., the most feasible alternative, should be identified.
7. Recommendation:	State your recommendation. There should be no need to defend it; this should have been covered in the last section. If needed, elaborate on the recommendation to add clarity.
8. Implementation:	Describe the implementation plan. Include resource requirements: financial, human, space, etc. Describe the time frame requirements, control and measurements that will be needed to ensure goals are met. Measurements should be tied directly to solving the problem, and adequate tracking mechanisms such as ROA, decrease in cycle time, or NPV should be used to quantify the success of the project. Contingency plans should be developed which address any high risk aspects of the solution

Table 2. Current costs scenario — application to a finger nail clipper development.

Category	Projected Cost ($)	Cost per Product ($/clipper)
Labor Costs		
Small Clipper:		
Assembly	60,000	0.10
Handling	36,000	0.06
Large Clipper		
Assembly	16,500	0.11
Handling	10,500	0.07
Total	123,000	0.17 (avg. clipper)
Fabrication Costs		
Small Clipper:		
Materials	96,000	0.16
Piece-Parts	72,000	0.12
Tooling	6,000	0.01
Large Clipper		
Materials	30,000	0.20
Piece-Parts	21,000	0.14
Tooling	4,500	0.03
Total	229,500	0.31 (avg. clipper)
Subtotal (on-going costs)	352,500	
Engineering Costs: Avg. 10 weeks per product	173,600	0.23
Total Cost	526,100	0.71 (avg. clipper)

Table 3. Proposed costs 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	
Subtotal (on-going costs)	231,000	
Engineering Costs: Avg. 10 weeks per product	187,000	0.25
Total Cost	418,000	

Table 4. Clipper break-even cost analysis.

Issue	Analysis Result
Estimated Payback Period for Development Costs	6 months
Projected Savings for First 100,000 Products	$16,200
Projected Cost Savings for Next 650,000 Products	$105,300
Expected Average Cycle Time Savings for each 100,000 product lot	38% of current work days

Table 5. Examples of common energy flows.

displacement	rotation	linear force
power	time	stress
deflection/strain	vibration	torque
electricity	magnetism	heat
human force	pneumatic	noise
friction force	oscillating force	hydraulic
solar energy	sound (acoustic)	pressure
light		

Table 6. Basic device/product function (active verb) classes.

Function Class	*Basic Functions*	*Alternatives (Synonyms)*
Channel	Import	Input, Receive, Allow, Form Entrance
	Export	Discharge, Eject, Dispose, Remove
	Transport	Channel, Lift, Move
	Transmit	Conduct, Convey, Transfer
	Stop	Insultate, Resist, Protect, Shield,
	Guide	Direct, Straighten, Steer
Store/Supply	Store	Collect, Contain, Reserve
	Supply	Fill, Provide, Replenish
Connect	Couple	Connent, Assemble, Join
	Mix	Add, Pack, Blend, Combine, Coalesce
Branch	Branch	Divide, Diverge, Switch, Valve
	Filter	Strain, Filtrate, Purify, Percolate, Clear
	Separate	Release, Detach, Disconnect, Disassemble, Release, Subtract
	Remove	Polish, Cut, Sand, Drill, Lathe
	Distribute	Scatter, Disperse, Diffuse, Empty
	Dissipate	Absorb, Dampen, Dispel, Diffuse
Control Magnitude	Actuate	Start, Initiate
	Regulate	Control, Allow, Prevent, Enable, Disable, Limit, Interrupt
	Change	Increase, Decrease, Amplify, Reduce, Normalize, Multiply, Scale, Rectify
	Form	Compact, Crush, Shape
Convert	Convert	Transform, Gyrate, Liquefy, Solidify, Evaporate, Condense, Integrate, Differentiate, Process
Support	Stabilize	Steady
	Secure	Attach, Mount, Hold, Fasten, Lock
	Position	Orient
	Translate	
	Rotate	Turn, Spin
	Allow DOF	Constrain, Unsecure, Unlock
Signal	Sense	Perceive, Recognize, Discern, Check, Locate, Verify
	Indicate	Mark
	Display	
	Measure	Calculate, Compare, Count
	Clear	

Table 7. Definitions of device/product function classes.

Function Class	*Definition*
Channel	to cause a direction of travel or path for a material or energy.
Store/Supply	to accumulate or provide material or energy.
Connect	to join two or more flows (materials or energies).
Branch	to cause a material or energy to no longer be joined or mixed.
Control Magnitude	to alter or maintain the size or amplitude or material or energy.
Convert	to change from one form of flow type to another (e.g., one energy type to another energy type).
Support	to secure firmly a material or energy path into a defined location.
Signal	to provide information to, within, or out of the system boundary.

Table 8. Function structure organization and flow checks.

Question	*Check/Guideline/Action*
Are physical laws maintained?	E.g., validate conservation of mass and energy.
What is the new state of flow for each subfunction? Is this state valid and correct?	Label input/output states.
Are system and subsystem (assembly) boundaries clearly shown?	Define system boundary from process description or activity diagram. Subsystems (assemblies): starting point — define as a group of functions where the energy flow does not change (e.g., no relative motion)
Are all functions (noun) form independent?	If not, the function should be generalized.
Are the subfunctions atomic? Can each subfunction be replaced by a device or structure that only performs that function?	Refine subfunction into a set of atomic subfunctions, without adding unnecessary detail.
Do alternative ordering or placement or number of subfunctions exist?	If so, develop alternative function structures or subfunction structures.
Are all subfunctions product or device functions?	If not, the subfunction(s) is a user function (not performed by the product). Convert the subfunction to the device functions that must support the user function. If leaving the user function in the function structure adds clarity, double box it to show a distinction.
Are certain functions included as “wishes”?	If so, place a dashed box around the function to show that it is auxiliary or secondary.
Are certain functions “prolific,” meaning that they affect or are affected by flows of many other subfunctions (e.g., “support impact loads”)?	If so, place a ground symbol on the subfunction and only include primary flows through it.
Is the entire function structure sequential, i.e., the subfunctions are connected one after another in a dependent sequence or chain?	If so, product parallelism (assemblies/ subsystems) have not been identified. All of the customer needs are dependent. Parallelism of functions that do not directly depend on one another should be separated.
Do redundant functions exist?	Remove or combine redundant functions.
Do functions exist outside the system boundary?	If so, they should be clearly distinguished and maintained for clarity only, such as a user function.

Table 9. Partial customer needs list — Batter Up! Application.

Batter Up Project
Customer Needs

Interviewer(s): Seventh Inning Stretch Team
Date: 9/95
10 Number of Customers
0 5 Weighting Scale
75 % Must Confidence
Average Customer:
Male/Females, age 12-21 yrs. old, students
Persons with severe mental/physical disabilities

Customer Need	WT
• Manufacturing	2
- Easy to build/duplicate	4
- Affordable	3
• Set Up	
- Can be used in several positions	4
- Useful for different grip abilities	1
- Adjustable for different skills	MUST
- Various social settings	3
• Operation	
- Hits ball consistently	MUST
- Operates easily	3
- Ball flies differently	3
- User is independent	5
- Resets itself	2
• Stimulates Sensory Modes	
- Visual	1
- Tactile	3
- Auditory	4
• Store/Maintain	
- Compact transport/storage	4
- Simple maintenance	3

Table 10. Partial morphological matrix — Batter Up! Application.

Functions	Mechanical	Hydraulic	Electrical	Misc.
Adapt to Handedness	Gears, Pulleys, Wheels, Pegs, Pins	Water / Air Pressure	Solenoid, Servo Motor	
Accept Person	Walking, Rolling to Product	Riding a Water Wave, Flying		
Accept Bat	Slot, Groove, Hole, Guide Rail, Ridge	Fluid Suction		Magnetic Attraction
Position Bat	Pegs, Axis Movement	Piston Cylinder	Solenoid, Servo Motor	Magnets
Secure Bat	Clamp, Vice, Belt, Brace, Latch	Fluid Suction	Electrical Charge (Static Cling)	Velcro, Magnets, Adhesion
Initiate Bat Swing	Conveyor, Lift, Mechanical Impulse, Catapult	Water Jet, Piston Cylinder	Electrical Impulse	Magnetic Repulsion
Guide Bat	Guide Rails, Parallel Plates, Friction, Loop on Bat, String, Hole in Bat	Jet Stream		Magnetic Restriction / Attraction
Channel Bat	Human Input, Gravity, String	Air Flow, Water Pressure		Magnets, Explosion
Accept Ball	Mount, Cartridge, Hoop	Tube		
Adjust Ball Height	Jack, Pegs, Pulley System, Lever	Air Pressure	Electric Current	Magnets, Explosion
Maintain Ball Height	Clamp, Mount	Air Pressure, Fluid Suction		Magnets, Adhesion
Propel Ball	Loop, Impact	Air Suction, Jet Stream, Water Pressure		Magnetic Attraction, Explosion
Accept Energy	Lever, Four Bar, Crankshaft, Rope	Tube, Pipe, Fan, Windmill,	Electrical Inlets	Metal Surfaces, Panels, Fuses
Store Energy	Translational / Rotational Spring, Material Deformation, Rubber Band, Pendulum, Bat Movement	Fluid Column, Compressed Air (Balloon, Bladder)	Batteries, Capacitor	Magnetic Field, Solar Panels, Chemical
Transform Energy	Gears, Belt / Sprocket, Lever, Four Bar, Cam, Rack and Pinion, Universal Joint	Piston Cylinder	Motor, Generator	
Transmit Energy	Linkages Bearings	Pipe, Volume Deformation	Wires, Volt Potential Energy	Magnetic Field

Table 10 (continued). Partial morphological matrix — Batter Up! Application.

Functions	Mechanical	Hydraulic	Electrical	Misc.
Initiate Vibration	Button, Lever, String, Switch, Key		Laser	
Control Vibration	Shaker, Unbalanced Motor, Virotube, Centrifuge	Pneumatic, Wave Machine, Water Pulse, Bubbles	Sound Waves (Bass)	Magnets
Terminate Vibration	Button, Lever, String, Switch, Key		Laser	
Make Sound	Chimes, Bell, Drums, Siren, Klaxon	Whistle, Horn, Water Waves	Speaker	Chemical Reaction, Explosion
Stop Bat	Block, Slow with Spring, Sponge, Pillow, Rubber Stopper, Friction	Water / Air Resistance		Magnets
Reset Function	reapply functions: Position Bat, Secure Bat, Accept Ball, Adjust Ball Height, Accept Energy, Store Energy			
Product Stability	Weight, Clamps, Stakes, Balance, Strength of Materials,	Suction Cups		Gyros, Magnets, Adhesion of Part Joints
Universal Design	Global Function			
Inclusion	Global Function			

Table 11. Partial customer needs list — Electric Wok Redesign.

PROJECT: ELECTRIC WOK **Customer Needs**	
Interviewer(s):	
Date:	
Number of Customers: 9	
Weighting Scale: 1 - 10	
Average Customer: Male/Females, age 20-30, Attending college, Small apartment kitchen, No automatic dishwashing equipment	
Customer Need	**WT**
• Purchase	
- Cost	7
• Transport in package	
• Unpackage	
• Clean	
- Non-stick surface	7
- Watertight	3
Detachable from the heating	3
unit	
• Return to kitchen storage	
- Compact for easy manipulation	8
- Heat contained in wok	2
- Impact resistant	5
• Store in kitchen	
- Compact for small	8
storage	
• Remove from kitchen storage	
• Transport to serving room	
- Aesthetically pleasing	4
- Doesn't slide on tabletop	2
• Turn on	
- Heats and cools quickly	6
- Long extension cord	6
- Temperature switch readable	2
- Off switch included	2
• Add raw food	
- Large volume capacity	4
- Temperature indicator	3
- Temperature controls remain cool/don't get	2
hot	
• Cook food	
- Flat bottom for frying	3
- Small, rounded bottom for stir-fry	MUST
- No ridges on inner surface	5
- Able to stand on own	7
- Detachable heating unit to remove heat when cooking	2
- Temperature uniform across inner surface	MUST
- Steady-state temperature uniform	4
- Capable of high temperature	1
- Handles remain cool/don't get hot	3
• Remove cooked food	
- Contents can be poured out	4
- Easy to handle	MUST
• Throw out	

Table 12. Partial morphological matrix — Electric Wok Redesign.

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		
4. Convert Electricity to Radiation	Heating Coil	Halogen Heat Lamp	Washable Coil	Silicon Rubber Pad	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	None	
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		