AN ABSTRACT OF THE THESIS OF

Peter G. van Tamelen for the degree of Master of Science in Mechanical Engineering
Presented on May 22, 2008.
Title: Identifying Customer Requirements and Designing for Modularity in Developing Specialized, Low Production Volume Products.

Abstract approved:

Ping Ge

Field biologists are in need of more specialized and technical equipment than they are able to produce on their own in order to collect data more efficiently or gather data that is not currently available. This presents a challenge for design engineers because these products are typically highly specialized and are only needed in limited numbers. Thus, identifying customer requirements and minimizing design and production costs for low production devices are critical components of the design process. When identifying customer needs at the early design stage, many of the needs may be unspoken, especially when the design problem spans multiple disciplines. I compared the ability of a written survey and focus group to discover unspoken requirements for specialized products. Customer requirements for a new larval collector were generated in collaboration with biologists using both methods. The basic methodology includes: 1) select questions, 2) select subjects, 3) interview techniques, 4) extract useful information from the survey, 5) analysis, and 6) verification and validation. With extensive biological experience, I evaluated the requirements gathered and determined if there were any unspoken ones that were missed. Compared to focus groups, written surveys identified basic requirements better but were not as good at identifying attractive requirements. Both methods performed equally in identifying performance requirements. However, both methods failed to identify all the basic or

attractive requirements even if the results for both methods were combined. Thus, having a deep customer understanding is critical in identifying unspoken customer requirements. Field biologists desire specialized, low production volume products at moderate to low cost. For high production volume products, modularity has been shown to increase diversity, flexibility, and customer satisfaction and decrease assembly, repair, subsequent product design time, but modularity may also limit performance and innovation and requires more initial design time. There is little information regarding the implementation of modularity for specialized, low production volume products. This thesis presents a method for incorporating modularity into the design of specialized products with low production volume. I tested this method by designing a device to collect marine larvae as they arrive on the shore. My first-generation prototype performed much better than other existing devices, decreasing sample processing time by more than half, but it was expensive. To reduce the production costs, I utilized the modularity of the new design, identified the functional modules where off-the-shelf components could be used to fulfill each module's functional requirements, yielding a more economic second-generation prototype, the design project is on-going, without compromising the performances. Another benefit from this modularity-based design is that several variations of the larvae collectors can be easily evolved from this collector because of the flexibility offered by introducing the modularity into the new design. This experience has led us to conjecture that modularity-based design may offer a promising approach for producing high-quality products with affordable price in the design of specialized, low production volume products.

Identifying Customer Requirements and Designing for Modularity in Developing Specialized, Low Production Volume Products

by

Peter G. van Tamelen

A THESIS

submitted to

Oregon State University

In partial fulfillment of
the requirements for the
degree of

Master of Science

Presented on May 22, 2008
Commencement June 2009

Master of Science thesis of Peter G. van Tamelen presented on May 22, 2008.

APPROVED:

Major Professor, representing Mechanical Engineering

Head of the School of Mechanical, Industrial, and Manufacturing Engineering

Dean of the Graduate School

I understand that my thesis will become part of the permanent collection of Oregon State University libraries. My signature below authorizes release of my thesis to any reader upon request.

Peter G. van Tamelen, Author

ACKNOWLEDGEMENTS

Several people have provided invaluable assistance on this project. First, I would like to thank my advisor, Dr. Ping Ge, for accepting me as her student and making sure I was content progressing on my research. She also provided helpful guidance in many aspects of my work. I would also like to thank the other members of my committee, Dr. Tim Kennedy, Dr. Robert Paasch, and Dr. Chiang, for comments on my thesis. Dr. Kennedy was an invaluable teacher of mechanics, and Dr. Paasch provided enthusiasm for the design of various components. In addition, Dr. Irem Tumer helped tremendously during the writing (and numerous revisions) of Chapter 2. Several other students, Clint Peterson, Jon Mast, and Amanda Comer were also particularly helpful and contributed greatly to Chapter 1. I appreciate the patience and enthusiasm of Sarah Dudas, Joe Tyburczy, Gil Rilov, and Dr. Bruce Menge, the biologists who participated in this project. Several other biologists have been particularly supportive of my engineering pursuits and include Carol Blanchette, Gordon Kruse, Mike Stekoll, Mark Denny, and Dave Carlile.

I would like to give special thanks to my family. My wife, Lynn Humphrey was willing to move away from Alaska and supported me tremendously, allowing me to focus on my schoolwork. My eldest, Neal cheerfully accepted our move, provided great companionship, introduced me to world of the Pokemon trading card game, and dragged me off to numerous tournaments. My youngest, Luke, spent his early formative years watching me study, and I hope that some of it rubs off. This would not have been possible without the support of such a wonderful family.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

1. INTRODUCTION

With the rapid development of new technologies, many opportunities exist for making dramatic improvements in the way field biologists collect their data as well as increasing the types of data that can be collected. This increased access to biological information will enhance our understanding of natural communities and thus enhance our ability to manage biological resources and predict community responses to climatic or other changes. Fisheries and other resource managers often make decisions based upon inadequate data with large uncertainties. New devices can greatly increase the rate of data collection while reducing costs and improving data quality. Global climate change or other anthropogenic factors may result in dramatic shifts in biological communities. Enhanced biological sampling equipment will advance our ability to monitor and understand these changes, leading to better predictions of responses to future changes. I believe there are a tremendous amount of design possibilities that can be addressed by properly trained design engineers, and this combination of fields will continually present new and interesting design challenges.

Despite rapid advances in technology, many field biologists continue to collect data inefficiently using paper and pencil and struggle to devise methods to collect the data they need. Most broad statements regarding the state of the Earth's natural resources, such as fishery populations, are based upon surprisingly little data with large uncertainties. Thus, the need for more rapid and efficient collection of field biological data is apparent and the technological capability of filling this need currently exists, but there are few trained engineers focusing on this problem that understand its nature and urgency. Typically, biologists with little or no engineering training, act as their own designers and producers of equipment. They often piece together a gadget from existing devices with little thought devoted to designing for end product quality and reliability over various habitats.

The focus of my research is to develop and test design engineering methods that will enhance the ability of engineers to collaborate with field biologists to develop equipment that meets their specific needs. Biologists often have very specific requirements for their desired devices and determining these needs can be challenging when similar products do not yet exist or the needs are very technical in nature. Biologists may focus more on the basic requirements for new products but on desirable needs for technical devices. The first chapter of this thesis evaluates various methods for collecting customer requirements from biologists. Several methods are compared in their ability to identify basic, desirable, and unspoken customer requirements. Additionally, the devices desired by field biologists are often needed in low numbers, from 1-500, so many of the current design practices developed for large production volume products may not be applicable. Many of the needs and functions for these specialized devices are often similar, especially within specific disciplines or habitats. In the second chapter, I adapt current methods for increasing modularity in products to specialized, low-volume production products. These adaptations are designed to increase the efficiency of the design and production of devices needed by biologists. These general design engineering methods were tested by developing a new device for collecting larvae as they arrive on wave-swept rocky shores for field biologists.

Understanding larval dynamics is critical to predicting the adult population dynamics of many marine species including most commercially important species. An increased interest in larval dynamics over the past two decades has made it clear that population fluctuations of many marine species are driven by events that occur during their larval phase (Gaines and Roughgarden 1985, Myers and Cadigan 1993, Zheng and Kruse 1998, 2000, Caselle 1999, Menge et al. 2003). Despite the importance of larval dynamics in determining adult population fluctuations, there have been no major improvements in our methods for sampling, measuring, and assessing the abundance and distribution of larvae (Harris et al. 2000). In particular, new larval sampling devices are urgently needed in environments where traditional methods are either impossible or too expensive, such as the very nearshore environment, in the surf zone, and onshore. For the majority of the current larval samplers, the developers of the above devices have been predominantly biologists who do not have the necessary engineering training or background in designing and testing an engineering system. The larval samplers they developed, though functional at a certain level, have limitations in their accuracy and effectiveness in many environmental scenarios. Thus, I initiated an interdisciplinary approach with collaborations between marine field biologists and engineering designers to develop new larval collectors that will yield better accuracy, consistency, and cost-effectiveness than current designs, and will be able to sample in a wide range of environments, including areas where we cannot currently sample.

Through this process of designing, building, and testing a new larval collector, I was able to assess several methods for collecting customer requirements and test a method for incorporating modularity early in the product design phase. Written surveys were the best method for identifying basic needs for the device, but focus group discussions excelled at determining desirable requirements. Having experience using similar devices in similar habitats was useful for identifying unspoken customer requirements. Under ideal situations, using a combination of all three methods would yield the most complete set of customer requirements. After customer requirements were identified and engineering requirements developed, incorporating modularity during concept generation resulted in a highly modular product without additional design work. Because of the modular nature of the device, many off-the-shelf components could be used in the final product design, reducing manufacturing costs. Future products could also take advantage of previous product designs that are modular, by using previously identified and tested modules that perform similar functions. To further enhance the usefulness of modular designs, a database specific to a company or agency could be developed that kept track of modules and their functions as well as the design documents associated with that module. Such a database could reduce or eliminate the institutional knowledge now kept with individual engineers, reducing the loss of this knowledge upon the departure of senior personnel.

2. IDENTIFYING CUSTOMER NEEDS ACROSS DISCIPLINES: COMPARING A WRITTEN SURVEY AND FOCUS GROUP

2.1 BACKGROUND

An important aspect of product design is identifying customer needs at the early design stage. Many of these needs may be unspoken, especially when the design problem spans multiple disciplines. I compared the ability of written survey and focus groups to discover unspoken requirements for specialized products. Customer requirements for a new larval collector were generated in collaboration with biologists using both methods. The basic methodology includes: 1) select questions, 2) select subjects, 3) interview techniques, 4) extract useful information from the survey, 5) analysis, and 6) verification and validation. A design team member, with extensive biological experience, evaluated the requirements gathered and determined if there were any unspoken ones that were missed. Compared to focus groups, written surveys identified basic requirements better but were not as good at identifying attractive requirements. Both methods performed equally in identifying performance requirements. However, both methods failed to identify all the basic or attractive requirements even if the results for both methods were combined. Thus, having a deep customer understanding is critical in identifying unspoken customer requirements.

In product development, developing a clear set of design requirements to steer the design process and establish product specifications is essential (Ulrich and Eppinger 2000). It is estimated that poor product definition due to ambiguous design requirements plays a role in 80 percent of all time-to-market delays (Ullman 2003). Often poor production definition can be traced back to missing or unspoken customer needs. This problem is usually amplified in multidisciplinary projects where there are stakeholders from varied backgrounds. The goal of my research is to assess the ability of different methods for gathering customer requirements to capture these unspoken requirements in a multidisciplinary project.

An important factor in the success of a product is customer satisfaction. Kano’s model of customer satisfaction distinguishes three types of customer requirements based on the way they satisfy the customer (Matzler and Hinterhuber 1998, Figure 2.1). The must-be, or basic, requirements are the basic criteria of a product. They are expected features and as such, will not increase satisfaction with their presence. They will, however, lead to dissatisfaction if they are not met. One-dimensional, or performance, requirements are those that are typically stated by the customer. They will either dissatisfy or satisfy the customer depending on the degree to which they are met. Finally, attractive requirements present significant opportunities in gaining a competitive advantage. These are unexpected features that satisfy the customer if present, but will not dissatisfy the customer if they are absent. The must-be and attractive requirements are the ones that tend to be unspoken by the customer.

Customer needs are expressed as written statements that are developed by interpreting the information gathered from customers (Ulrich and Eppinger 2000). Design requirements start out as qualitative descriptions of what customers need or want and are then transformed into quantitative engineering requirements to facilitate the physical embodiment of the product. There is usually not an obvious relation between the customer needs and the corresponding design specifications for system realization (Hintersteiner 2000). Since design direction is greatly influenced by these engineering requirements, it is crucial to clarify customer requirements and identify definite design specifications for them as early as possible in a design process. Some requirements may be unspecified; they are considered to be relatively unimportant or they are assumed to be intuitive and are never explicitly stated. It is the responsibility of the designer to consider all of the requirements for the design even if they are unstated or perceived as unimportant (Hintersteiner 2000).

At times customers do not know what they want, and requirements may be underspecified. Customers may make educated initial guesses regarding their needs; however, if a design is still not sufficiently specified, the designer may have to make estimations about engineering requirements. Analyzing the set of requirements will help to discover these inadequacies. A successful designer is able to interpret what the customer really needs when adequate, explicit requirements are not given. This may be facilitated by observing design trends and making predictions, or by creating customer needs where there were none before. These approaches can be successful if the customers are well understood and there is sufficient communication (Hintersteiner 2000). Later, as more knowledge of the product is gained, the requirements may be refined and properly specified during the product development cycle.

Active customer participation is the foundation for identifying unanticipated customer requirements in a timely fashion (Hintersteiner 2000). Collaborative product development projects, where there are multiple stakeholders from differing backgrounds, present a more challenging work environment for designers. Errors in designs often are the result of miscommunication between domains, rather than within the domains where designers are experts (Odell and Wright 2002). Effective communication between the designers and customers is important throughout the product development process to prevent requirement issues from affecting the delivery of a product. To facilitate the interface between the customer and the design team, it is important to make communication as open and as simple as possible. There must be an understanding of the potential barriers and impediments to communication between involved parties. Real impediments to communication may exist for which there may not be any simple solution. There may also be perceived barriers that emerge from the history and culture of the group and the individuals involved (Hintersteiner 2000). Fostering open communication requires strong social relationships built on trust between customers and developers. This approach is effective in both developing requirements and enhancing communication throughout the product development process. Going through a product assessment process together, a customer and design engineer can help create a better understanding of product direction and design requirements.

Despite the importance of developing customer requirements, there is little research that directly compares various methods for gathering customer requirements. This study compares three different methods for gathering customer requirements and compares the number and type of requirements identified by each method. Additionally, the identified customer requirements gathered using the standard techniques were reviewed by a field marine biologist with lengthy experience with similar products to identify any additional requirements that were not revealed using the standard methods. Written surveys excelled at identifying must-be requirements but were not good at identifying attractive requirements. Focus group discussions identified many attractive requirements, but did not identify all of the must-be requirements. Finally, both methods failed to identify several attractive requirements suggested by the experienced person. I suggest a combination of methods is required to gather a full set of customer requirements before product design and development, and if possible employ engineers that have experience with similar products that can identify any unspoken requirements.

2.2 STRUCTURED OR SEMI-STRUCTURED METHODS FOR IDENTIFYING CUSTOMER NEEDS

Understanding customers and their desires can enhance the ability of a company to quickly produce new and successful products. Most customers may not be able to articulate their needs simply because they are unaware of what is possible or that they even have a need for a product improvement (Leonard and Rayport 1997). By combining knowledge about what is technically feasible with a deep understanding of customer needs, it is possible to envision new products that will meet the future needs of customers. With rapidly developing technologies, features are often rapidly incorporated into products without sufficient thought devoted to the desires of the customers (Neale and Corkindale 1998). This results in products that have many technological features but are not well-accepted by customers. If, on the other hand, a deep understanding of customers is incorporated as part of the design process, then innovations can be easily incorporated without losing the user orientation (Veryzer and Borja de Mozota 2005). In addition, when new product design teams are multidisciplinary and include members from all phases of the production process, a deep understanding of the customers and their needs can speed the development process. Such a user orientation will enhance the development process by increasing idea generation, and inducing collaboration, resulting in better products and services that are more readily adopted by consumers (Veryzer and Borja de Mozota 2005). A deep understanding of the customer and their needs and desires enhances the whole design and manufacturing process and results in superior products and services.

Gathering customer requirements requires considerable time, planning, and design; however, this can be minimized if the gathering process is well structured. Table 2.1 shows a general outline that can be used, regardless of the specific data collection method, to assist designers in the data gathering process (Ullman 2003). There are currently three main methods widely used in industry to determine customer requirements: 1) surveys, 2) interviews or focus groups, and 3) observations or “be the customer”. These methods may vary in the quality and quantity of data they enable the designer to collect and in their relative effectiveness.

Survey and Questionnaire Design

Surveys or questionnaires are composed of mainly closed-ended questions that target the specific opinions of the customer about a well-defined product (Ullman 2003). They do not readily enable the designer to determine unspoken or assumed needs because the analyst only gains answers to the questions they ask and are not able to determine what the customer may have really wanted to tell them (Otto and Wood 2001). The closed-ended questions used in surveys are typically formulated using one of four ways: 1) yes-no-don’t know, 2) ordered choices, 3) unordered choices, or 4) ranking. In the first method, the customer simply responds to a posed question with a “yes” for agreement, “no” for disagreement, or selects “don’t know”. Ordered choices is an extension of this form that usually offers five graduations from “strongly agree” to “strongly disagree” from which to choose. Using unordered choices, also known as multiple choices, the designer provides a list of possible answers to the question from which the customer selects their answer. Finally, ranking questions will require the customer to rank a list of statements (e.g. A is better than B is better than C). The survey collection method can be fairly effective if the requirements are for the redesign of an existing product or for a new product in a well-understood field (Ullman 2003). Overall, when compared to the other two common ways to collect customer requirements, surveys result in the lowest quality of information (Otto and Wood 2001).

Interviews and Focus group

Interviews and focus groups involve analysts meeting with potential customers either individually or in small groups and asking open-ended questions to determine customer needs (Ullman 2003). These meetings usually take place in the customer's environment (Otto and Wood 2001). An interview includes one customer and one or more analysts, while focus groups typically include multiple customers and two or more analysts. One analyst will take the role of moderator, asking questions to guide, but not control, the discussion. The remaining analyst(s) will act as note takers, recording customer statements relating to their needs. Both variations of this method rely heavily on asking "why", or exploratory questions that, especially in focus groups, generate discussion (Otto and Wood 2001, Ullman 2003). When compared to surveys, observations or being the customer, interviews and focus groups provide the best information when gathering requirements for a product that does not yet exist (Ullman 2003).

There are two specific interview or focus group techniques, both of which involve meeting with the customer(s) as they use a previous or similar product. The first of these techniques, the Like/Dislike Method, is characterized by the analyst asking questions as the customer uses the product about what they like and dislike. Answers to questions about what the customer likes may provide information about functions that are expected or required in the product. While customer input about what they dislike often leads to information regarding what would delight the customer (Otto and Wood 2001). Table 2.2 below shows a data collection form that can be useful when using the Like/Dislike Method (Otto and Wood 2001).

The second technique is called the Articulated-Use Method and is similar to the Like/Dislike Method. In this case, the analyst comes to the interview or focus group with only one predetermined question. This question takes a form similar to "walk me through a typical session using the product". The analyst watches, listens and asks "why" questions as the customer goes through using the product from start to finish (Otto and Wood 2001).

Observational Methods

The collection methods known as "be the customer" and observations are very similar in that they require the product to be used during the collection process. In the first of these two, the designer acts as the customer using the product to determine customer experiences. This can be effective, but requires considerable time from the designer. In addition, this method is not possible for all products because the designer may not be skilled to act as the customer (e.g. surgeons' scalpel) (Otto and Wood 2001).

The observation method typically consists of the designer watching customers use the device (Ullman 2003). For instance, a designer may walk around in a grocery store and observe how the customers use their grocery carts. From these observations, customer requirements can be generated based on how the carts were used, what worked well, and what could be improved. Both of these methods are only usable if the product for which the requirements are being gathered is a redesign or similar to a previous product.

Although all of the gathering methods considered can be effective for determining customer requirements in certain scenarios, there is no single method that currently exists that is known to work well for determining unspoken or assumed customer needs.

"Bias" and Other Potential Issues in Gathering Data

In all of these methods there is the potential for bias to enter the data due to things such as personal and social factors, information and communication, and cognitive factors. These concerns can arise depending on the group of customers questioned, the particular product to be designed, or even the environment or medium through which the questioning takes place. Personal and social biases can result from factors such as gender, status, environment, or if the product is personal in nature. Biases may also enter data from communication factors, which may include domain terminology, and misleading or unclear language. Finally, cognitive biases may come from something as simple as the "say-do" problem; it is often more difficult to verbalize an activity than to demonstrate it (e.g. tying shoelaces). In addition, collection techniques rely on the customer's memories of using the previous product, and these memories may be lost or distorted which also can result in cognitive bias. To reduce the presence of these biases, customer questions can take the form of hypothetical experience questions. These questions usually take longer to create but the customer will typically answer them more quickly and the designer will be able to collect data that is less affected by these biases (Cohene and Easterbrook 2005).

Other factors that may affect the gathering of customer requirements include the number of customers that are questioned and the number of designers that analyze the data from these questions. Studies have shown that for interviewing, in order to determine 90 – 95% of customers' needs for a product, about 20 – 30 customers must be interviewed. In addition, in one particular study, seven analysts were required to identify 99% of the total needs that could have been identified from a set of interview transcripts (Griffin and Hauser 1993). This illustrates the importance of the number of customers and analysts in a customer requirement collection process.

2.3 CASE STUDY AND RESEARCH METHODOLOGY

Understanding larval dynamics is critical to predicting the adult population dynamics of many marine species including most commercially important species. An increased interest in larval dynamics over the past two decades has made it clear that population fluctuations of many marine species are driven by events that occur during their larval phase (Gaines and Roughgarden 1985, Myers and Cadigan 1993, Zheng and Kruse 1998, 2000, Caselle 1999, Menge et al. 2003). For most species with a free-swimming larval stage, the majority of mortality occurs during the larval phase, making the prediction of adult population size extremely difficult. Despite the importance of larval dynamics in determining adult population fluctuations, there have been no major improvements in our methods for sampling, measuring, and assessing the abundance and distribution of larvae (Harris et al. 2000). In particular, new larval sampling devices are needed in environments where traditional methods are either impossible or too expensive, such as the nearshore environment in the surf zone. Virtually all of the current larval samplers were developed by biologists without any engineering training or background. The larval samplers they developed, though functional at a certain level, have limitations in their accuracy and effectiveness. A systematic engineering design approach, starting with the collection of customer requirements, will yield a design for an intertidal sampling device that will perform efficiently across a wide range of habitats with acceptable cost (Pahl and Beitz 1989, Suh 1990, 2001, Otto and Wood 2001, Ullman 2003).

Developing a new and effective larval sampling device will allow scientists to better understand the role of larval dynamics in population regulation. This understanding may have immense implications for many fishery scientists and managers (Mace 1994). If we understand the factors that cause major population fluctuations, fisheries scientists can produce more precise population estimates and fishery managers may allow greater harvests because they are faced with more certainty (Hilborn et al. 1993, Rice and Richards 1996). Efficient and economical larval collectors can enhance the management of many commercially important marine species. Those species that have a planktonic larval phase are often characterized by large swings in population size that appear to be driven by the success of their larvae (Myers and Cadigan 1993). Predicting changes in population size is a key component to fisheries management and for some species that means understanding the larval phase of their lifecycle (Gilbert 1997, Barrowman and Myers 2000). A first step toward understanding larval dynamics is to be able to adequately collect the larvae given the limited resources of many fisheries managers and scientists. In this thesis, I utilize the findings of my research on gathering customer requirements to develop customer requirements for a new larval collector to be used in the intertidal on the Oregon Coast to collect barnacle and mussel larvae.

Customer requirements were gathered for the larval collector using two methods, a survey and a focus group (Figure 2.2). By using at least two methods, it enables a comparison to be made regarding the effectiveness for determining unspoken requirements. For each method I followed the same principle steps that consist of: 1) select subjects; 2) select questions; 3) interview techniques; 4) extract useful information from the technique; 5) analysis; and 6) verification and validation.

The first collection method utilized was a survey composed of closed- and open-ended questions (Appendix 1). This survey was distributed to three biologists who are potential customers for the larval collector. Questions included in the survey covered topics such as cost, size, weight, transportation, sampling parameters, and the general use of the device.

After receiving the completed written surveys, each one was reviewed by each of three analysts independently. Each analyst attempted to review each returned survey independently of the other surveys. The resulting customer requirements were compiled in all possible combinations of 2 surveys for each analyst and for all surveys for each analyst. Finally, the requirements generated by each analyst in all possible combinations of 2 analysts and for all three analysts were compared. During comparisons, any redundant customer requirements were removed. This procedure allowed calculation of the average number of customer requirements generated for 1-3 surveys and 1-3 analysts.

After all three surveys were returned, the same biologists were questioned using a focused group interview. One analyst acted as a moderator, guiding the discussion, while two other analysts recorded notes using a table similar to Table 2.2. A fourth analyst with experience in field of biology observed the focus group. Questions posed by the moderator focused mainly on the desired use and functions of the product as well as what the biologists like and dislike about the existing device. Finally, the requirements generated using both methods were combined and presented to the analyst with experience in filed biology who reviewed the requirements and added any additional requirements that were not identified.

2.4 RESULTS AND DISCUSSIONS

Using the written surveys, the average number of customer requirements increased with the number of reviewed surveys from about 20 for one customer to more than 25 for all three customers (Figure 2.3). Two analysts increased the number of customer requirements by 2-3 above those generated by 1 analyst, but there was only slight increase with the addition of the third analyst. The effect of increasing surveys was greater than the effect of increasing analysts.

From the focus group process, a total of 34 customer requirements were generated (Appendix 2). Compared to the written survey, the focus group identified 8 additional attractive requirements and one performance requirement more than the written survey. However, the focus group did not generate 9 of basic requirements identified by written methods but added 4 more basic requirements.

The analyst with experience in field biology identified 16 additional requirements that were not identified by either the focus group or the questionnaire method. Each of the methods traditionally used to gather customer requirements failed to identify all possible requirements. Most of the requirements generated by the biologist analyst were in the attractive category, but there were 4 basic requirements as well. If the 59 requirements generated by all three methods represent the complete set of requirements for this device, the proportion of customer requirements identified by each method can be assessed. The focus group identified slightly more requirements than the written survey with each method generating between 50 and 60% of the total (Table 2.3). Both methods combined, however, identified 86% of the total. When the requirements are divided into the three Kano categories, basic, performance, or attractive, both methods identified virtually all of the performance based requirements. The written surveys performed better than the focus group at identifying basic requirements, but the focus group outperformed the written methods in generating attractive requirements (Table 2.3).

Methods of Identifying Customer Requirements

Understanding customers has long been known to be an important business practice but few improvements have been made in the past two decades (Swaddling and Miller 2003). Traditional techniques for understanding customers, such as customer satisfaction surveys, are often inherently flawed and fail to acquire the required customer knowledge (Flint 2002, Swaddling and Miller 2003). However, new methodologies for gaining customer knowledge are developing and formal processes are being proposed (Flint 2002, Joshi and Sharma 2004). These can lead to much better customer knowledge that can allow new product developers to foresee customer needs and rapidly produce new products that are readily accepted by customers. By implementing business changes that encourage deep customer knowledge, companies can facilitate the design process by increasing idea generation and inducing collaboration.

One of the most successful techniques for gaining customer knowledge is to observe customers in an environment where they would normally use the product (Flint 2002, Veryzer and Borja de Mozota 2005). These ethnographic approaches can yield insights into products that otherwise go unnoticed and lead to innovative products (Leonard and Rayport 1997). With technological innovation occurring at a rapid pace, the desire to develop new products incorporating new technology often overwhelms the user orientation (Neale and Corkindale 1998, Flint 2002). If a user oriented design approach is combined with a deep understanding of customer desires, new innovations can be easily and rapidly incorporated without losing the user orientation (Veryzer and Borja de Mozota 2005), avoiding technology driven innovations.

The most common methods currently used for gathering customer requirements are surveys, “be the customer” or observations, and interviews or focus groups. These methods vary in the quality and quantity of information they produce as well as their relative effectiveness. Surveys typically result in the lowest quality of information because the analyst is only able to collect customers’ opinions about specific questions. This does not give the customer the ability to reveal to the analyst what they truly wanted to say regarding the product. “Be the customer” or observations are methods that rely strongly on the existence of a previous product comparable to the new product that is being developed. Analysts often do not have the skills or the time to use these methods.

Of these three methods, interviews or focus groups provide the highest quality and quantity of information. As demonstrated in the larval collection design case study, written surveys excelled at identifying must-be requirements but were not good at identifying attractive requirements. Focus group discussions identified many attractive requirements, but did not identify all of the must-be requirements. Finally, both methods failed to identify several attractive requirements suggested by the experienced person. I suggest a combination of methods is required to gather a full set of customer requirements before product design and development, and if possible employ engineers that have experience with similar products that can identify any unspoken requirements.

The Importance of Social Relationship with Customers

In addition to the above methods, by asking potential customers about specific features or functions they like or dislike in a previous or similar device, this method can be more effective than the other two methods discussed for determining unspoken or assumed requirements. Through the literature and experimental investigation in this work, it has come to my realization that: no matter what method or combination of the methods is to be used, a solid social relationship with the customer (knowing your customer) is of special importance. The importance of knowing the customer has long been known but there still seems to be a general lack of customer understanding among new product developers (Swaddling and Miller 2003). This may be due, in part, to the reliance of new product developers on customer satisfaction surveys. These surveys sample only recent customers who judge the product against their expectations for that product. These surveys usually indicate that customers want more product features for less money. The information that is really needed to know the customers is very different. First, all potential customers must be sampled and not just the customers that happened to buy the product. Second, potential customers must indicate what will make them satisfied and how their current needs are being met. Third, responses should be relative to the alternatives available and not the expectations of customers. Finally, new product developers must understand how important a product is to a customer and for what they are willing to pay (Swaddling and Miller 2003).

Despite the well-documented usefulness of knowing the customer, there is very little theory or research as to how to obtain this knowledge (Joshi and Sharma 2004). Gaining customer knowledge is most cost-effective before the launch of a new product and preferably before the design phase begins. This process is evolutionary with the following characteristics: 1) it is ongoing before and throughout the design process, 2) it can generate new ideas at each stage, and 3) it is action-based, trial and error learning. Because of these properties, gaining customer knowledge has many implementation barriers for companies (Joshi and Sharma 2004). The amount of time devoted to these activities is highly variable and difficult to predict, making budgeting for gaining customer knowledge difficult. This process also has a high failure rate due to the trial and error nature of the learning; therefore, companies must provide and maintain motivation despite failures. If a company chooses to gather a deeper understanding of customers, it must provide the resources to personnel involved in gaining customer knowledge and reward those efforts that result in increasing knowledge and not just those that lead to better products. Companies can reap further benefits from gaining customer knowledge by creating cross-functional teams, so the customer knowledge can be distributed throughout the new product development process.

Even if companies embrace the above protocols to increase their customer understanding, new product development teams will often fail for several reasons (Flint 2002). The methods used to gain customer knowledge are becoming more sophisticated, relying more frequently on anthropological and ethnographic techniques (Cagen and Vogel 2002, Flint 2002, Veryzer and Borja de Mozota 2005). Frequently these techniques require specialized training to implement properly and most new product development teams lack this training. Finally, the methods that are often implemented, such as customer satisfaction surveys, are inherently flawed and will not lead to greater customer understanding (Flint 2002). To overcome these deficiencies, Flint (2002) has proposed a formal process for understanding the customer that involves: 1) in-depth interviews using specialized techniques that go well beyond customer satisfaction surveys, 2) ethnographic approaches where developers spend time with and observe customers in detail, 3) learning how customer values change over time as well as current customer values to predict customer values in the future, and 4) scanning technological breakthroughs and evaluation of these breakthroughs relative to customer needs so that innovation remains customer driven and not driven by technology. The goal of deep customer understanding goes beyond understanding current, well-articulated customer needs to understand what those needs will be in the future (Flint 2002).

Areas of Future Development

There is still a huge opportunity in research towards devising methods to capture unspoken customer requirements. Overall customer satisfaction and product success can be greatly increased by designing to satisfy these requirements. This project of gathering customer requirements for a larvae collector showed that there are no clear methods to capture unspoken customer needs in interdisciplinary projects. Although this project was a relatively small and simple project, it is likely that other projects have similar difficulties in the requirements gathering phase of product development.

In my study, both written surveys and the focus group had unspoken customer requirements that were not identified. These unspoken requirements tended to be attractive requirements in the written surveys, but were mostly basic requirements in the focus group. Because of this complimentary nature, a combination of both written and focus group methods performed much better than either separately. Having an analyst with practical experience with products similar to the new device added substantially to the list of customer requirements. Based upon these results, it is recommended that both written and verbal methods be used to gather customer requirements focusing on the basic and attractive requirements of the product. If at all possible, analysts should have experience in the field in which the device will be used to identify or supplement the requirements gathered by other methods.

Table 2.1. General Data Gathering Outline.

1	Specify the Information Needed
2	Determine the Type of Data-Collection Method to Be Used
3	Determine the Content of Individual Questions
4	Design the Questions
5	Order the Questions
6	Take Data
7	Reduce the Data

Table 2.2. Data Collection Form.

Question	Customer Statement	Interpreted Need	Importance
Typical uses			
Likes			
Dislikes			
Suggested Improvements			

Table 2.3. The proportion of all customer requirements identified by the written survey and focus group methods and both methods combined. The requirements were divided into 3 categories according to the Kano model.

	Kano Model Category			
	Attractive	Performance	Basic	Total
Written	16.7	83.3	72.4	50.8
Focus Group	50	100	55.2	57.6
Both Methods	50	100	86.2	72.9

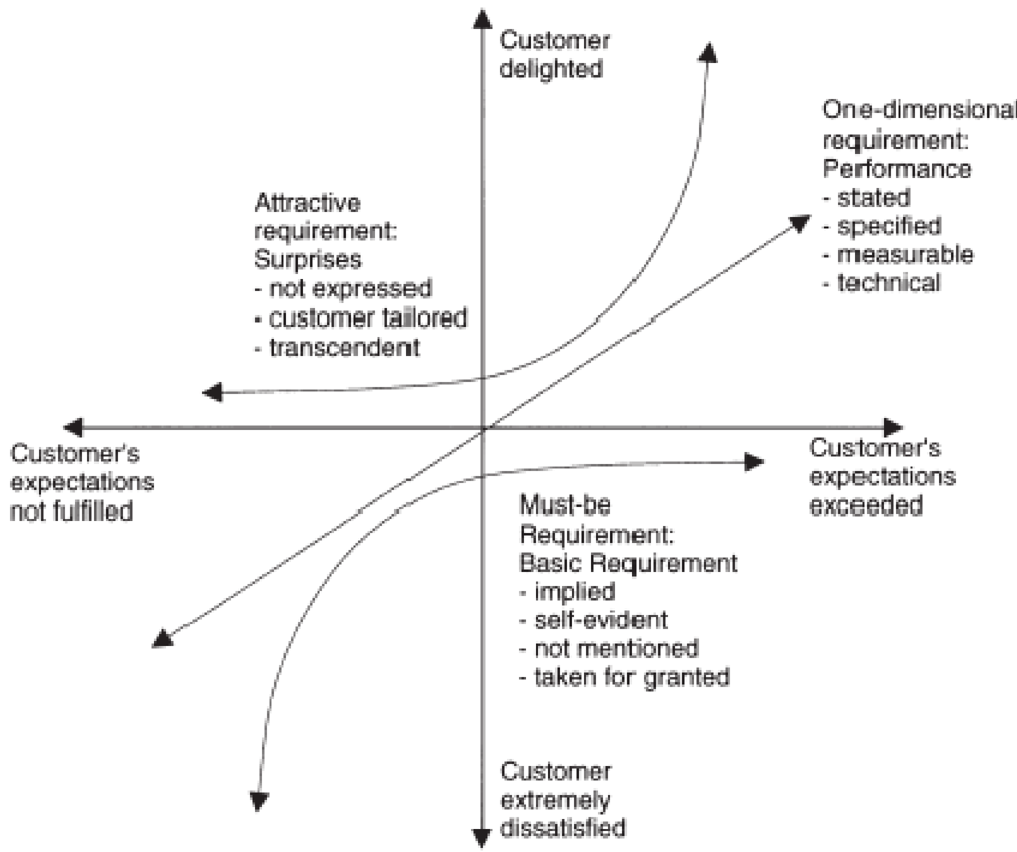

Figure 2.1. Kano's Model for Customer Satisfaction.

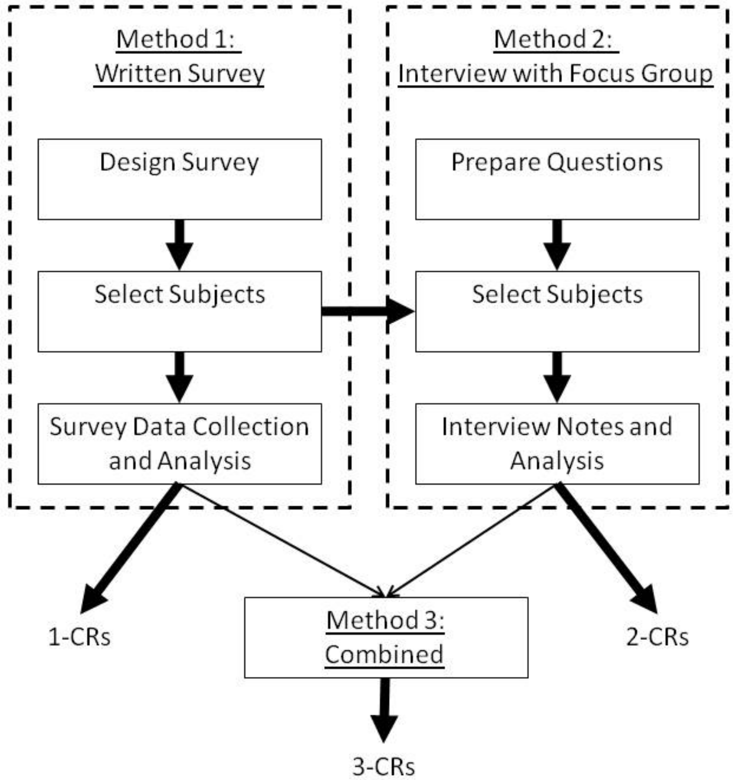

Figure 2.2. Research Methodology.

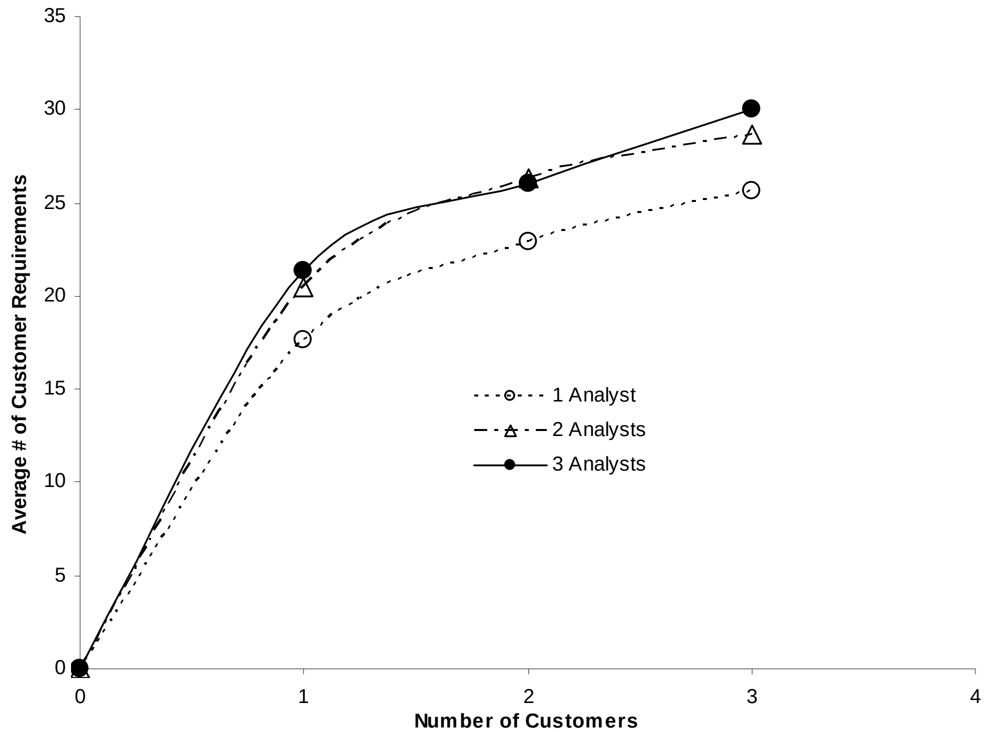

Figure 2.3. The average number of customer requirements generated from a written survey for an onshore larval collector using different numbers of customers and analysts.

3. A MODULARITY-BASED DESIGN APPROACH FOR SPECIALIZED, LOW PRODUCTION VOLUME PRODUCTS

3.1 BACKGROUND

There is an increase in the demand for low production volume products as a result of increased product complexity and desire for more specialized products. For high production volume products, modularity has been shown to increase diversity, flexibility, and customer satisfaction and decrease assembly, repair, subsequent product design time, but modularity may also limit performance and innovation and requires more initial design time. There is little information regarding the implementation of modularity for specialized, low production volume products. This chapter presents a method for incorporating modularity into the design of specialized products with low production volume. I tested this method by designing a device to collect marine larvae as they arrive on the shore. My first-generation prototype performed much better than other existing devices, decreasing sample processing time by more than half, but it was expensive. To reduce the production costs, I utilized the modularity of the new design, identified the functional modules where off-the-shelf components could be used to fulfill each module's functional requirements, yielding a more economic second-generation prototype, the design project is on-going, without compromising the performances. Another benefit from this modularity-based design is that several variations of the larvae collectors can be easily evolved from this collector because of the flexibility offered by introducing the modularity into the new design. This experience has led us to conjecture that modularity-based design may offer a promising approach for producing high-quality products with affordable price in the design of specialized, low production volume products.

Product developers are incorporating a more user-oriented approach to design and collaboratively involving users in the design process. The focus is shifting from “This is what I make, won’t you please buy it” to “This is what I want, won’t you please make it” (Swaddling and Miller 2003). This attitude can be accommodated to a large degree with high volume products such as electronics and computers by designing highly modular products. This flexibility is much more difficult to satisfy with low production volume products due to the high overhead associated with developing new and customized products. With the paradigm shift to make products that customers request rather than selling products that are already made, the total volume of any particular product sold will decrease. Some customers will desire highly specialized products with extremely low volume of less than 500-1000 and some as low as 10 or fewer. Examples of this type of product include specialized scientific equipment, some spacecraft, and some recreational equipment (e.g. roller coasters). In most of these cases, future customer requirements are unknown and largely unpredictable, so flexible product design is essential to accommodate future needs. Decreases in production volume can dramatically increase both manufacturing and design costs per unit as other costs remain relatively fixed (Ullman 2003). Manufacturing costs can also be reduced substantially with good designs as well as efficient manufacturing processes.

Flexibility in design can be met by a number of different approaches (Qureshi et al. 2006), leading to products that are more easily customized. Modularization serves to both isolate specific functions that can be used in other products as well as to minimize the interface connections between modules, allowing easier design for new or different modules. Both of these effects have been shown to increase the flexibility of a design (Qureshi et al. 2006). Modularity in design has been embraced because it can improve the performance of a product in several ways (Lau Antonio et al. 2007). Modularity can easily increase the diversity, flexibility, and customization of products by having interchangeable modules that perform different functions (Rajan et al. 2004). Having an interfacing modular product can also reduce assembly costs because all modules easily fit together and can decrease the development and deployment time for new products (Rajan et al. 2004). Finally, customer satisfaction is increased due to fast response times, more customization, and faster repair times as faulty modules can easily be replaced. Additionally, manufacturing can be distributed more easily to other companies or countries. There are, however, a number of potential costs to designing for modularity associated with high production volume products. Designing modularity requires more initial design time (Jose and Tollenaere 2005) and can be difficult especially with more complex products (Holmqvist and Persson 2003). Modular products may not have the same quality as more integrated products because optimal designs may conflict with the modularity requirements. Using modular products can constrain innovation by limiting designers to available modules and the overall function is obscured by the individual functions of the modules (Holmqvist and Persson 2003).

The potential costs of modularization are often ameliorated with high production volume products by spreading the cost among many units. Consequently, much of the research on designing for modularity has focused on high production products or on the manufacturing methods used to make those products. This is mainly due to the increased diversity of products and reduced production costs associated with modular design. Modular products can easily be customized to individual users without increased costs when products are assembled from modular components. To achieve this all modules must have compatible interfaces, and consequently, much of the thinking has focused around the interfaces between modules and insuring various components are compatible. This focus on module interfaces, however, is inappropriate for low production volume products because the production costs will not be decreased enough to justify the additional design cost. Also, if modules have compatible interfaces, some design criteria, such as size and weight, may be difficult to satisfy. If modularity were incorporated early in the design process, many of these potential costs could be reduced or eliminated while retaining most of the benefits. This paper proposes a method to incorporate modularity in the early design phases of low production volume and specialized equipment.

To illustrate this method, I have redesigned a specialized, low production volume product using my methods and documented improved performance. Marine biologists are currently using a device to collect larvae as they arrive on shore that has many problems and may not be effective, so I designed a new larval collector. Modularity was incorporated at the earliest design stages by grouping customer requirements by function and in the identification of the functional requirements. During the functional decomposition of the device, I identified potential functional modules that were likely to have existing or easy to design solutions. After finding solutions to the selected functional modules, I then designed the interfaces between these modules to produce a proof-of-concept prototype. After concept selection, there was no attempt to redesign the prototype to improve modularity. The modularity index and design structure matrix of this prototype were similar to published values for other products considered to be modular, and the prototype performance was equal to or better than the existing product in all aspects. Finally, to facilitate subsequent designs I show how to incorporate the functional modules and associated interfaces in a database that will preserve much of the "institutional" knowledge gained from designing this product. Several examples of subsequent products based upon the functional modules in the current product are given.

3.2 A MODULARITY-BASED DESIGN APPROACH

A modularity-based design approach was developed to incorporate modularity into the earliest phases of design of specialized, low production volume products (Figure 3.2). When gathering customer requirements (Chapter 1) they are grouped into broad functional categories to facilitate the identification of functional requirements of the device. When forming functional requirements, broad level requirements are identified first and then these are subdivided into lower level groups or components. During this process, any functional requirements that have either a solution already identified or are likely to have been solved previously are identified. This procedure indentifies potential modules at this early stage of design, even before component level functions are identified or even considered. After identifying the functional requirements based upon the customer requirements, several solutions for each functional requirement may be identified. There are many potential sources to find solutions for these functional requirements, and this is a critical stage that differentiates good designs from great designs. Being able to recognize solutions to functional problems is essential for great designs, and inspiration can come from many sources including everyday life and nature. Solutions generated by nature are often overlooked by engineers, but these solutions are often some of the most efficient because there is very strong pressure to expend as few resources as possible to solve a particular problem, leaving more resources for growth or reproduction. At this stage, each functional solution, at any level in the functional hierarchy, represents a single module in the final design. Solutions from everyday life are particularly important for low production volume products, because a mass produced solution can usually be used for less cost than a custom designed solution. During the concept generation and evaluation stage of the design process, these functional modules can be interchanged amongst themselves to create many different overall concepts. Thus, at the concept evaluation stage the design is modular. After selecting a concept with the various functional modules, the interfaces of the modules can then be considered and modified to allow all of the modules to be assembled and function properly together. The focus is on identifying functional modules first and then adjusting the interfaces between the modules to produce a functional prototype. There is no subsequent redesign to enhance modularity after concept selection.

3.3 A CASE STUDY AND RESULTS

I implemented the modularity-based approach in Figure 3.1 to design a new larval collector (see Figure 3.2). In this case a previous device was already in use, so I could compare the performance of my new, modular collector relative to the currently used device of more integral design. One of the main concerns of the biologists was to separate the larvae from the sand in the water at some sites. Their traps often collected samples that either took several hours to process or the samples were discarded due to large amounts of sand. Thus, one of my performance criteria was the amount of sand collected and the processing time. In addition, I also compared the number of larvae collected and ease of use relative to the current collector. The new larval collector was placed within 0.5 meter of a previous version between 25-31August 2007. Samples were collected every two days, and the first sample was discarded due to lack of larval killing agent in the new collector, leaving two comparative sample dates.

There is no widely used method to design products to maximize modularity (Gershenson et al. 2004). Pimmler and Eppinger (1994) proposed using a matrix that represents the structure and function of the product, the design structure matrix. To increase the modularity of a product, several methods of clustering have been proposed (Sosale et al. 1997, Coulter et al. 1998, Stone et al. 2000, Zhang and Gershenson 2003) and compared (Guo and Gershenson 2004). In order to compare the methods, an index of modularity was developed and used to evaluate the performance of each modularity method for redesigning four different products. This index is simply the average component relationship within modules minus the average relationship between modules. This index can accommodate different relationship strengths but does not account for the number of different types of relationships, such as energy, information, and material. I developed a design structure matrix (Pimmler and Eppinger 1994) for the completed larval collector, calculated an index (Guo and Gershenson 2004) of modularity for this device, and compared my index to those published for other modular products. Thus, I was able to assess the modularity of my new larval collector relative to other products that are considered modular.

Problem Description: Onshore Marine Larval Collector

Marine biologists interested in the population dynamics nearshore animals have realized the importance of the free-living larval phase of these organisms (Gaines and Roughgarden 1985, Menge et al. 2003), but have been hampered in their studies due to an inability to sample larvae during critical life history stages (Harris et al. 2000). In particular, larvae of intertidal animals such as barnacles and mussels that live on wave-swept rocky coasts can be caught offshore by plankton nets, but it is currently very difficult to capture these larvae at any point between the open ocean and where the larvae land on the rocky shores. Thus, the critical transition stage from open-ocean to settling on the shore is essentially unknown for most organisms due to our inability to capture these larvae. To address this need, I have designed a device that will collect larvae as they reach rocky shores. The production volume for this device is expected to be less than 500. Other marine biologists, however, may be interested in adapting some components of this device for other purposes.

The onshore larval collector consists of a pyramid shaped outer shell that houses baffles to encourage the separation of sand particles from larvae, a filtering mechanism, and a device to measure the volume of sampled water (Figure 3.2). The entire device is anchored to the irregular rocky surface using a set of tracks, screws, and bolts. This device was inspired by organisms such as abalone, keyhole limpets, and prairie dogs that utilize the movement of surrounding fluids to move water or air through their bodies or borrows by taking advantage of Bernoulli's principle (Vogel 1981). By having an opening on a surface that is subject to higher flows than a connected opening in lower flows, the fluid will be moved through the object due to the pressure differential created by the difference in fluid flow.

Larval Collector Design

From the identified functional requirements for the larval collector, five main functional modules were identified (Figure 2.3). The modules were created by grouping functional requirements such that existing solutions could easily be implemented. The larval collector had four main functional modules: 1) attach to the rocks, 2) create water flow and provide structure, 3) filter and store larvae, and 4) measure and record water flow. The attachment function was satisfied by using screws to attach two tracks to the irregular rock surface. Stainless steel bolts fit in the tracks and could be moved along the tracks to accommodate variations in placement of the tracks and still hold the collector securely in place. This solution was inspired by woodworking T-slots for securing various jigs and fixtures. Water flow was created by the shape of the device, taking advantage of Bernoulli's principle. This concept was inspired by several biological examples (Vogel 1981). Sand was separated from larvae by taking advantage of the density differences between the two. Water flow was directed upwards and slowed to allow the dense sand to settle while the larvae, which are close to neutrally buoyant, remained in the water. The water flow was then directed downward through a removable filter that trapped the larvae and held them until collection. The filtering system is similar to a very small plankton net. The filter chamber also housed a killing agent to prevent the larvae from eating each other. Finally, water flow was measured as the water exited the device by turning a propeller, similar to a windmill, and the rotations were recorded using a bicycle computer. The identified solutions were then modified and adapted such that they could be assembled to meet the needs identified in the customer requirements.

Prototype Performance and Evaluation of Modularity

Relative to previous onshore larval collectors, the new modular version performed well. The modular collector trapped more barnacle larvae and only had trace amounts of sand compared to the old collector that had an average of 45 ml of sand. Due to the absence of sand, sampling time was reduced from an average of 2.5 hours to 25 minutes. Deployment time and sampling time in the field were about the same for both collectors and users identified some minor advantages of the new collector over the old collector in these regards. Unfortunately, the modular collector did not effectively collect mussel larvae because these larvae have a density much closer to sand than do the barnacle larvae. At sites where sand is not an issue, the modular collector can easily be adapted to not exclude sand and also collect mussel larvae. Due to water leakage and heavy sand infiltration, the flowmeter did not function properly.

The design structure matrix for this device is divided into four main modules and one of these modules contains three submodules (Figure 3.4). Two of these main modules perform two separate functions that are integral within the module. The structural module creates water flow and separates sand while the filter module filters larvae and prevents backflow, but these functions cannot be separated within the modules. With this modularity division, I calculated an overall modularity index of 0.21 and an index of 0.33 within the flowmeter module. These values are similar to those calculated by Guo and Gershenson (2004) for several modular products. To calculate the index, I used an average of the four relationship matrices that describe the spatial, energy, material, and information relationships among the components and modules. If a weighted average is used that places a higher weight on spatial and energy relationships to account for the constraints in changing these relationships (Whitney 2002), the modularity index increases slightly.

3.4 OBSERVATIONS AND REFLECTIONS

Modularity and Production Volume

There are many benefits of modularization and with high production volume products many of the costs are greatly reduced. Product flexibility can be enhanced by modularity (Rajan et al. 2004). If module interfaces are standardized, then it is just a matter of switching modules to create new product functions. Also, new modules can be designed, to further increase product diversity. The added time of organizing and implementing this mass customization can be ameliorated by the large number of products. Product modularity can also reduce production costs. With high production volume, assembly costs can be significant and modular products take less time to assemble compared to more integral products. In addition, entire modules can be outsourced to companies better suited to produce a particular module. With low production volume products, these benefits still exist, but the costs increase dramatically. The method outlined here may reduce the costs of designing for modularity while retaining many of the benefits, but there are additional reasons to incorporate a modular design.

Modular design can ease maintenance of products (Otto and Holtta 2004). With the product broken into functional units that only interact minimally with other units, it will be easier to locate malfunctions. A malfunction is often manifested as a loss of some function in the device. Knowing the impaired function can lead to the malfunctioning module and the failure can be isolated more quickly in a modular design compared to an integral design. In addition, malfunctioning modules may be easily replaced in modular design rather than replacing the malfunctioning component. The replaced module can then be repaired later with little down time for the device. Except for the original design time for modularity, this benefit of modular design is independent of production volume. Additionally, well-defined interfaces also make the system more amenable to systems health management (Johnson 2007) as well as safety engineering (Leveson 2004).

The design of additional new products is often easier with modular products compared to integral products. By using existing modules, new products can often be designed without a full redesign of the existing module. This is especially true for electrical signal transmission systems where interfaces are well-defined and often standardized and signal flow is unidirectional reducing the chance of feedback loops and making connections easy (Whitney 2002). If interfaces are standardized within a product line, then designing new products is relatively easy as many modules can be readily interchanged. If, however, the interfaces are more complex, then new product design can be more difficult but it will likely be easier than designing a new integral product where all the interfaces between modules and components need to be initially defined. Again, production volume plays a critical role in design. In cases where a small number of products are to be made and few or none of the functions are likely to be needed in the future, designing an integral product would be more efficient than a modular product due to the added cost of designing for modularity. With larger volumes, the added cost of designing for modularity is spread among all the products and becomes negligible. If, on the other hand, some functions are likely to be needed in the future, then designing for modularity may make sense for low production products.

Larval Collector Performance

In designing the larval collector, I produced a product that had relatively high modularity with little additional design time. This was accomplished by incorporating modularity from the earliest stages of the design process. I first identified and understood all customer requirements. After gathering customer requirements and grouping them according to potential functions, a functional model was produced that specified the known functions and interactions between the functions. At this early stage, potential modules were identified with potential solutions considered in some cases. This created the foundation of the modularity in the final product. Current methods to determine modules require more information than was available at this stage and were of limited value. With the major modules in place, further functional decomposition was carried out within the major modules and sub-modules were identified. This process continued down to the component level of the product. By incorporating modularity early in the design stage I was able to eliminate the use of more traditional modularity techniques that typically occur after concept selection.

The larval collector produced by this method performed much better than the predecessor with a more integral design by collecting a similar number of larvae, greatly reducing the sample processing time by reducing the sand volume, and being equal to or better than the predecessor in user friendliness. It may be possible to increase the modularity of this product by rearranging the components using one of the clustering techniques reviewed by Guo and Gershenson (2004). For this product, however, this may not be worth the effort as it already has a fairly high modularity index and the cost in reorganizing the components would likely outweigh the advantages of increased modularization. One of the main reasons for implementing modularity in low production products is to utilize the current designs in future products. The modules identified for this product are already being employed in conceptual designs on future products. The attachment system is highly adaptable to different shapes and sizes and should prove useful in many designs. The structure module is being considered as a possible method of creating water flow through a moored larval collector, and the separate sand function solution is employed in a pump version of the onshore larval collector. Finally, the flowmeter module is being adapted to measure water flow in the intertidal environment as well as recording the immersion time.

Looking Forward: A Structured Database

These modules and their functions have served as a template to begin structuring a database (Figure 3.4). The fields in the database include function verbs and nouns, module name, qualifiers to indicate the intent of the module, design history, file locations and names, customers, and other relevant information. A database of this nature would be useful within a company or organization to catalog solutions for various functions as well as all relevant information associated with that solution, but its broader use may be limited. The functions for which a particular company may need solutions are likely to be similar over time and including functions outside of that company may generate many inappropriate results. Private companies, in particular, may be very sensitive about their solutions to particular functions and unwilling to share information. On the other hand, this type of database could also house information on the products of competitors or other potential solutions to functions that may be useful to the company. The onshore larval collector uses both of these types of outside information. The solution function of creating water flow by using Bernoulli's principle employed by various animals is shown in the example database (Figure 3.5). Similarly, the function of a bicycle computer is also in the database. These two function solutions are derived from nature and external companies. Finally, such a database would retain a large portion of sequestered institutional knowledge. If a design engineer recorded his/her design efforts in the database, the solutions would be retained within the company for use by others. The biggest challenge to implementing such a database is to design it to be easy to use and to get designers to use it. With a well-designed database, it should take a minimal amount of time to input the essential information into the database, being on the order of 0.5 hours every 3-6 months of design time.

3.5 SUMMARY

High production products with relatively low complexity will benefit from modularization that focuses on interfaces and creates standard interfaces (Lau Antonio et al. 2007). As production volume decreases, the benefits of interfacing modularity decrease but the functional modularity may still result in substantial benefits. Thus, I expect functional modularity to be important for low production volume products. The importance of interfaces should increase as product complexity increases due to the interactions between modules. Numerous modules at various levels without well defined and standardized interfaces may result in unanticipated interactions between the modules resulting in system failure (Leveson 2004). Finally, if the idea of functional modularity is taken to the extreme and interfaces are ignored completely, then the creative design process is emulated where different solutions to various functional problems can be freely combined to develop innovative new designs. This may be a good model for developing a database of functional solutions to aid in the design process. Including some standard metadata features into the database could result in a database that captures some of the historical knowledge within a company or agency that is now typically held with experienced designers. As design solutions are created to solve various functions, it would be relatively easy to input the information into a database, taking on the order of a few minutes. The database could reference drawings, notes, and other pertinent information for each solution. With a large number of these design modules catalogued, a design engineer could select the appropriate verb and noun and be presented with all the previous solutions to that function.

There are two critical needs that need to be addressed by future research. First, a new method for developing a modular structure needs to be developed that can be used in the early design stages. This method needs to be easy to implement and must not require extensive knowledge about the product. The matrix methods for modularization have proved to be robust and are intuitive, quantitative, and conceptually simple although they can quickly become complex and cumbersome. These matrix methods would be a good starting point for developing a new early design modularization method. Because many of the relationships within potential modules are unknown at the early design stage, a new method will probably need to focus on minimizing the relationships between modules rather than maximizing those within modules. Second, information about the relationship of the degree of modularity and the realized benefits needs to be generated. How modular does a product need to be to benefit from that modularity? One way to pursue this would be to catalogue a number of products that range in their modularity and correlate their index of modularity with parameters indicative of the benefits and costs of modularization. If the benefits of modularization can be realized with limited modularity, than the method of modularization used during the initial design stages will be less critical and should not seek to optimize the modularity.

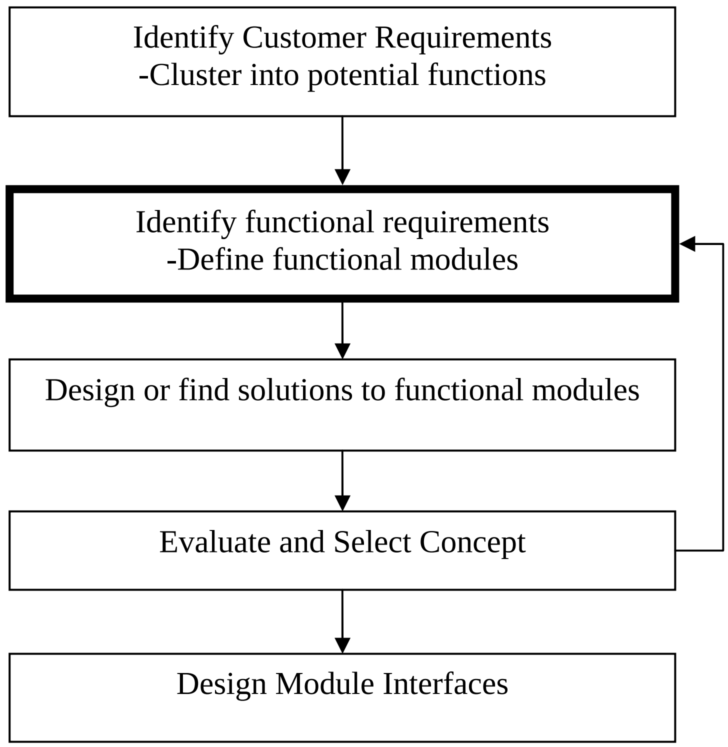

Figure 3.1. Methodology Overview: a Flow chart displaying steps for designing modularity into low production volume products. The stage outlined in bold is the primary step where modularity is incorporated.

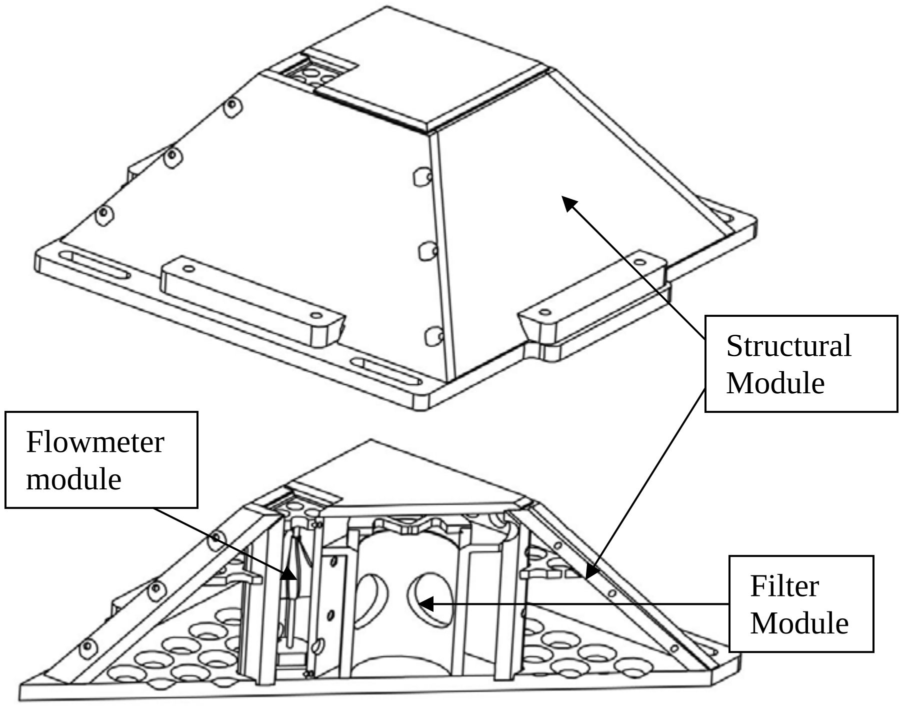

Figure 3.2. Onshore larval collector. The top view shows the collector in its entirety and the bottom view is a cross section with three of the four main modules indicated. The fourth module that attaches the collector to the rocks has been omitted.

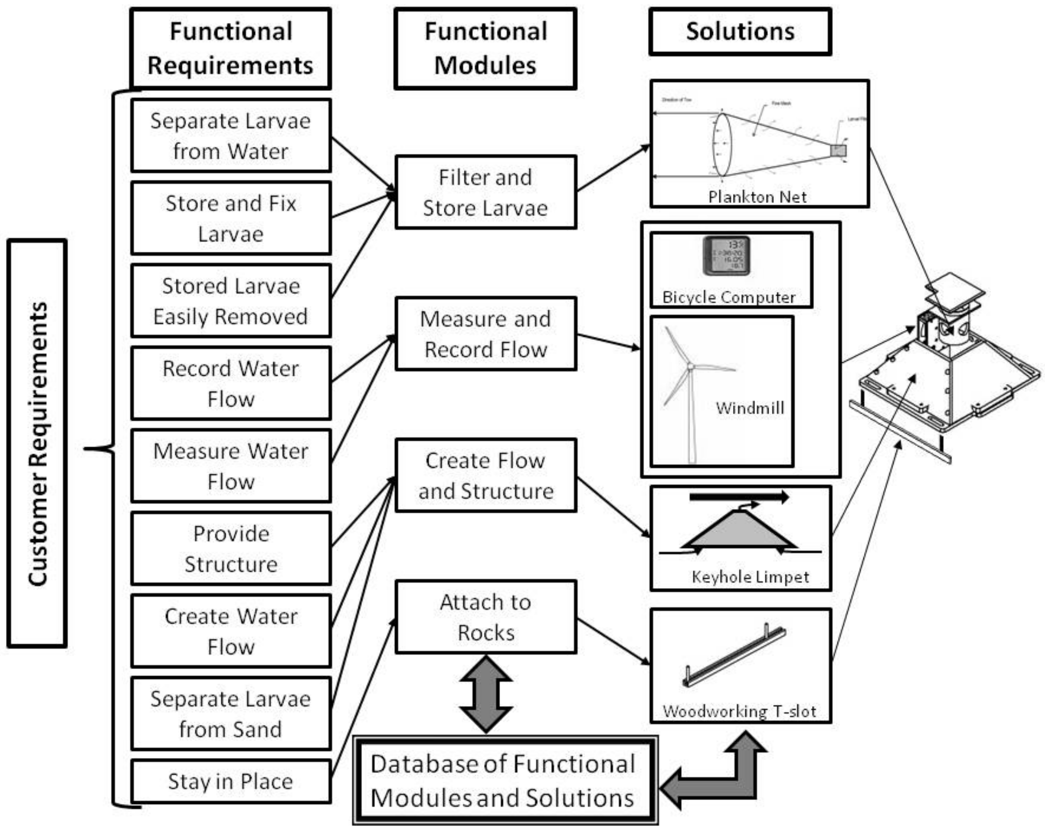

Figure 2.3. Diagram showing the design sequence for the larval collector. Customer requirements were collected and functional requirements were generated which were then grouped into functional modules. Solutions were identified for each functional module and then the interfaces between modules were modified to create the final product. A database would interact with both solutions and function modules.

Figure 3.4. Design structure matrix for the onshore larval collector. Values in the cells are averages of the 4 matrices for each type of flow. The modules are outlined and named from the upper left to lower right as 1) attachment, 2) structural, 3) filter, and 4) flowmeter. The flowmeter module is divided into three submodules.

Output		Input 1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
1	Rock Screws	X	2																							
2	C-Track	0.8	X	2.4	2																					
3	Spacers		0.8	X	0.8	2.4																				
4	Attachment Bolts		0.8		X	2																				
5	Base			0.8	0.8	X	0.1	1.3	0.5					0.1					0.4							
6	Baffle					0.9	X	0.5	0.9																	
7	Shell					1	0.6	X	0.9	1.6																
8	Inner Box					1.4	0.2	1	X	0.8	0.1	0.1		0.6			0.4		0.4							
9	Lid							0.8	0.2	X	0.9	0.1			0.4	0.4	0.4	0.4								
10	One-way Lid								0.2	0.5	X	1.3	0.1	0.8												
11	Filter Ring								0.1		1.3	X	0.9	1.6												
12	Filter										0.2	2.2	X													
13	Filter Support					0.8			0.9				0.2	X		0.8										
14	Flow Meter Front														X	0.8	0.4		0.4							
15	Flow Meter Left					0.4								1	0.8	X	0.1	1.3	1.3	0.9						
16	Flow Meter Right					0.4			0.8						0.8	0.1	X	1.3	1.3	0.9						
17	Flow Meter Back															0.9	0.5	X	0.9	0.9						
18	Flow Meter Base					0.8										1.3	0.9	0.9	X	0.1	0.4					
19	Flow Meter Top															1.3	0.9	1.3	0.1	X	0.4					
20	Fan Shaft																		1.2	1.2	X	2.5				
21	Fan																				1.2	X				
22	Magnet Disc																				2.5		X			
23	Sensor																		1.2				0.1	X	0.4	
24	Wire																							1.3	X	1.2
25	Bike Computer														0.4	0.4	0.4	0.4	0.4					0.4	0.5	X

Figure 3.4

Figure 3.5. Basic structure of a design database with some example entries taken from the example given in the text. Some entries have been deleted for the last three devices or modules for clarity. This structure is not necessarily complete and is intended to only as an example of the type of entries and fields in such a database. In a true relational database, any of these entries could be searched and multiple items per entry would be allowed. Also, tables of similar terms could be referenced allowing boarder searches to be conducted.

Database Fields	Example Entries			
Device or Module	LIMPET - Onshore Larval Collector	LIMPET Support System	Bicycle Computer	Abalone
Module of:	None	LIMPET	LIMPET Flow Meter	
Function Verb	Collect	Attach	Records	Move
Function Noun(s)	Larvae	Device	Rotation	Water
Qualifers	On or near substrate	On wave beaten substrate	Records and stores number of rotations (needs calibration and conversion)	
Designer	Peter van Tamelen		Specialized	Nature
File Locations (Current File Storage Location\...)	\Projects\OnshoreLarvae\Square3\Assem1		None	
Notebook	Onshore Larval Sampler			
Notebook #	1			
Company/Instituion	Oregon State University		Specialized	
Month Started	January			
Year Started	2007			
Prototype Test Month				
Prototype Test Year	2007			
Initial Customer(s)	Sarah Dudas, Joe Tyburczy, Gil Rilov, Bruce Menge			
Drawing Program	SolidWorks			
Program Version	2006 SP4.1			
Notes:				

Figure 3.5

4. CONCLUSION AND FUTURE WORK

In order to create new devices that allow field biologists to collect needed data more efficiently or to gather data that is currently impossible to collect, a formal engineering approach is needed. Generally, these devices will need to be highly specialized and will typically be produced in low numbers, requiring the adaptation of current engineering design techniques to address these traits. Most engineering design techniques are aimed at producing large numbers of devices suitable for fairly general applications. There are some well-funded examples of highly specialized, low volume products, such as spacecraft, but the budget for developing such products is often much greater than the funds available to biologists. Thus, new or modified engineering techniques are needed to make highly specialized products available to biologists with modest budgets.

I designed and tested a prototype device in collaboration with field biologists to begin to develop techniques to enable engineers to efficiently design similar products. This initial product was a new larval collector that could collect larvae as the reach wave-swept rocky shorelines. The goal of this research project was to identify which method or combination of methods for gathering customer requirements performed best in this situation and to develop design techniques that can utilize off-the-shelf components and reduce design time for similar products in the future.

The first step in developing a new product is to generate a thorough list of the requirements for the device. There are many methods for collecting customer requirements, but little evidence documenting the efficacy of these techniques. In chapter 1, I compared three methods of collecting customer requirements from biologists. Written surveys were effective at identifying basic requirements, and focus group discussions identifying performance and attractive requirements. To fully identify the customer requirements, I suggest that a combination of both be used. One way to do this efficiently would be to have the customers respond to a written survey and then immediately meet to focus on obtaining more attractive requirements. To get the best information possible, at least 3 customers should be involved in this process. If fewer customers are queried, some requirements may not be identified, but if too many are employed, the focus group could become unproductive. Additionally, an engineer with experience using the device or similar devices in similar situations can add substantially to the identification of customer requirements.

Although modularity is typically used for high production volume products to increase customization and decrease manufacturing costs, designing low production volume products for modularity may yield benefits. When I incorporated modularity early in the design process to meet the functional requirements of the device, the resulting prototype was highly modular with little additional design effort. When modules satisfy individual functional requirements, finding off-the-shelf components that meet the functional requirements is easier. Incorporating off-the-shelf components reduces manufacturing costs by reducing the need for custom made parts. In this case, the interfaces between modules need to be adapted to produce a complete product. Modular design to meet functional requirements also makes designing future products with the same or similar functional requirements easier. If the solutions to functional requirements are catalogued in a well-designed database, they will be available to future designers regardless of the loss of senior personnel, reducing the loss of “institutional” knowledge. Given these advantages to designing for modularity and the minimal associated costs, modular design makes sense for highly specialized, low production volume products.

Using these methods for collecting customer requirements and designing for modularity, I designed and tested a prototype larval collector. This device outperformed other versions by virtually eliminating the collection of excess sand reducing sample processing times to about 25% of the previous times. However, reducing the collection of sand also resulted in lower collection rates of mussel larvae that have about the same density as sand and are thus difficult to separate. In areas with low sediment loads in the water, mussel larvae can still be collected but any suspended sand may also be collected. Additionally, the electronic collection of water volume data, if it had worked, would also substantially reduce sample processing time by eliminating the need to make and weigh dissolution blocks that were used previously. By designing for modularity, the functional modules developed for this device can by incorporated into several other products with similar functional requirements.

This collaboration between field biologists and design engineers yielded a new and useful product that will enhance our understanding of larval dynamics. The methods and techniques developed and tested in this thesis will enhance the ability of engineers to continue to design and produce specialized, low production volume equipment for field biologists as well as field scientists in other disciplines. With these new devices, biologists should be able to collect data more efficiently and obtain data that is not currently possible to collect, enhancing our understanding of the natural world and its resources. Currently, many of the management decisions are based on surprisingly few data, and the development of new data collection devices will result in decisions based upon more and better information.

BIBLIOGRAPHY

Barrowman, N. J. and R. A. Myers. 2000. Still more spawner-recruitment curves: the hockey stick and its generalizations. Canadian Journal of Fisheries and Aquatic Sciences 57:665-676.

Cagan, J. and C. M. Vogel. 2002. *Creating Breakthrough Products: Innovation from Product Planning to Program Approval*. Prentice Hall, New Jersey.

Caselle, J. E. 1999. Early post-settlement mortality in a coral reef fish and its effect on local population size. Ecological Monographs 69:177-194.

Cohene, T. and S. Easterbrook. 2005. Contextual risk analysis for interview design. In: *Proceedings - 13th IEEE International Conference on Requirements Engineering*, Institute of Electrical and Electronics Engineers Computer Society, Piscataway, NJ, pp. 95-104.

Coulter, S. L., B. Bras, M. W. McIntosh and D. W. Rosen. 1998. Identification of limiting factors for improving design modularity. Proceedings of the 1998 ASME Design Engineering Technical Conference – 10th International Conference of Design Theory and Methodology. Atlanta, GA.

Flint, D. J. 2002. Compressing new product success-to-success cycle time: deep customer value understanding and idea generation. Industrial Marketing Management 31:305-315.

Gaines, S. and J. Roughgarden. 1985. Larval settlement rate: a leading determinant of structure in an ecological community of the marine intertidal zone. Proceedings of the National Academy of Sciences, USA 82:3707-3711.

Gershenson, J. K., G. J. Prasad and Y. Zhang. 2004. Product modularity: measures and methods. Journal of Engineering Design 15:33-51.

Gilbert, D. J. 1997. Towards a new recruitment paradigm for fish stocks. Canadian Journal of Fisheries and Aquatic Sciences 54:969-977.

Griffin, A. and J. R. Hauser. 1993. The voice of the customer. Marketing Science, 12:6-12

Guo, F. and J. K. Gershenson. 2004. A comparison of modular product design methods based upon improvement and iteration. Proceedings of the ASME International Design Engineering Technical Conference & Computers and Information in Engineering Conference. Salt Lake City, UT.

Harris, R. P., P. H. Wiebe, J. Lenz, H. R. Skjoldal, and M. Huntley. 2000. *ICES Zooplankton Methodology Manual*. Academic Press, London.

Hintersteiner J. D. 2000. Addressing changing customer needs by adapting design requirements. In: *First International Conference on Axiomatic Design, ICAD2000*, pp. 290-299.

Hilborn, R., E. K. Pikitch, and R. C. Francis. 1993. Current trends in including risk and uncertainty in stock assessment and harvest decisions. Canadian Journal of Fisheries and Aquatic Sciences 50:874-880.

Holmqvist, T. K. P. and M. L. Persson. 2003. Analysis and improvement of product modularization methods: their ability to deal with complex products. Systems Engineering 6:195-209.

Johnson, S. B. 2007. Introduction to system health management in aerospace.

Jose, A. and M. Tollenaere. 2005. Modular and platform methods for product family design: Literature analysis. Journal of Intelligent Manufacturing 16:371-390.

Joshi, A. W. and S. Sharma. 2004. Customer knowledge development: antecedents and impact on new product performance. Journal of Marketing 68:47-59.

Lau Antonio, K. W., R. C. M. Yam and E. Tang. 2007. The impacts of product modularity on competitive capabilities and performance: an empirical study. International Journal of Production Economics 105:1-20.

Leonard, D. and J. F. Rayport. 1997. Spark innovation through empathic design. Harvard Business Review.

Leveson, N. 2004. A new accident model for engineering safer systems. Safety Science 42:237-270.

Mace, P. M. 1994. Relationships between common biological reference points used as thresholds and targets of fisheries management strategies. Canadian Journal of Fisheries and Aquatic Sciences 51:110-122.

Matzler, K. and H. H. Hinterhuber. 1998. How to make product development projects more successful by integrating Kano’s model of customer satisfaction into quality function deployment. Technovation 18:25-38.

Menge, B. A., M. Bracken, M. Foley, T. Freidenburg, G. Hudson, C. Krenz, H. Leslie, J. Lubchenco, R. Russell, and S. D. Gaines. 2003. Coastal oceanography sets the pace of rocky intertidal dynamics. Proceedings of the National Academy of Sciences, USA 100:12229-12234.

Myers, R. A. and N. C. Cadigan. 1993. Density-dependent juvenile mortality in marine demersal fish. Canadian Journal of Fisheries and Aquatic Sciences 50:1576-1590.

Neale, M. R. and D. R. Corkindale. 1998. Co-developing products: involving customers earlier and more deeply. Long Range Planning 31:418-425.

Odell, D. and P. Wright. 2002. Concurrent product design: a case study on the pico radio test bed. *Masters Thesis, University of California at Berkeley*.

Otto, K. and K. Holtta. 2004. A multi-criteria framework for screening preliminary product platform concepts. Proceedings of the ASME International Design Engineering Technical Conference & Computers and Information in Engineering Conference. Salt Lake City, UT.

Otto, K. N. and K. L. Wood. 2001. Product Design: Techniques in Reverse Engineering and New Product Development. Prentice Hall, New Jersey.

Pahl, G. and W. Beitz. 1989. *Engineering Design: A Systematic Approach*. Springer-Verlag, New York, New York.

Pimmler, T. U. and S. D. Eppinger. 1994. Integration analysis of product decompositions. Design Theory and Methodology 68:343-351.

Qureshi, A., J. T. Murphy, B. Kuchinsky, C. C. Seepersad and D. D. Jensen. 2006. Principles of product flexibility. Proceedings of the ASME International Design Engineering Technical Conference & Computers and Information in Engineering Conference. Philadelphia, PA.

Rajan, P. K., M. J. Van Wie, K. L. Wood, K. N. Otto and M. I. Campbell. 2004. Empirical study on product flexibility. Proceedings of the ASME International Design Engineering Technical Conference & Computers and Information in Engineering Conference. Salt Lake City, UT.

Rice, J. C. and L. J. Richards. 1996. A framework for reducing implementation uncertainty in fisheries management. North American Journal of Fisheries Management 16:488-494.

Sosale, S., M. Hashemian and P. Gu. 1997. An integrated modular design methodology for life-cycle engineering. Annals of the CIRP 46: January.

Stone, R. B., K. L. Wood and R. H. Crawford. 2000. A heuristic method for identifying modules for product architecture. Design Studies 21:5-31.

Suh, N. P. 1990. *The Principles of Design.* Oxford University Press, New York, New York.

Suh, N. P. 2001. *The Principles of Design: Advances and Applications,* Oxford University Press.

Swaddling, D. C. and C. Miller. 2003. Understanding tomorrow's customers. Marketing Management 12:31-35.

Ullman, D. G. 2003. *The Mechanical Design Process. Third Edition.* McGraw-Hill, New York, New York.

Ulrich K.T. and S. D. Eppinger. 2000. *Product Design and Development, Second Edition*. McGraw-Hill, New York, New York.

Veryzer, R. W. and B. Borja de Mozota. 2005. The impact of user-oreinted design on new product development: an examination of fundamental relationships. Journal of Product Innovation Management 22:128-143.

Vogel, S. 1981. Life in Moving Fluids: The Physical Biology of Flow. Princeton University Press, Princeton, NJ.

Whitney, D. E. 2002. Physical limits to modularity. Massachusetts Institute of Technology Engineering Systems Division, Working Paper Series ESD-WP-2003-01.03-ESD Internal Symposium.

Zhang, Y. and J. K. Gershenson. 2003. An initial study of direct relationships between life-cycle modularity and life-cycle cost. Concurrent Engineering Research and Applications 11:121-128.

Zheng, J. and G. H. Kruse. 1998. Stock-recruitment relationship of Bristol Bay Tanner crab. Alaska Fishery Research Bulletin 5:116-130.

Zheng, J. and G. H. Kruse. 2000. Recruitment patterns of Alaskan crabs in relation to decadal shifts in climate and physical oceanography. ICES Journal of Marine Science 57:438-451.

APPENDICES

APPENDIX 1. Larvae Collector Requirements Survey

What objectives would you like to accomplish? (list and rank)

Describe the typical environment in which the device will be used.

Describe the general process of transporting and setting up the device on location.

Describe the general process of removing, handling, and transporting larvae from the environment.

What would be about the desirable size of the device?

a) a coffee cup
b) a toaster
c) a computer
d) a 5 gallon bucket
e) other:____________________

About how much should it weigh?

a) Cup of coffee (~1lb)
b) Melon (~4lbs)
c) Gallon of milk (~8lbs)
d) Bag of dog food (~20lbs)
e) other:_____________________

What is the desired time for a single sample?

a) hour
b) day
c) week
d) month
e) other:_____________________

What is the desired lifetime for the device?

a) days
b) weeks
c) months
d) years
e) other:_____________________

How much would you expect this device to cost?________________________

What do you like about the current device(s)?

What do you dislike about the current device(s)?

Are there any additional features that you would like in a new device?

APPENDIX 2. Final List of Customer Requirements

The list of customer requirements for an onshore larval sampler written surveys, focus group, and experienced analyst. The method that identified each requirement is indicated in the right columns and the Kano category (B=Basic, P=Performance, A=Attractive) for each requirement is given. The requirements are grouped by major function.

CR#	Kano Category	Written Survey	Written Survey	Focus Group	Peter
Sampling Features					
1	B	Collect larvae	X	X	
2	B	Measure water volume for density	X	X	
3	A	Function unattended from 3-6 hrs up to 1-2 days	X	X	
4	A	Collect multiple samples per collection period	X	X	
5	B	Sample regardless of water level	X		
6	A	Actively sample seawater	X	X	
7	B	Reject sand from collection samples	X	X	
8	A	Record flow type during larval collection	X	X	
9	B	Sample seawater independent of flow conditions	X	X	
10	A	Record water level during larvae collection		X	
11	A	Sample a discrete amount of water		X	
12	A	Multiple devices can be synchronized to sample at same time		X	
13	P	Capable of sampling large volumes of water		X	
14	A	Fixing agent is mildly toxic		X	
15	A	Known fixative levels in samples		X	
16	B	Multiple sampling orientations		X	
17	A	Measure time of immersion or other variables			X
18	B	One-way flow so collected larvae stay			X
19	A	Cease sampling and recording if clogged			X
20	A	Collection height range adjustable or specified			X
21	A	Capable of targeting different types or sizes of larvae			X
Servicing Features					
22	B	Removable collection containers	X	X	
23	B	Fixing agent should kill larvae but not ruin DNA	X	X	
24	B	new fixative can be added	X		
25	A	Serviceable in low light conditions		X	
26	A	Visual confirmation of assembly (positive feedback)		X	
27	A	Easily cleanable surfaces		X	
28	A	Easily located (at night, under canopy)			X
29	B	Easily read and recorded ID			X
30	A	Associate collection containers with individual device			X
31	A	Sample containers ready to go when removed			X
32	A	Gloves not necessary			X

Physical Features					
33	B	Withstand harsh physical environment	X	X	
34	B	Withstand large and rapid temperature changes	X	X	
35	B	Withstand corrosive seawater environment	X	X	
36	B	Protect moving parts from sand and organisms	X		
37	B	Bolt to rocks with bolts	X	X	
38	B	Attach near/in mussel beds	X		
39	B	Easily carried by one person	X	X	
40	B	Multiple devices carried by one person	X		
41	P	Installation in less than 4 hrs	X	X	
42	P	Easily and quickly serviced in field	X	X	
43	P	Easily replaceable parts	X	X	
44	B	Deploy and maintain for 3 months	X	X	
45	B	Lifetime of years	X		
46	B	Smaller than 5 gal bucket (preferably coffee cup size)	X		
47	B	Weighs less than 20lbs (preferably about 1 lb)	X		
48	P	Cost less than $50 but more if saves time	X	X	
49	P	Minimal labor in assembly	X	X	
50	B	Low-profile body	X		
51	B	Stored for 9 months in lab		X	
52	B	Usable in any language		X	
53	B	Sturdy and robust parts withstand several collection cycles		X	
54	B	Adaptable attachment system (drill holes not perfect)			X
55	A	Nesting or stackable for transportation and storage			X
56	A	Provide a carrier for sample containers			X
57	B	Collections containers are discrete, rugged and easily handled			X
58	A	If batteries-easily last season but must replace every year			X
59	A	Device is adaptable to other environments			X