A usage coverage based approach for assessing product family design

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Chapter I

1. Introduction to the research

This chapter presents an introduction to the research which is reported in this thesis. It describes the challenges of mass customization and product family modeling both to industrial and academic domains, which form the background of this research work.

1.1. Introduction

The aim of this research is to model the usage context, relative product family assessing indices, and the method of how to optimize an existing product family regarding the various usage contexts expected by the consumers. These assessing indices and approaches can support diagnosis on the product family's performance regarding the variety of products in the product family in a competing market.

The major need is to support decision-making for designers and companies while restructuring and redesigning a product family in order to create a better fit to various actual usage demand of the market. The industry is now facing the dynamic economy, the highly competitive world wide located suppliers and the complex market requirements. Many market-oriented companies develop rashly new product families without a comprehensive study of potential product's usage context. They become quickly outpaced by their product complexity due to uncontrollable expansion of the product family. The thesis behind the research is to build a process and indices which can support these companies in making better and well-founded decisions about the product family and furthermore to make the product family more adaptive to target markets.

One interesting example, extracted from the Manual of Karcher high pressure washers, reveals the requirements for the analysis usage context and the initial attempts by the companies. Karcher supplies the market with a series of products – a product family of washer designed for different market segments, Figure 1-1.

Figure 1-1 Karcher high pressure washer series

These products differ from technique features and price, but share certain main components between one and the other, as listed in Table 1-1. The predefined performances by constructor, which are equal for all the users in the target market segment, increases with the cost the users should afford.

Table 1-1 Karcher high pressure washer series

<table>
<tr><th></th><th>Market Segments</th><th>Series No.</th><th>Price</th><th>Principal Platforms</th></tr>
<tr><td>K2</td><td>Entry-level class (occasional)</td><td>K2.38M+</td><td>113.00</td><td>Universal Motor, Ncor® Pump</td></tr>
<tr><td>K3</td><td>Medium-duty class (regular)</td><td>K3.86M+</td><td>160.00</td><td rowspan="2">Induction Motor, Ncor® Pump</td></tr>
<tr><td>K4</td><td>Comfort class (frequent)</td><td>K4.91M+</td><td>200.00</td></tr>
<tr><td rowspan="2">K6</td><td rowspan="2">Performance class (intensive)</td><td>K6.90M+</td><td>310.00</td><td>Induction Motor, Aluminum Pump</td></tr>
<tr><td>K6.95M+</td><td>360.00</td><td rowspan="3">Induction Motor, Brass Pump</td></tr>
<tr><td rowspan="2">K7</td><td rowspan="2">Top class</td><td>K7.20MX+</td><td>380.00</td></tr>
<tr><td>K7.85MX+</td><td>480.00</td></tr>
</table>

In order the help the user to choose appropriately from the numerous products in the family, the manual gives a subjective schematic diagram Figure 1-2. The potential usage context is represented by "degree of dirtiness" and "surface to clean". It is a good attempt and intuition help for user to make buying decision. For the designers, the questions of whether the given product family is well designed and positioned, and of whether these is cannibalization among the products, are even interesting to analyze. On the other side of view to see this problem, we believe the usage context can supply designers more objective and accurate prompts while making product family design decisions.

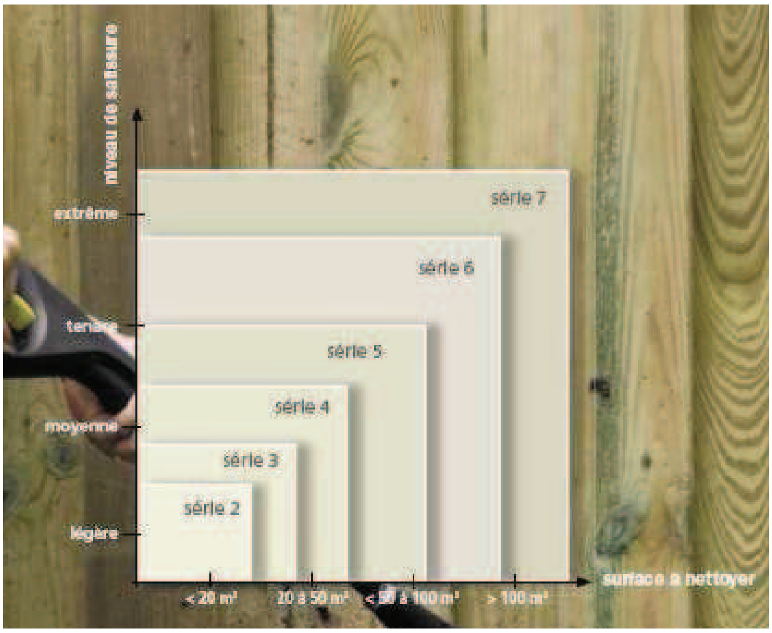


Figure 1-2 Performance evolution with usage contexts (dirtiness and surface to clean)

So far, most of the rare academic research concerned with assessment of product families focus around structure similarities and economic models (Meyer and Lehnerd 1997). The main objective of product family design is to allow a particular standardization degree which forms the platforms, and still leave product flexibility to adapt to various usages. Scale-based product family development process has a strong practicability in development cost and is widely used in the industrial domain. Many relative researches exist also in design engineering (Otto and Wood 2001).

1.2. The Challenge from industrial domain

"Any customer can have a car painted any color he wants as long as it is black": Henry Ford's famous maxim marks the beginning of meaningful mass production thought in the industrial age. While Ford's production model was indeed a pioneer in the revolution of mass production, he was also a pioneer in mass customization since more than 5% of Ford's production was mass customized (Alizon, Shooter et al. 2007). Figure 1-3 shows the evolution of the main production method from 1914 till now: from craft production to mass production, then to lean production and finally to mass customization. Mass customization requires an increasingly distinct number of products on sale while volume per product stays relatively low. This has introduced the challenge of fulfilling various market requirements while keeping production costs low.

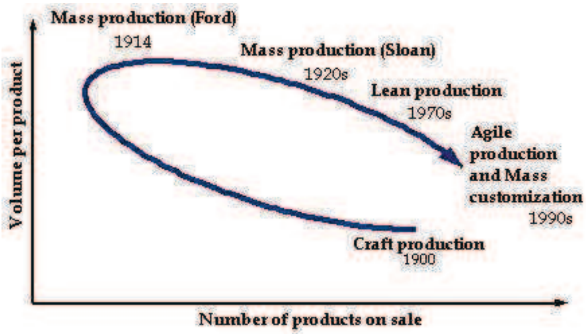


Figure 1-3 The evolution of production method (Pine 1993)

In a global business world manufacturing companies face ever growing opportunities and threats. Many companies are facing today an unprecedented trend of individualization of demand. While having the opportunity to satisfy increasingly diverse customer needs, exploiting new technologies and gaining access to formerly inaccessible regions and markets, companies also face increasing threats from existing and new competitors. Moreover, the globalization is a major driver for customer expectations in terms of lower price level and availability of products that suits whatever needs the customer may have (Pine 1993). Thus, the concept of mass customization emerged, which is defined by (Jiao and Tseng 2000) as "producing goods and services to meet individual customer's needs with near mass production efficiency". While customization is a known strategy in many B-to-B markets, today's buyer's markets are also compelling consumer companies to increasingly offer customized products. A recent Forrester report (Johnson 2006) confirmed the attractiveness to customers of purchasing customized products. Customers are better educated with higher income levels, less likely to compromise, and pay more attention to personal usage adaptation of a given product.

Two examples (Simpson, Marion et al. 2007) involving two consumer product companies and their product lines are presented. Even when considering outsourcing, platform-based product development principles can still yield tangible improvements in production costs over the life of the product.

Greater use of computer technology in design engineering, the reduction of time-to-market and consumer participation in design have all helped make the competition in consumer product development much fiercer. Marketplace globalization, the proliferation of niche markets, increased competitive pressures, and demand for customized products have rendered the practice of isolated design and production of individual products nearly obsolete. Across many industries, the prevailing practice is to design families of products that exploit commonality to take advantage (Simpson, Marion et al. 2006). Companies and product designers have to capture the elements which are hardly noticed by traditional design processes, such as usage context (Yannou, Chen et al. 2009). Product family development concept has been widely accepted both in academic and industrial contexts. Companies like Sony, Black & Decker and Volkswagen, for instance, have successfully implemented strategies to design an entire family of products based on modular-based and/or scale-based platforms to satisfy a wide variety of customer requirements, while benefiting from the advantage of economies of scale (Meyer and Lehnerd 1997). The development of product families has made company production processes and supply chains more flexible. The measurement of usage satisfaction for a given product family is a significant factor in the evaluation and decision-making processes of product family design or redesign.

1.2.1. New trends lead to research

Nowadays the manufacturing industry has been facing the particular challenge of the demand of quick responses to dynamic and various customer needs. The increasing complexity of product design, the rapidly changing design and product technologies enhancements maintain all companies in fast paced environments. The most important point facing this challenge is the company's ability to adapt its design to diverse market requirements within a short time and at a relatively low cost. Mass customization enhances profitability through a synergy of increased customer-perceived value and cost reduction in production and logistics.

Mass Customization

Mass customization is designed to deliver highly customized products with mass production efficiency. While discussed in the literature for more than a decade, mass customization has only recently been introduced to a large extent (Piller and Kumar 2008). The ongoing globalization of business and the general rise in living standards is a major driving force in the change of most markets as they become increasingly more diverse. Customers today are not very likely to accept

Henry Ford's product offering with "any color as long as it is black".

Consumer Markets

Consumers are becoming increasingly aware of the fact that they can express their personality through the products they buy and use – and people want to stand out from the mass and be regarded as unique individuals. Therefore it is no longer sufficient to have the same products as others. Consumers demand products that fit their individual usage – ultimately custom made products but in reality in a trade off with the price level (Pine 1993).

Durable Product

Consumers encounter often in daily life the products which may be reused several times. Consumer durable products are these that do not quickly wear out and may be applied for different service situation during the life cycle. Thus the adequacy between durable products and supposed usage conditions is not a trivial question for product family development as well as its assessment. Consumers come across various usages and they usually prefer to choose the product that completes most of their diverse expected usages with lower expense (Sullivan and Steven 2003).

Conclusion: The essence of mass customization and consumer markets lies in the product family design.

1.2.2. Rationalization of existing products

Companies burdened by demand diversity are often enticed by initiatives as mass customization, lean production, just-in-time, build-to-order, etc. An important first step before engaging in implementation of such initiatives is to rationalize the products.

When rationalizing the products, it is important not to focus on a single product. This will only lead to incremental improvements not nearly enough to secure successful implementation of any of the above mentioned. It is necessary to focus on rationalizing product families to achieve the needed effects. Unfortunately, only limited quantified and operational methods and process are available to support making decisions about rationalizing product families.

The result is that product committees and project managers who are engaged in decision making are often forced to base their decisions on a patchwork of details rather than a complete overview of both marketing study and engineering study.

1.3. The challenge from research domain

The business challenge of growing complexity and the exigency of market environment for product families has created a need for tools and models which provide guidance on how to improve product families and enable modeling of the complex interaction of marketing research and engineering research. This need has been addressed by different research methods.

As mentioned, earlier literatures provide several engineering models to measure the performance of a product family (Meyer and Lehnerd 1997). However, these measures can only be used to indicate whether the product family is doing well or not – something is subjective and ignores the relations with customer specific usage situation and expectation.

There some research has been made on commonality indices for evaluation of product families (Thevenot and Simpson 2006) (Martin and Ishii 1997). These indices basically focus on a comparison of the physical components of different products in a product family.

Otto and Holtta-Otto (Otto and Holtta-Otto 2007) present a technique based on multi-criteria evaluation. This method includes 6 indicators scores (complexity, customer, flexibility, organization, variety and after sales) representing different views on the product family.

However, the above performance measures are confined to manufacturing and engineering aspect of product family assessment. None of them indicate the profound reasons why the product family is performing well in respect to target market requirements.

Hence relations between the products and market requirements, and a synthesized study of these two sides become very interesting to analyze when evaluate a product family's state regarding to the ability to offer the necessary product variants effectively and efficiently.

The role of marketing research begins with the initiation of a product development and serves as verification target in the following design steps (Otto and Wood 2001). Figure 1-4 illustrates the well-known V cycle in product development process and iteration concept in each developing step. A study on target market requirements is always essential to product development. The study of validation relations that link the engineering and marketing is an appealing inter-disciplinary subject (Gupta and Samuel 2001). Bernard et al. in their books "La conception industrielle de produits, Vol. I, II, III" (Yannou, Christofol et al. 2008) present a general frame of new product design, which combines the enterprise organism, design decision-making and specification-performance management.

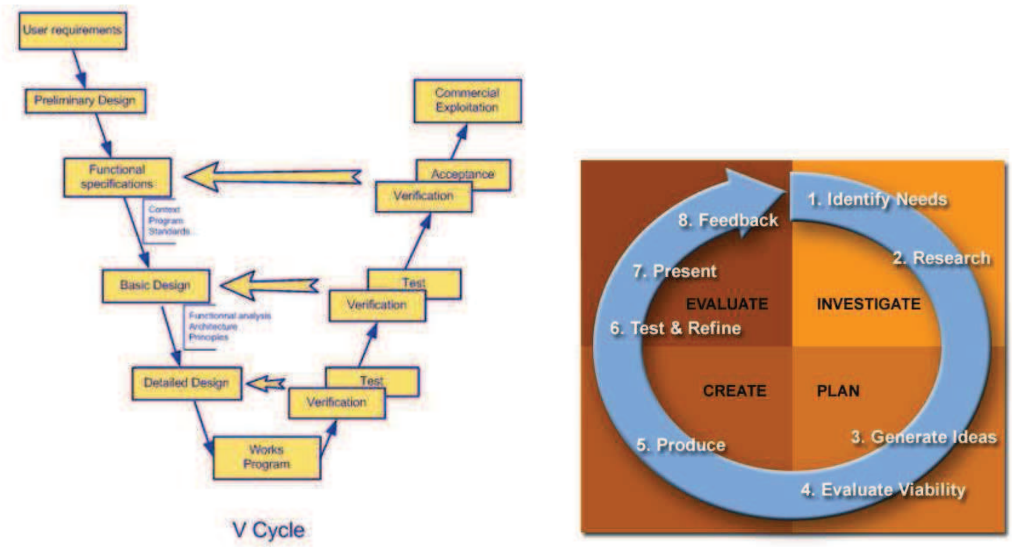


Figure 1-4 The V cycle in product development and iteration (Otto and Wood 2001)

A major school of thought is using Conjoint Analysis to conduct market research and furthermore serve product development (Green and Srinivasan 1978). Based on the conjoint analysis, the formulation of demand function proposed by (Hazelrigg 1998) formed the basis of a framework for decision based engineering design. Abundant similar works appears in successive marketing research.

In combining engineering and marketing research for product development, (Michalek, Feinberg et al. 2005) revealed a process of Analytical Target Cascading (ATC) to link marketing and engineering. The complex system is decomposed into hierarchical and interrelated marketing-engineering subsystems, each can be analyzed and optimized separately and then coordinated. However, the ATC model is built atop well-established marketing methodologies, such as conjoint, discrete choice modeling and demand forecasting, which require abundant pre survey work to identify the part worth of each attributes.

1.4. Response to the challenges: scientific approach

1.4.1. Research objectives

This research is supposed to be in the field of applied research, i.e. the research and its results focus on practical applicability of the process and models. In the following, the research objective is divided into a main research objective and several sub-objectives. The main objective can be characterized as a practical objective whereas the sub-objectives are more theoretical nature and serve as means to full fill the main objective.

Main objective:

The main objective of the research is mainly described as below:

To develop a process and models that can support designers while analyzing and diagnosing a product family by several objective indices and visual charts and hereby support decision-making about re-design of the products with the intention to rationalize the product family composition and product features in reply to market demand variety

Sub-objective 1

In order to focus the research and address the factors that are most likely to contribute to success of the research, a fundamental understanding of the target market composition and the factors which would influence the variety of the products in the family is evidently necessary Hence:

To develop an understanding and further a model of which elements in usage and product characters are relevant to study in the diagnosis of a product family's performance with regards to various market usage segments.

Sub-objective 2

Subjectively built indices for product family assessment are deficit in both industrial applications and academic researches. Moreover, the success of product family assessing process lies in the relation model of the previous factors identified in sub-objective 1. Hence:

To model explicit relations between market usage factors, product design factors and perceived performances. Develop objective indices for the evaluation of product families under multi-criteria decision environment.

Sub-objective 3

Verification of the research results is indisputable, in at least one real case study. Hence:

To develop visualized charts for aiding product family redesign decisions. Test the research results in a real case to prove its applicability and worth.

1.4.2. Research methods

Applied research

The research reported in this thesis begins with a practical problem and accordingly a phenomenon in industry and literature is analyzed and diagnosed. This is an applied research type that is accessing and using some part of the research communities' accumulated theories, knowledge, methods, and techniques, for a specific, often state, commercial, or client driven purpose (Delbert and Neil 2002). Applied research deals with practical problems and is generally empirical. Because applied research resides in the messy real world, strict research protocols must often be relaxed. Figure 1-5 presents a method to address the interplay between the practical and theoretical work in applied research.

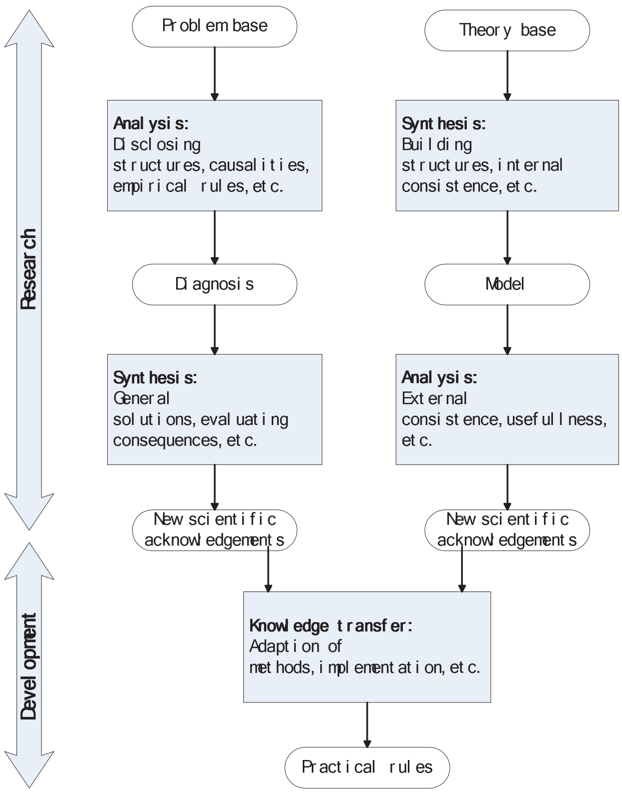


Figure 1-5 A method to address the interplay between the practical and theoretical work in applied research (Delbert and Neil 2002)

As problem areas are discovered in the industrial setting they are analyzed in the context of the theoretical basis, whereupon theoretical hypotheses and problems are formulated. The solutions developed to address these problems must be subjected to evaluation and critique from practitioners as well as the academic community to check their validity and applicability. Thus, the solutions are applied under real circumstances, i.e. in the industrial setting or other test cases and examples.

Case study

On one hand, the case study as a research methodology allows the researcher to study the phenomenon in real circumstances. On the other hand it can be difficult to state general conclusion based on a case study. As research methodology the case study resembles action research, with the exception that the case study does not imply interference by the researcher, thought it can be difficult to avoid since the mere presence of the research can lead to changed behavior of the involved (Yin 1994).

Engineering design research framework

The research follows the approach described in the framework set up by (Blessing and Chakrabarti 2002). The framework illustrated in Figure 1-6 describes a process beginning at formulating the success criteria (aim) of the research. Next step is to study the object and through observation and analysis get an understanding of the factors that influence the success criteria (description I). This understanding enables the research to prescribe actions (e.g. methods) to address the influencing factors in the desired direction (prescription). Finally the effects of the prescribed methods are observed and analyzed (description II). The knowledge gained in this process can then be used to evaluate and either validate or improve the initial description and prescribed actions.

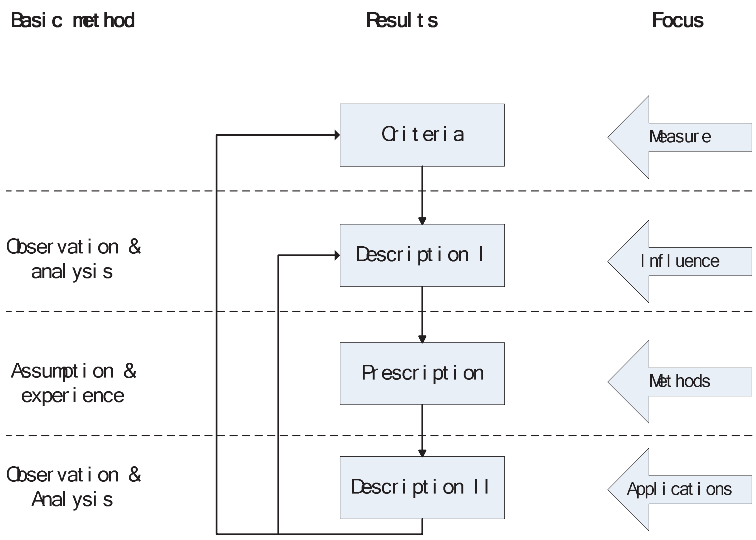


Figure 1-6 Engineering design research framework from (Blessing and Chakrabarti 2002)

1.4.3. Research process

The design of the thesis research process is based on the above described approaches and methods, and utilizes particularly the Engineering Design Framework (Blessing and Chakrabarti 2002). Several types of design research can be derived from the model to form the research process in Figure 1-7. The process has been guided by three major stages.

1. First of all, a complete literature research is performed in order to identify and determine the overall

2. The above observations have finally defined the thesis research environment and frame which consists of a comparison of existing product family assessment technique and our new usage model integrated assessing process.
3. This stage applies the developed model and invented indices for a case study

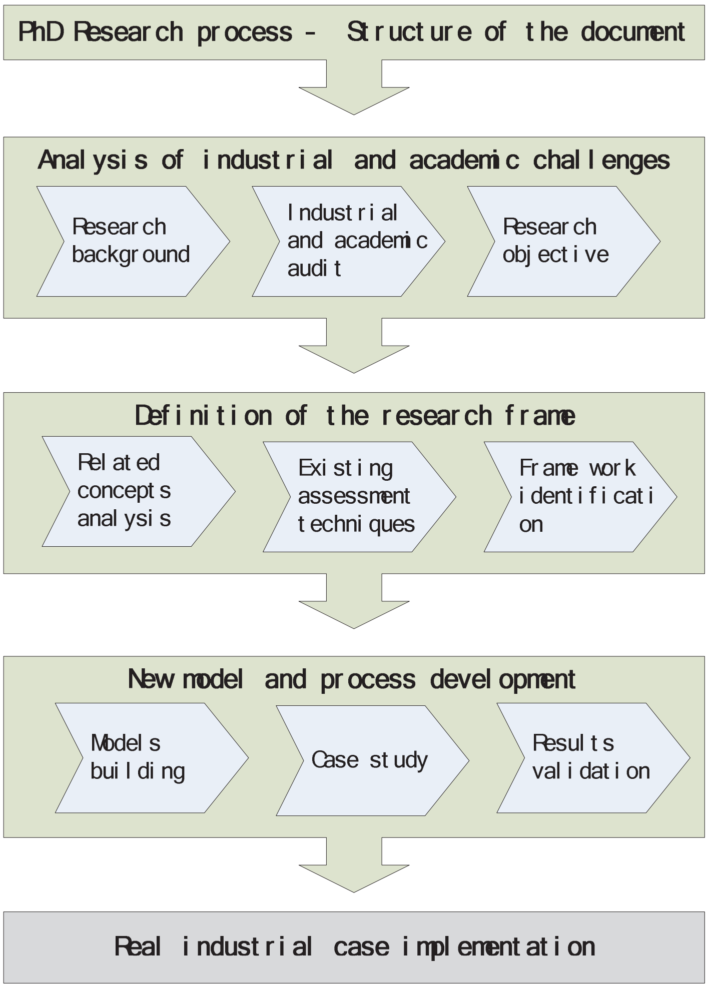


Figure 1-7 Research framework of the thesis

1.5. Structure of the thesis

This section tries to explain the structure of the thesis and the argumentation that lies behind the chosen structure. As illustrated, the thesis is divided in five chapters which describe the research process defined in above paragraph.

Chapter 1 presents an introduction of the background and objectives of the research. It describes the industrial challenge of individualized consumer demand for products, as well as the research challenge of assessing product families, which form the background of this research work. The scientific approach used in the research work is presented, in which is included a description of the research objectives, the research methods used. Finally, a discussion of the strategy used for verification and validation of the research work.

Chapter 2 discusses the theoretical basis upon which the research work is founded. It will go through a series of different research fields and disciplines, and describe the reason that they are relevant to the research work presented in this thesis. The current state-of-the-art of product family assessment tools and methods in literature are also presented. The methods and tools are reviewed and compared with the intention of identifying their limits and advantages. Marketing model, computation methods, tools or elements of these which could contribute to support this research work are analyzed.

Chapter 3 introduces the principal concept of usage context model and the developed modeling formalism. Usage context based assessing indices that can support decision-making in the process of redesign the products in a product family and product family positioning are developed also in this part. The monopoly and competing market environments are analyzed separately.

Chapter 4 reports the experiment of applying the model and process developed in the Part 3 in a jigsaw product family case.

Chapter 5 recapitulates the results of the research work by reviewing the research objectives which are formulated at the beginning of the thesis and summing up the contribution from this research work. This part also elaborates on the experiment which is made to the jigsaw product family and the limitations of the developed indices, model and process. Finally, it points out prospective areas for future research and applications.

Obviously, the real progress of the research work has not been sequential and even rather iterative. The thesis is structured in this way because it is considered logical cognitively and much reader-friendly.

Chapter II

2. State of the art and literature review

2.1. Introduction

The framing of the research gives ways for a body of knowledge upon which the research is founded. This section will go through a series of different research fields and disciplines, all of which are fundamentals of this research. It is, however, important to note that the contributions of this research lies within an engineering design and product development context.

The frame of reference for this research work is divided in five sections;

- **Marketing research in engineering design**

This section discusses the marketing research issue related to product development. Since firms design products both appealing to consumers and feasible to production. The resulting marketing and engineering design goals are driven by consumer preferences and engineering capabilities, two issues that should be addressed coordinately.

- **Engineering design process**

This section presents theories and models - especially product models and product development process - within the design engineering and design science community. All the thesis research work belongs to an engineering design process.

- **Product family development**

This section presents the conceptual framework used in relation to multiple product development, i.e. mass customization, platform-based product development, modularization, commonality-diversity, etc.

- **Product family assessment techniques**

This section presents several existing product/product family assessment techniques and tools.

By revealing their existence, limitation and potential development, their relations with this thesis can be extracted.

- **Advanced calculation techniques**

Since this thesis research is based on a quantitative and objective goal for the possible solution of assessing product family design/redesign. The advanced calculation techniques, such as constraint programming, genetic algorithm, etc., cannot be avoided. This section gives certain introduction and basic concept of these calculation techniques.

2.2. Marketing research in design engineering

This section discusses the marketing research issue related to product development. Product development is a costly and time consuming process studied by the practitioners and academics in both marketing research and engineering design. The entire product development process typically is broken down into a number of stages which are addressed separately in product optimization. Each discipline works under constraints and guidelines set by the other. However, since firms design products both appealing to consumers and feasible to product. The resulting marketing and engineering design goals are driven by consumer preferences and engineering capabilities, two issues that should be addressed coordinately.

Michalek et al. in works (Michalek, Feinberg et al. 2005; Michalek, Feinberg et al. 2008) revealed a process of Analytical Target Cascading (ATC) to link marketing and engineering. In these works, the complex system is decomposed into hierarchical and interrelated marketing-engineering subsystems, each of which can be analyzed and optimized separately and then coordinated.

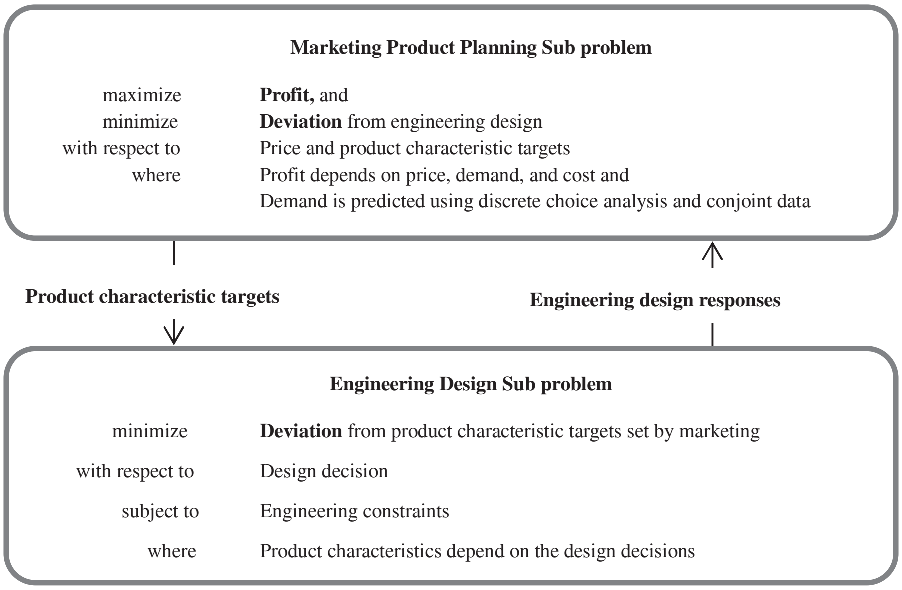


Figure 2-1 ATC formulation of the product planning and engineering design product development sub problems (Michalek, Feinberg et al. 2005)

The ATC works by viewing a complex system as a decomposable hierarchy of interrelated subsystems, each of which can be analyzed and optimized separately and then coordinated. Each of the sub systems should be modeled mathematically and solved iteratively until the joint system converges upon a consistent optimal product design, within user-defined tolerances.

The marketing sub system is built atop well-established marketing methodologies, such as conjoint, discrete choice modeling and demand forecasting. Product line optimization problem is addressed also by Michalek et al. (Michalek, Feinberg et al. 2008), which shows that coordinate marketing and engineering models produces joint solutions superior to those using a disjoint sequential approach and the consumer heterogeneity has a substantial impact on the design of resulting product line. In the marketing sub-model, conjoint choice data is firstly collected and discrete choice method with various utility models are applied on the data to assess the demand.

Another research field of combing marketing research results lies in the user-centered design, which defines a general process for including human-centered activities throughout a development life-cycle (Figure 2-2). They use survey and questionnaire to get user's feedback (Hoyle 2009). Discrete choice analysis is used to get user's preferences (Wassenaar and Chen 2003; Wassenaar, Chen et al. 2005). Anderson et al. (Anderson, Palma et al. 1992) shows the different discrete choice model and customer's preference models. Subtle differences can be applied according to real design cases and context.

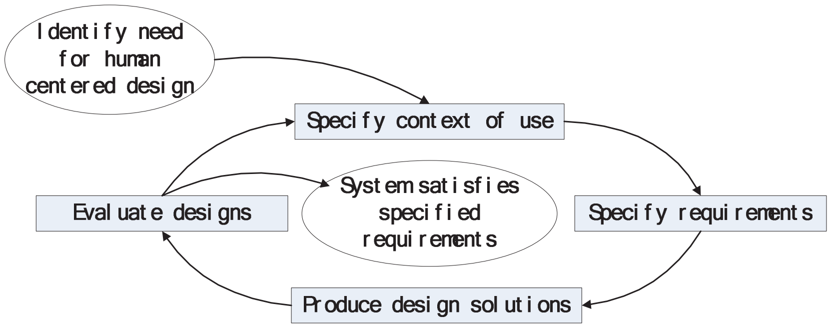


Figure 2-2 User-centered design

To sum up, the marketing research cannot be avoided when we assess the design of a product family. However the related researches are far from complete. The following sections open up several engineering related marketing research orientations. Firstly, consumer's buying decision process is reviewed to figure out the factors that affect the process. Then existing usage model and contextual information researches in marketing related design engineering are went through.

2.2.1. Consumer's buying decision process

The marketing sub-model deals with essentially how to estimate the demand with given product design alternatives. The central question for researchers is: How do consumers respond to various product alternatives? Figure 2-3 shows the stimulus response model of buyer behavior: the marketing and other stimuli enter the consumers' "black box" and product certain responses. Product, Price and Consumer Characteristics are the factors most concerned by the researchers while try combing design engineering and marketing. The product design specification affects consumers' preference and consumer characteristics influence how he perceives and reacts to the stimuli.

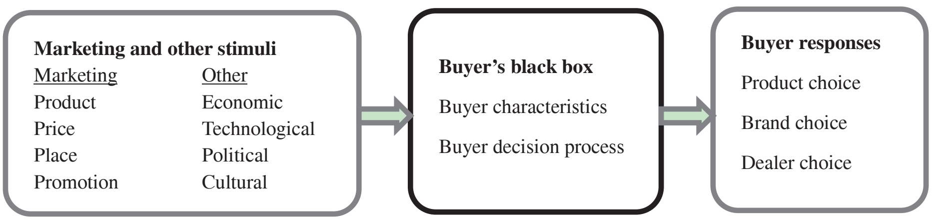


Figure 2-3 Model of Buyer Behavior (Kotler and Armstrong 2009)

The buyer decision process consists of five stages: need recognition, information search, evaluation of alternatives, purchase decision, and post purchase behavior. The **alternative evaluation** stage is how the consumer processes information arrives at product choices. How consumers go about evaluating product alternatives usually depends on the individual consumer and the specific buying situation. In certain cases, consumers use careful calculations and logical thinking. The consumer will be satisfied or dissatisfied in post-purchase behavior; this stage influences consumer's future buying decision and brand loyalty. What determines whether the consumer is satisfied or dissatisfied with a product lies in the relationship between the *consumer's expectations* and the products' *perceived performances*. If the product falls short of expectations, the consumer is disappointed; if it meets expectations, the consumer is satisfied; if it exceeds expectations, the consumer is delighted. However, the measurement of the relationship is relatively hard since the variety of consumer's expectation under different usage context. This is a challenging research topic from the designers' point of view. Such measurement during product design or redesign process is important and appealing.

Figure 2-4 Buyer Decision Process (Kotler and Armstrong 2009)

In this research, we focus on consumers' product choice and assume consumers are relatively savvy about the products and their expected usages and expected performances.

✧ **Consumer's buying decision process in relation to this research**

The consumer buying decision process is an important stage of assessing a product designs, as well as product families design. Since the consumer's satisfaction lies in the relationship between the *consumer's expectations* and the products' *perceived performances*, our research begins with an analysis of the factors which play key roles behind the decision process.

2.2.2. Usage model and contextual information

The modeling of usage can be traced to marketing research. Traditional information - processing research in consumer choice behavior has typically contented itself with stimulus and subject task manipulations. Deterministic preference/choice models are generally based on the premise that products are valued for the attributes they possess and that customers seek to maximize their "utility" by choosing desired combinations of attributes (Green and Srinivasan 1978). Thus products offering similar combinations of levels of attributes are likely to be more competitive.

However, emerging streams of research seek to emphasize the role of usage context and goals in consumer's learning and use of that knowledge in decision-making. The emphasis on the matching between situational requirements and product benefits appears in consumer behavior research since last century (Srivastava 1981). Situational influences were seen as moderating consumer choice. This close correspondence between situational factors and product attributes leads to the question: what are situational factors? Belk in his works (Belk 1974; Belk 1975) proposed that environmental factors should include all variables not included in the description of persons or products – "all those factors particular to a time and place of observation which do not follow from a knowledge of personal (intra-individual) and stimulus (choice alternative) attributes and which have a demonstrable and systematic effect on current behavior", as illustrated in Figure 2-5. Belk also listed five groups of situational characteristics represent the general features of the definition of situation in the sense of consumer's buying behavior:

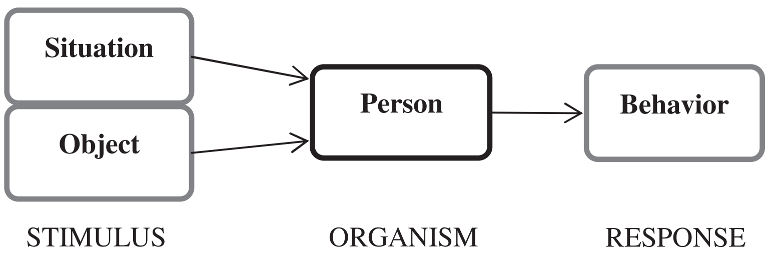


Figure 2-5 A revised S-O-R paradigm (Belk 1975)

1. *Physical surroundings* are the most readily apparent features of a situation, such as geographical and institutional location, deco, sounds, lighting, or other material

surrounding the stimulus object.

2. *Social surroundings* provide additional depth to a description of a situation, like other persons present, their characteristics, their apparent roles and interpersonal interactions.

3. *Temporal perspective* is a dimension of situations which may be specified in units ranging from time of day to season of the year, like time since last purchase, time since/until payday.

4. *Task definition* features of a situation include an intent or requirement to select, shop for, or obtain information about a general or specific purchase.

5. *Antecedent states* are momentary moods (such as acute anxiety, pleasantness, hostility) or momentary conditions (such as cash on hand, fatigue) rather than chronic individual traits.

Even though this classification of situational factors is comprehensive in marketing research, little related research in engineering design community appears. The situational factor of consumer's usage context is crucial for product design or redesign evaluation.

Ratneshwar et al. (Ratneshwar and Shocker 1991; Ratneshwar and Warlop 1993) suggested that usage context plays a key role in consumer problem-solving by impacting the discriminability of choice alternatives and that the implicated processes might vary with situational familiarity. Contextual goals and constraints might help the consumers to discriminate acceptable alternatives from a much larger available set. Even when the situation is relatively less familiar and the decision-maker has to take a more constructive approach to evaluating the alternatives, situational constraints might still facilitate discrimination and quick decisions by focusing the consumer's attention on context-relevant product features. In general, the particular features that get the decision-maker's attention are likely to be those that have relevance for the goal context of the ongoing situation (Huffman and Houston 1993). The role of usage context in consumer choice is one of guiding the search for and evaluation of potential solutions. He et al. (He, Hoyle et al. 2010) combined usage context model and choice model for demand prediction applications. Recent research on usage context in marketing leads to an exhaustive analysis of usage anticipation and diffuse, in consumer behavior (Shih and Venkatesh 2004) (Hoffmann, Roehrich et al. 2006)

(Hoffmann, Mathieu et al. 2008)

However, the research of usage situational/contextual information in design engineering aspect has been little advanced because of lacking of interdisciplinary marketing-engineering development. The consumer participated interaction design (Bergman 2000) especially in IT products such as software, mobile phone, navigation system, etc, break out decade ago. In the domain of hi-tech product design, context-aware systems - knowing the activity context and taking it into account for system behavior - are emerged. Context-aware system for mobile cartography has been shown in (Reichenbacher 2003), which used formalization to describe situations and contexts for finding typical context patterns. For other new product or product line design, such marketing and engineering considerations are also highly interdependent.

The concepts of usage context are introduced in design engineering in work of (Green, Palani et al. 2004; Green, Tan et al. 2005; Green, Linsey et al. 2006), (Yannou, Chen et al. 2009). Green et al. have published three successive papers on the subject, with the goal of forming a comprehensive product design methodology that includes contextual factors. Important first steps in the field were taken, including the definition of key terms and concepts. Usage context, as it relates specifically to products, is defined as the unique combination of application and environment in which a product is used. Furthermore, usage context is framed as one part of a larger product design context, which also includes market and customer context. This hints at the key role that all three contexts play in guiding the choice of the customer. During the course of the studies, customers were found to have distinct product preferences under different usage contexts. Luo (Luo 2011) also recently mentioned the importance of usage context difference towards product family design, by using a tolerance range in design parameters to represent the real product usage context variance. Additionally, evidence supported that contexts could be differentiated based upon functional attributes, indicating a link between engineering parameters and perceived usefulness, which occurs under the influence of different usage contexts. Yannou et al. (Yannou, Chen et al. 2009) presented a Usage Coverage Model (UCM) so as to get a more thorough marketing model based on sets of permitted usages for a product-service instead of the conventional perceived marketing attributes, in which a taxonomy of variables is suggested to setup the link between the design parameters of a product-service and the part of a set of expected usages that may be covered. The concept of quantified individual performances during usage is proposed which offers the advantage of linking with user experience to introduce the perceived quality of a product's service. In the following work (Yannou, Wang et al. 2010) (Wang and Yannou 2011), the UCM concept is applied with a power tool product: jigsaw. The physics describing the behavior, usage context and consequently the performances of a jigsaw is established. When users choose to buy an adapted jigsaw, they may imagine different usage scenarios in which the product may be applied. Given index reveals whether the product fulfills customers' requirements and expectations.

✧ **Usage model and contextual information in relation to this research**

One principal objective of this research is to figure out the relation between consumer's usage variation and product family evaluation. The understanding of the existing usage models in marketing research and engineering research is the first step to develop a new usage. Combining usage model for product family design assessment is less subjective than that with the axiomatic or heuristic assessment methods. Related traditional techniques are enumerated in the following section.

2.3. Engineering design process

The engineering design process is a formulation of a plan or scheme to assist an engineer in creating a product. The engineering design is defined as (Ertas and Jones 1996):

The process of devising a system, component, or process to meet desired needs. It is a decision making process (often iterative) in which the basic sciences, mathematics, and engineering sciences are applied to convert resources optimally to meet a stated objective. Among the fundamental elements of the design process are the establishment of objectives and criteria, synthesis, analysis, construction, testing and evaluation.

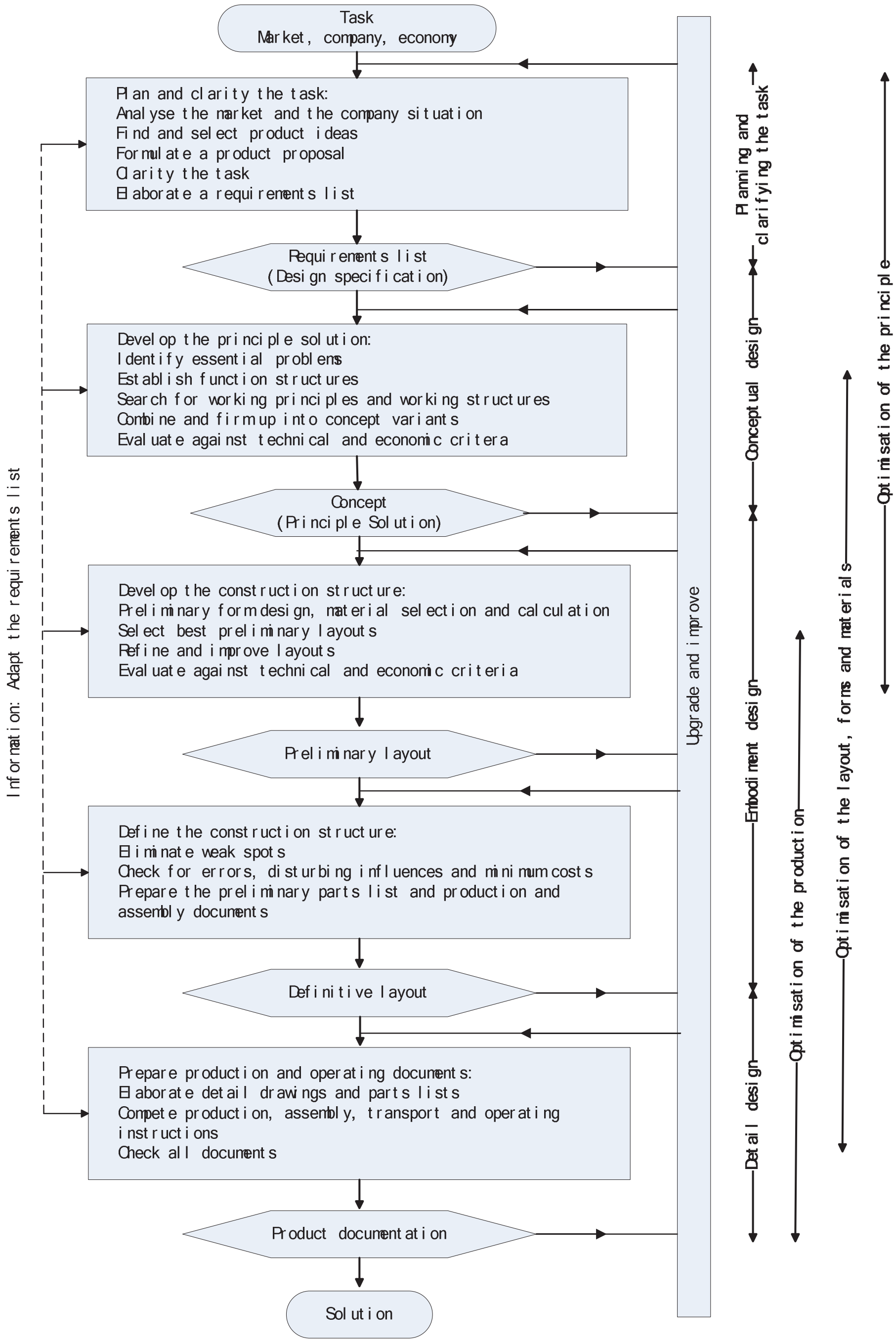


Figure 2-6 Steps of the planning and design process (Pahl and Beitz 1999)

As shown in Figure 2-6, the engineering design process is a multi-step process including the *planning and clarifying the task*, *conceptual design*, *feasibility assessment*, *embodiment design*, *detailed design*, *production planning and tool design*, and finally *production* (Ertas and Jones 1996; Pahl and Beitz 1999). The sections to follow are not necessarily steps in the engineering design process, for some tasks are completed at the same time as other tasks. This is just a general summary of each step of the engineering design process.

1. Planning and clarifying the task

To start a product development, a product idea is needed that looks promising given the current market situation, company needs and economic outlook. Consideration should be given to the existing applicable literature, problems and successes associated with existing solutions, costs, and marketplace needs. Reverse engineering can be an effective technique if other solutions are available on the market. This activity leads to the formulation of a *requirements list*.

2. Conceptual design

Once an engineering issue is clearly defined, solutions must be identified. These solutions can be found by using ideation, or the mental process by which ideas are generated. The following are the most widely used techniques: trigger word, morphological chart, synectics, and brainstorming (Ertas and Jones 1996).

This step consists of abstracting the essential problems, establishing function structures, searching for suitable working principles and then combining those principles into a working structure. Conceptual design results in the *specification of principle*.

3. Feasibility assessment

The purpose of a feasibility assessment is to determine whether the engineer's project can proceed into the design phase. The solution variants that do not satisfy the demands of the requirements list have to be eliminated; the rest must be judged by the methodical application of specific criteria. This is based on two criteria: the project needs to be based on an achievable idea (technical criteria), and it needs to be within cost constraints (economic criteria).

4. Embodiment design

The embodiment design bridges the gap between the design concept and the detailed design phase. During this phase, the construction structure (overall layout) of a technical system in line with technical and economic criteria is determined, started from a concept as working structure or principle solution. Embodiment design results in the *specification of layout.*

5. Detailed design

The detailed design portion of the engineering design process is the task where the engineer can completely describe a product through solid modeling and drawings. Arrangement, forms, dimensions and surface properties of all the individual parts are laid down, the materials specified, production possibilities assessed, costs estimated and all the drawings and other production documents produced. The result of the detail design phase is the *specification of production*.

The advancement of Computer-Aided Design programs have made the detailed design phase more efficient. This is because a CAD program can provide optimization, where it can reduce volume without hindering the part's quality. It can also calculate stress and displacement using the finite element method to determine stresses throughout the part. It is the engineer's responsibility to determine whether these stresses and displacements are allowable, so the part is safe.

6. Production planning and tool design

The production planning and tool design is nothing more than planning how to mass produce the project and which tools should be used in the manufacturing of the part. Tasks to complete in this step include selecting the material, selection of the production processes, determination of the sequence of operations, and selection of tools, such as jigs, fixtures, and tooling. This task also involves testing a working prototype to ensure the created part meets qualification standards.

7. Production

With the completion of qualification testing and prototype testing, the engineering design process is finalized. The part must now be manufactured, and the machines must be inspected regularly to make sure that they do not break down and slow the production.

✧ **Engineering design in relation to this research**

New product variants are added, and existing product variants are modified in order to meet changing customer needs. In order to understand the products (as a result of the design process) it is also important to understand the design process itself. One of the objectives of this research is to formulate an analysis framework for product assessment, and it therefore seems natural to include into the model, aspects that are important to the subsequent product development activities. It then also seems natural to understand the frame of design processes, while studying the need for such an analysis framework. Moreover, the integrated product development scheme in itself is relevant, as the idea of a concurrent analysis of market and product assessment aspects originated in this work.

2.4. Product family development

Companies typically do not survive based on revenues from a single product but rather offer a variety of closely related products, all of which also must be evolved overtime. So it is critical to make effective configuration choices for the corporate set of products. The concept of multiple products development contains several different paradigms, which related to more efficient and effective development and production of product variety, such as portfolio architecture, mass customization, etc. The platform product architecture and modularization are most efficient architectures in product family development. These topics are not within the core of this research work, but the conceptual framework behind the different multi-product development paradigms are closely related to the challenges in product family assessing process.

As shown in these works (Alizon, Marion et al. 2007) (Simpson, Alizon et al. 2007), companies therefore need to use a concurrent engineering process to develop product families and product platforms efficiently. Based on concurrent engineering principles, four processes are proposed for systematic product family design using two platforming approaches - top-down and bottom-up - and two development drivers: product-driven and platform-driven.

In the following sections, several multiple products development techniques and concepts, which are more or less related to the thesis research, are listed and analyzed for the sake of the behind conceptual framework and potential research challenges.

2.4.1. Portfolio architecture

Product portfolios are the set of different product offerings that a company provides, in which exist product families or product lines. A company can choose from a variety of different strategies for providing these multiple offering: it can make each product completely unique, share a common system or choose some method in between. There are market and cost advantages to any approach. Product portfolio architecture is the system for laying out components and systems on multiple products to best satisfy current and future market needs (Otto and Wood 2001).

- **Fixed unsharing portfolio architecture**

A fixed unsharing portfolio architecture is defined as when each product in a portfolio is unique and shares no components or systems with any other product member in the portfolio. This architecture is typically applied when the product has very high volumes, implying that economies of scale exist to remain competitive. Since the market may seek variety, the fixed architecture may provide only one option to the entire market and be less than ideal for many customers (single offer), or it meets all market variety naturally (robust offer). The single offer, such as mentioned the first Model-T Ford was black – and black only, becomes less and less interesting for nowadays customer requirements. On the other hand, the robust offer, which severs various target markets with unique architecture, reveals great technique difficulties and cost problem.

- **Platform portfolio architecture**

When a company offers products that share components, modules, or systems to meet market variety, the configuration layout within the set of products and their shared elements is called a platform portfolio architecture. Literature describes a whole range of different definitions of platforms. It is not part of this research to provide yet another definition, but it is useful to give a small review of existing definitions and viewpoint on product platforms in order to discuss the notion and to create an understanding suitable for the work in this thesis.

The common components, modules, and systems are also called the platform, and the supported products are called variants (Meyer and Lehnerd 1997). Product platform definitions range from "set of common components, modules, or parts from which a stream of derivative products can be efficiently developed and launched" to the "collection of assets, i.e., components, processes, knowledge, technique, people and relationships, that are shared by a set of products", in a larger sense (Ulrich and Eppinger 2000). The Product platform can have a narrow definition or broad definition according to the designers (Simpson, Marion et al. 2006).

Product platforms are a useful means to enable reuse of parts, assemblies, technologies, concepts, knowledge, etc. and hereby reduce complexity and improve the business potential. A large academic part of researchers agree that a product platform is the way to achieve both commonality and variety at the same time. The most important difference to the traditional single product development approach is the development of a common platform:

- Development of the product platform, from which distinctive product variants can be derived
- Development of the variant product variants based on the product platform

Through this research and a series of consultancy projects it is a clear experience that both types of platforms - as well as intermediate combinations - are found in industry. It seems to make little sense to make one universal definition of a platform, but it does make sense to note a few core elements of all product platforms: The product platform defines a reusable core from which a series of product variants may be derived; The product platform is a design preparation and it has an intention of creating a positive "commonality" effect in the products meeting with one or more life phase systems.

A product platform is often related to the term modular and/or scalable. These two aspects are discussed in the following sections.

Modular platform based product families:

The term modular architecture is used when the product architecture is decomposed of a certain kind of subsystems, which have standardized interfaces and contains only one or a few functionalities (Ulrich and Eppinger 2000).

A **module** is a unit whose structural elements are powerfully connected among themselves and relatively weakly connected to elements in other units. This is actually the core of modularization, because the split between generic and variable characteristics is possible due to the weak integration between the elements and units. This also enables interchangeably for upgrading, differentiation or other purposes (Baldwin and Clark 2000). The purpose or intention of a module is another very important aspect that separates the module from an ordinary subassembly. Stadler et al. (Stadler and

Hosnedl 2002) provides yet another definition of a module. He says that a module is a decomposition of a product into building blocks (modules) with specified interfaces, driven by company-specific reasons. The company specific reasons are referred to as module drivers. That is, a module is introduced to the product, product family or product assortment architecture with the intention of creating a positive effect in the product's or products' meeting with one or more life phase systems.

Modules are divided by the **interfaces**. The decomposition described in the module definitions is only possible due to a careful design of interfaces. The ability to replace one module with another without changing the interface on either side is in fact the key to effective creation of product variety. The interfaces often determine the possible configurations within the product architecture and reflect the intention of the platform, whether it is efficient production, easy upgrade of products, easy service of products, etc.

A module platform based product family is defined as the set of products support at any one time by a modular platform.

A modular product platform has a clear mapping from functional units to physical subsystems with the following characteristics (Ulrich 1995):

- Sub-systems (modules) implement one or a few functional elements in their entirety
- The interactions (interfaces) between sub-systems (modules) are well defined and are generally fundamental to the primary functions of the product

The Figure 2-7 below illustrates the sharing of components (platform) within a family of products. In the figure, common functions are the same for all products, variant functions are the same but the attributes are different, and unique functions are specific to an individual product (Alizon, Shooter et al. 2006).

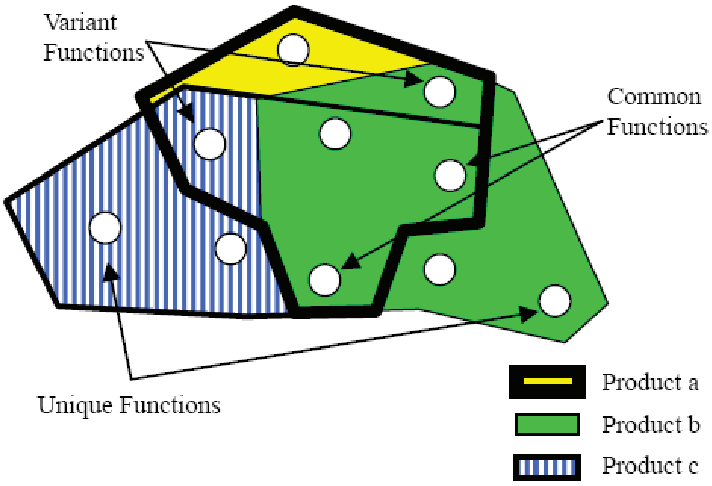


Figure 2-7 Illustration of a product family sharing functions (Alizon, Shooter et al. 2006)

Scalable platform based product families:

There is another type of platform architecture is the scalable platform. Here, the products in the family share no common components, but are all the same except for size. What are common among the variants are the production or development activities used to create the products. With a scalable platform, the functions of the product variants are basically identical. As an example, Pratt and Whitney's jet engine family is a scalable platform (Simpson, Siddique et al. 2006).

✧ **Product platforms in relation to this research**

Product platforms are particular relevant in relation to assessing a product families performance regarding effective and efficient creating of the desired product variety, because assessing the existing product family is natural first step in developing a product platform, which are to substitute and/or supplement the existing products. The modularization principle makes it possible for some parts of the product to be held constant and standardized and others held free to vary, thus enabling the possibility of a co-optimization of product variety and commonality at the same time. And the diagnosis and proposed remedies of such an assessment are very likely to contain elements from the field of multi-product development.

Also, product platforms are a recognized means to create product variety effectively and efficiently. The conceptual framework that lies behind platform-based product development and identification of product platform potential is consequently relevant to this research work.

2.4.2. Mass customization

The mass customization concept can be defined either broadly or narrowly. The broad one is the ability to provide individually designed products and services to every customer through high process agility, flexibility and integration (Davis 1989). For narrower, more practical concepts, Hart (Hart 1995) refers it as a system that uses information technology, flexible processes, and organizational structures to deliver a wide range of products and services that meet specific needs of individual customers, at a cost near that of mass produced item. Tseng et al. (Tseng and Jiao 2001) describes mass customization as production of goods and services to meet individual customer's needs with near mass production efficiency. According to Pine (Pine 1993) mass customization is a synthesis between the two long-competing systems of management: mass production of individually customized goods and services.

In mass production low costs are primarily achieved through economics of scale, i.e. lower unit costs of a single product through greater output and faster throughput of the production processes. In mass customization low costs are primarily achieved through economics of scope, i.e. the application of a single process to produce a greater variety of products or services cheaper and more quickly (Pine 1993). (Pine 1993) furthermore describes four types of mass customization:

Collaborative customization: Firms talk to individual customers to determine the precise product offering that best serves the customer's needs. This information is then used to specify and manufacture a product that suits that specific customer.

Adaptive customization: Firms produce a standardized product, but this product can be altered (customized) by the end-users themselves.

Transparent customization: Firms provide individual customers with unique products, without explicitly telling them that the products are customized.

Cosmetic customization: Firms produce a standardized physical product, but market it to different customers in unique ways.

Implementation of mass customization

In the work of Da Silveira et al. (Da Silveira, Borenstein et al. 2001), they list several external and internal factors to support the successful implementation of a mass customization strategy. The six factors most commonly emphasized in the literature are presented next

1. Customer demand for variety and customization must exist

In pursuing the desire to meet any customer demand one could easily motivated to add features that would only add extra costs and complexity. To avoid this it is important to create a clear vision of the actual market and customer demands.

2. Market conditions must be appropriate

A flexible product design is a prerequisite to implement mass customization. Product platforms and modularization are discussed in the subsequent section.

3. Value chain should be ready

Postponement is closely related to mass customization. Postponement is about postponing activities and creation of variety until an actual demand arises. Figure 3.12. illustrates different postponement strategies.

4. Technology must be available

Flexible processes are a prerequisite to obtain economics of scope, which is the means to achieve lower costs.

5. Product should be customizable.

The ability to capture and manage customer orders fast and reliable is a key success parameter to the implementation of mass customization.

6. Knowledge must be shared

Mass customization requires a lot from the company's information systems. It is important that systems for customer and sales orders are coupled to systems that manage purchasing, production planning, distribution, etc.

✧ **Mass customization in relation to this research**

The idea of providing customized products at near mass production costs is of course relevant to this research work. It is interesting that the mass customization demands not only attention to improving production efficiency or the like. Implementing a mass customization strategy requires attention to nearly all aspects of a company and the success is dependent on alignment between the different product life phase systems. This way of thinking is highly relevant to this research work.

2.4.3. Variety and commonality

As described in chapter 1 it is a core challenge for companies to offer products with great variety of products to the market (i.e. customization) and still make it possible to exploit the benefits of economies of scale in the production and supply chain. Traditionally, product variety has been considered as an equal trade-off, where variety is valuable in the market but is costly to obtain (Berglund and Claesson 2005). The thought behind mass customization, platform product development, modularization, etc. is deriving highly distinct products effectively by minimizing non value-adding variety and creating commonality in the products.

Commonality is not only about using the same components. If this was the case, we could conclude the equal trade-off between variety and commonality. That is not necessarily the case, though, because variety and commonality are relational properties in a product. Products have variety if they are perceived as different from a customer perspective and commonality if they are perceived as similar from a viewpoint from production phase. A well designed product family may have products with variety and commonality at the same time.

Variety

Variety is a property that is seen in relation to another product. Variety is especially desired in the life phase systems related to sales and marketing, i.e. externally (Huang 1996).

Commonality

Commonality is a property that is seen in relation to another product. Commonality is especially desired in the life phase systems related to the production of the products, i.e. internally (Huang 1996).

Because variety and commonality are perceived from different viewpoints simultaneously, two objects can be perceived as different (variety) in for instance the market and at the same time be perceived as common (commonality) in the different product life phase systems (e.g. in product assembly or manufacturing). One example of co-existing variety and commonality is the Swatch watches. The expression (design, colors, patterns, etc.) of different product variants is perceived as product variety in the market, but the assembly line cannot tell the difference and handles the different product variants as they were the same.

To summarize we explain variety and commonality as relational properties, and that it is possible to co-optimize them and leverage distinct products more effective and efficiently. This is fundamental concept behind mass customization and product platform strategies.

✧ **Variety and commonality in relation to this research**

The concepts of variety and commonality are relevant to this research, since the product family design concept is mainly based on the trade-off of variety and commonality, i.e. achieve to present the desired variety towards the market and simultaneously present a high degree of commonality towards the production system and supply chain. Consequently, identification of non-value adding variety and potential of co-optimizing variety and commonality are key subjects in relation to the product family assessment.

2.5. Product family assessment techniques

The following section will present a screening of existing methods and tools that are relevant to the product family assessment research framework and objectives. The state-of-the-art study in this section has two purposes:

- It has to clarify the limitations of the present research knowledge and working practice and help justify that there is in fact a research contribution in this thesis

- It has to serve as an inspiration for the prescriptive work in the thesis

This project takes it starting point in a product development paradigm and expands into the production working field. It incorporates marketing aspects from a research point of view, as the contribution lie within marketing research.

There are two challenges when reviewing relevant literature. The first challenge is the fact that this thesis covers the links between the two areas: marketing study and engineer study. The second challenge is the fact that the thesis has its starting point in the state-of-the-art in industrial and academic fields, and consequently validation and new development in these fields are important. There is not one united body of research dealing with alignment of the two domains and few research communities are working on this inter-disciplinary scale. Most of the available literature has its focus in an either process oriented viewpoint or product design and development oriented viewpoint. Moreover, few consider the aspect re-designing a product family with the intention of measuring the adequacy with market requirement and non-value-adding variant products. In the search for existing research on the topic of alignment and product family analysis in order to identify methods that both address the product family and the target market segments, a natural starting point is to search for models, process and objective indices from those two areas extract comparable research work.

In the following section the tools and methods are described one by one including an evaluation of how each method/tool meet the identified requirements.

2.5.1. MFD – Modular Function Deployment

The modular function deployment (MFD) (Ericsson and Erixon 1999) builds largely on the methodology of the QFD. MFD is more management- and less engineering-oriented and deals with the organizational interface between sales/marketing and product development. It is also based on functional decomposition, but in this method, modularity drivers other than functionality are considered. (Ericsson and Erixon 1999) formulate twelve so-called module drivers. The purpose of MFD is to enable cross functional teams to create a mapping from the physical structure of the products within a family to the functional structure of those products and to ensure that the functional structure corresponds to the demands of the customers.

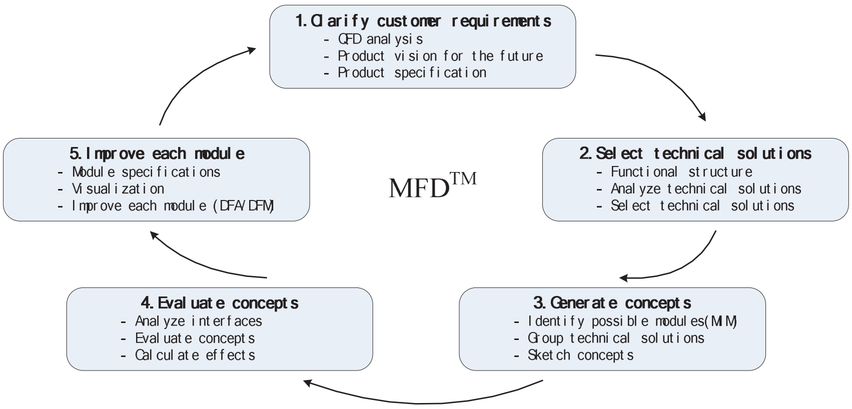


Figure 2-8 Modular Function Deployment methodology (Ericsson and Erixon 1999)

Figure 2-8 illustrates how the Modular Function Deployment method consists of five consecutive steps. The first step resembles that of the first House of Quality in which customer requirements are translated into product features. In the second step, designers screen a solution space for possible designs to carry the functions needed to support the customer requirements. In the third step concepts are generated on the basis of an evaluation of technical solutions against a list the module drivers. The module drivers are explained shortly in the following section. The fourth and fifth steps are rather traditional product development steps in which concepts are evaluated and modules refined.

Module drivers

The most important aspects in the MFD approach are the so-called module drivers. They are formulated as modularization incentives, i.e. different reasons to modularize a product family. Some drivers are more related than other drivers and each of them will have different implications on the product design. The first is ***carryover*** i.e. a specific function will carry over to different products and no technology changes are expected. The next two, ***technology evolution*** and ***planned product changes***, take both unexpected and expected changes into account. ***Different specification*** enables product variation and ***styling*** considers how the modularity choice would affect the appearance of the product. ***Common unit*** is the common function heuristic. ***Process /organization***, ***separate testing***, ***supplier availability***, and ***service/maintenance*** are related to the organizational effects of modularization. ***Upgrading*** allows future additions to the product. ***Recycling*** considers the afterlife of the product. One or a few modularity drivers are chosen according to the firm's strategy (Holtta and Salonen 2003).

The module drivers are used in the Module Indication Matrix (MIM) (Ericsson and Erixon 1999). The MIM is a matrix in which technical solutions are mapped against the module drivers. The twelve module drivers state the intention of a wish to create an effect in other life phase system by introducing modules to the product design.

✧ **Conclusion on the MFD**

The primary strength of the MFD tool is linking the module drivers to the technical solutions in the module indication matrix. But the MFD method solely deals with identification of potential physical modules. Although, half of the twelve module drivers are related to more effective generation of product variety the MFD tool does not enable modeling of such variety. Rather the method models the generic product that represents all products in a product family. The MFD method presumes that all variants in the product family are composed by the same technical solutions, i.e. the products must be relatively similar.

Keeping the module drivers - especially these related to product variety (*carryover*, *technology evolution*, *planned design changes*, *different specification*, *styling* and *common unit*) - in mind while analyzing the product family can support identifying the potential improvement for product family redesigning.

2.5.2. DSM – Design Structure Matrix

The Design Structure Matrix (DSM) (Ulrich and Eppinger 2000) can be used to organize product development tasks or teams to minimize unnecessary rework and thus help manage and speed up the development process. The DSM can be also used to define modules within a single product's architecture. In the component or function based DSM – architecture DSM, components or functions are placed on the row and column headers of the matrix. Components or functions are then mapped against each other and their interactions are marked in the matrix as shown in Figure

2-9. Spatial, energy, information, flow, and material interactions of the elements can also be presented in a DSM with various coupling coefficients and symbols (Alizon, Shooter et al. 2006). This approach takes a starting point in the decomposition of a product into components/functions and an identification of interfaces/relations among these (Pimmler and Eppinger 1994).

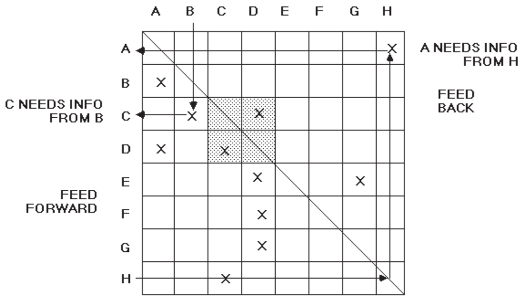


Figure 2-9 An example of a Design Structure Matrix (Holtta-Otto and de Weck 2007)

Once functions or components and their interactions are placed in the DSM, a clustering algorithm can be applied to group the subsystems so that the interactions within clusters are maximized and between them are minimized (Browning 2001). The outcome of a DSM is a proposal for potential modular product architecture. There are some similarities between the DSM approach and the Modular Indication Matrix provided by the MFD method described above in section above. The main difference is that the subsystems are not mapped against drivers of modularity or other external factors. Instead, they are mapped against each other for correlation purposes, in order to cluster subsystems that are closely interrelated and separate those that are not. The Design Structure Matrix does have the ability to hold a large amount of information and mature clustering algorithms exist.

✧ **Conclusion on the DSM**

The DSM method is a powerful tool to identify potential modular structures. Unfortunately, the DSM method focuses solely on the interrelation between elements (parts, assemblies, organ, etc.) in the product structure, without considering marketing studies. In this way the DSM method generates a proposal for a modular product structure without regards to what effects are expected. This is a major disadvantage for the method. Furthermore, the DSM method is primarily a tool that can be used for re-design of single products and does not support handling of product variety unless they have more or less identical structures. Even if (Alizon, Moon et al. 2007) propose a 3 dimensional

DSM method for product families' module identification, this method is rarely applied because of the complexity and lack of efficient algorithms.

2.5.3. QFD – Quality Function Deployment

The design team should understand the customer needs, expressed in their voice. They should understand the current product and how it satisfies these needs. The designers must find the weakly satisfied customer needs, their dependencies or interrelationships, and determine what product changes they can effect to improve these weak points. Therefore, the Quality Function Deployment (QFD) is a methodology for defining the customer's desires in the customer's own voice, prioritizing these desires, translating them into engineering requirements and establishing target for meeting the requirements (Akao 2004).

The focus of this thesis is not the translation of customer demands into product specifications yet the work does deal with the corresponding organizational interface between the marketing on one side and the product family design on the other side, as it deals with the facilitation of decision making on a product family level. Therefore QFD is relevant as it constitutes a semi visual methodology supporting the exchange of information across that barrier.

The matrix, called House of Quality (HoQ), illustrated in figure plays a central role in the QFD method. The VOC, Voice of Customer, is formulated on the basis of customer surveys, focus groups, the experience in the sales and marketing organization etc. They form the "What" in the left part, as rows with different customer demands. Each row continues into the correlation matrix in the center of the house (The How vs. What). The dependencies are mapped through the use of a scale denoting the strength of relationship from independent to highly dependent. The "How" on top of the matrix are then the product features that are needed to satisfy the "What". The bottom part of the house contains the targets specifications related to the "How".

Total of the houses cover the path from customer requirements to process controls in a factory. In the houses inputs are translated to outputs that form inputs for the subsequent house. Through a gradual change in viewpoint one can map the relation between a specific customer need, the design requirements arising from that need, the process characteristics needed, and finally the process capabilities.

✧ **Conclusion on the QFD**

Large QFD's can hold a substantial amount of information and the correlation matrices may become very large. It may compromise the ability to get an overview. On the other hand it is the strength of the QFD approach that the ability to map complex relations is present. In relation to the identified requirements the QFD method has its focus on modeling causal links and life phase system relations. The QFD method focuses on relations between the product design and the production system.

Besides the QFD method includes some aspects related to the requirements: customer perceived product offering, product structure, supply chain system, and critical design issues. Though, only to a somewhat limited extend. The key inadequacy of the QFD method is the fact that the tool is intended to be used for design and redesign of single products and does not facilitate handling of variety. It disqualifies the use of the QFD method in relation to re-design of product families as it is, but the method has some aspects that possibly could be applied in the analysis of product families.

Furthermore, the QFD method is not a particular visual model and the size of the matrices in the various houses of quality rapidly expands and it becomes troublesome to navigate the information. As with many other methods and tools, the process of making the houses is one of the key advantages as it brings together people from different departments. In that aspect one may find the process of making the houses more rewarding than the result itself (Otto and Wood 2001).

2.5.4. Evaluation Indices

There has been made extensive research on using indices (i.e. metrics) for evaluating different aspects of product families. Generally, all these methods base the evaluation of the product family solely on the physical structure of the products. That is, the indices basically focus on a comparison of the physical components and coherent interfaces within the product variants in a product family.

Several heuristic Product Family Indexes have been invented in academic field and applied for industries. Most engineering researches focus on the comparison of component and process.

Degree of Commonality Index (DCI) (Collier 1981)

The DCI is used to assess the commonality between the components in a number of product variant. It is the ratio between the number of common components in a product family and the total number of part in the family.

Total Constant Commonality Index (TCCI) (Wacker and Trelevan 1986)

The TCCI is modified relative index of DCI, which is normalized with fixed boundaries [0, 1].

Commonality Index (CI) (Martin and Ishii 1996)

Similar to DCI, the CI measures the number of unique parts in a product family. It is the ration between the number of unique parts in the product family and the total number of parts in the family.

Differentiation point Index (DI) (Martin and Ishii 1997)

The DI is used to indicate how much variety a process needs to handle compared to the number of processes and the number of final product variants offered.

Coupling index (CI)

The CI is used to indicate how coupled the components in a product is, i.e. If one change is made to one component how likely is it that this entails changing adjacent component.

Generational Variety Index (GVI)

The GVI is a number that indicates what elements in a product that is most likely to change over time, i.e. from one product generation to the next.

Percent Commonality (%C) (Siddique, Rosen et al. 1998)

Similar to DCI, this index measures the commonality based on tree main viewpoints: component, component-component connections and assembly.

Component Part Commonality Index ($CI^{(C)}$) (Jiao and Tseng 2000)

The $CI^{(C)}$ is extended version of the DCI, which takes into account product volume, quantity per operation, and the cost of component part.

Product Line Commonality Index (PCI) (Kota, Sethuraman et al. 2000)

The PCI measures and penalizes the differences that should ideally be common. From this index, many researches have focus on an appropriate commonality, not as the former ones claim maximum components share.

Commonality vs. Diversity Index (CDI) (Alizon, Shooter et al. 2006)

The CDI indicates the difference between the existing and the ideal trade-off, which is defined as follows: common functionality should use common components, unique functions should use unique components, and variant functions should use variant components.

Comprehensive Metric for Commonality (CMC) (Thevenot, Alizon et al. 2007) (Thevenot and Simpson 2007)

An extension version of PCI, the CMC is also a component-based commonality metric. It analyzes the data of manufacturing process, material, assembly scheme, production volume, initial cost.

✧ **Conclusion on evaluation indices**

Thevenot and Simpson (Thevenot and Simpson 2006) did a thorough comparison for these heuristic indicators since last decades. Each index has its advantages and limitation in application. Table 2-1 below lists and compares the factors considered when building up an index for product family assessment.

Table 2-1 Comparison of the included factors with existing indices

Commonality Indices	Components in products	Size and geometry	Materials	Manufacturing processes	Assembly schemes	C-C Connections	Component costs (fixed costs)	Component costs (linked to production volume, setup costs, etc)	Penalize non-differentiating components only	Penalize differentiating components
DCI	X									
TCCI	X									
CI	X									
PCI	X	X	X	X	X					
%C	X				X	X				
$CI^{(C)}$	X						X			
CMC	X	X	X	X	X			X	X	
CDI	X	X							X	X

Most of the indices mentioned above have a limit that an absolute high value has no signification for the design, unless doing relative benchmarking. Even a few have fully considered the necessary tradeoff between commonality and diversity within an index for product family design. Their targets to assessing whether the commonality or diversity is good or not are built up by a simple and subjective marketing study. Rare research gives explicit and objective indicators for product family evaluation regarding to target usage contexts

Furthermore, the evaluation indices can be used to tell for instance how similar and/or different products seen from a strictly physical component-based viewpoint the applicability of such indices is questionable. The variety and commonality can only be observed in relation to the customer perception or manufacture. The perception that the degree of commonality can be derive directly from the structure of the physical products. A comprehensive marketing study from the aspect of consumer is lacked.

2.5.5. Rationalizing product lines

Anderson et al. (Anderson and Pine II 1998) present a technique to rationalize product lines before implementing just-in-time, build-to-order, flexible manufacturing, etc. By rationalizing the product line the authors mean eliminating out-dated and less profitable products that should not distort a future mass customization setup.

The technique considers the following 12 rationalization criteria whereof the 5 first are quantitative and there rest qualitative:

1. *Sales volume*

The sales volumes of all products are analyzed using a Pareto sort format plot. The product variants sold in the highest volume have a higher probability of avoiding to be discontinued.

2. *Sales revenue*

Similarly, the sales revenue of all products can be sorted in a Pareto plot and analyzed.

3. *Part commonality*

One approach to analyze the part commonality is to make a list of commonality or preferred parts and plot the products according to percentage of common parts in a Pareto sort.

4. *Cost of variety*

The technique includes a method to calculate the cost of variety for each product under consideration. The calculation model includes costs related to inventory, production setup and changeover, materials, operations, customization/configuration, marketing, quality, service and flexibility. Again, the cost of variety is analyzed in a Pareto plot.

5. *True profitability*

Calculating the true profitability is somewhat a challenge. Activity Based Costing (ABC) can provide a realistic indication of profitability. Again, products having the highest profitability have a higher probability of remaining in the assortment.

6. *Polls and surveys*

Polls and surveys are presented as an alternative or supplement to calculating the true profitability of the products. Typically, factory workers, production planners, product managers, dealers, sales people, etc. have an opinion of what products are profitable or not. The idea here is to query these people for their opinions and experiences.

7. *Factory processing*

This step is particular concerned with identification of product variants that does not fit very well into a flexible manufacturing environment. The technique presents a list to especially skeptical of when analyzing the products.

8. Functionality

This step looks for opportunities to consolidate products that have similar (overlapping) functionality. For instance, if an old product is not discontinued and still competes with the new slightly improved replacement product.

9. Customer needs

This step states the importance of analyzing the variety in the product family from a customer view point.

10. Company core competencies

Products representing the company's core competencies with regards to technology, processing, product development, marketing, etc. should have a greater chance of staying in the assortment.

11. Clean sheet of paper scenario

A strong tool to prioritize the products is to role-play the scenario pretending to be a well-financed new competitor, i.e. what products would you have if you could start on a clean sheet of paper?

12. Future potential

The existing products are evaluated and prioritized subjectively according to their presumed future potential including aspects of technology, markets, demographics, corporate strategy, etc.

✧ **Conclusion on rationalizing product lines**

The rationalization technique presented above has its absolute strength in the broadness of aspects that are covered in the 12 steps. In relation to this research the technique provides a method prioritize the products according to their strategic importance to the business using quantitative as well as qualitative analyses. Furthermore, the technique includes experience from factory workers, production planners, product managers, dealers, sales people, etc. in the evaluation of the products. In this way contingent critical design issues are captured and can possibly be eliminated.

Besides the Pareto plots used to present the quantitative information the method does not provide any readily applicable tools, but merely presents a list of aspect that should be considered when rationalizing a product line, and as such it somewhat an exaggeration to term the list as a technique. This is considered to be a major disadvantage of the method.

2.5.6. Generic Bill-of-Material

The generic Bill of Material (BOM), which used to describe of related products in one all-embracing model by using generic and specific items, originates from the assemble-to-order environment (Vanveen and Wortmann 1987) since the beginning of mass customization. It is introduced to enable creation of a specific manufacturing BOM by replacing certain components, when the customer places an order.

The end-products typically have a number of variations for which a number of options are available to choose from. To make the number of combinations limits, there are always not too many options. A specific BOM is generated from the generic BOM by replacing the generic items with specific items. When all generic items are replaced by specific items the product is defined. The key to efficient generation of specific BOM's is to link the generic BOM to a set of parameters and customer options in such a way that when a full set of parameter values are obtained then the product is uniquely defined.

✧ **Conclusion on the generic bill-of-material**

The limitation is that the number of end-products can easily become too large to able to define specific BOM's for every single combination. Furthermore, forecasting, BOM-storage and maintenance become unmanageable (Vanveen and Wortmann 1987). Although, the objective of the generic BOM is to create a framework from which specific BOM's can be easily generated at customer order entry, it also a powerful method to describe the variety within a product family.

2.5.7. Decision Tree

The decision tree is used by (Tiihonen, Lehtonen et al. 1998) as a product configuration model, which basically represents all the valid combinations of the components that can be used to obtain the desired functions for the customer. Figure 2-10 illustrates a visual representation of the decision tree (product configuration model). The decision tree presents the multitude of component variety within a product family and by the use of positive combinatory relationships and incompatibility relations it defines the possible product configurations.

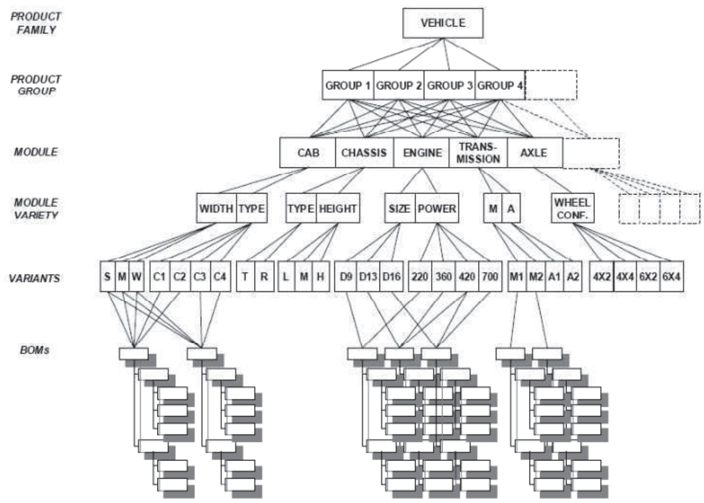


Figure 2-10 Example of product configuration model (Mesihovic and Malmqvist 2004)

✧ **Conclusion on the decision tree**

In relation to this research work the decision tree provides a product configuration method that can be used to handle constraints within the products' structure, i.e. a way to describe combinatory rules.

2.6. Advanced calculation techniques

2.6.1. Heuristic algorithms for product family design

Since the product family design problem constructs a multi-dimensional optimal problem, which not only requires optimal product family composition (product space) but also optimal product configuration (attribute space), the traditional combinatory algorithms are less preferred. The heuristic algorithms are widely used for their time-efficiency and nearly-optimal results.

Genetic algorithms have been applied to a wide variety of problems in the operations research literature. It is now widely used for it mature in design engineering and relatively good results and were first applied to the optimal product design problem by Balakrishnan and Jacob (Balakrishnan and Jacob. 1996), Alexouda and Paparrizos (Alexouda and Paparrizos 2001). Balakrishnan et al. (Balakrishnan, Gupta et al. 2004) have also used genetic algorithms on product line design problems. His follow research (Balakrishnan, Gupta et al. 2005) improved the performance of the algorithm for product family design.

Belloni et al. (Belloni, Freund et al. 2008) used pre-studied conjoint analysis data to model product family optimization problem and compared several heuristic algorithms: Coordinate Ascent Genetic Algorithm, Simulated Annealing Greedy Heuristic, Divide-and-Conquer Heuristic, Product-Swapping Heuristic, Dynamic Programming Heuristic (Kohli and Sukumar 1990), Beam Search Heuristic, Nested Partitions Heuristic. The results are compared with guaranteed optimality methodologies such as Enumeration, Branch-and-Bound, and Lagrangian Relaxation, in small dimensional problem. Four of the heuristic methods - simulated annealing, product-swapping, divide-and-conquer, and genetic algorithms - perform particularly well, consistently reaching near-optimal solutions even in the presence of measurement error.

2.6.2. Constraint programming technique

A Constraint Satisfaction Problem CSP (Tsang 1993) is defined by a 3-tuple (X, D, C) such that:

- $X = \{x_1, x_2, x_3 \dots, x_n\}$ is a finite set of variables that we call constraint variables with n the number of variables in the problem to be solved.

- $D = \{d_1, d_2, d_3 \dots, d_n\}$ is a finite set of variable value domains of X such that:

$$\forall\, i \in \{1, \dots, n\}, x_i \in d_i$$

A domain should be a real interval or a set of integer values.

- $C = \{c_1, c_2, c_3 \dots, c_p\}$ is a finite set of constraints, p being any integer number representing the number of constraints of the problem.

Solving a CSP amounts to instantiate each of the variables of X and at the same time satisfying the set of problem constraints C.

$$\forall\, i \in \{1, \dots, p\}, \exists\, X_i \subseteq X \,/\, c_i\,(X_i)$$

To do that, CSP solvers use a constraint propagation mechanism as a step by step interval (or domain) reduction process. Over the past years a variety of solving methods have been developed, which enable fast computation of CSP, and supply the user with intervals ensuring to contain all solutions of the CSP; this is the completeness property. A constraint should be any type of mathematical relation (linear, quadratic, non-linear, Boolean…) covering the values of a set of variables. Functions operate on values but constraints operate on domains.

Solving a CSP amounts to instantiate each of the variables of X and at the same time satisfying the set of problem constraints C. We can find information about propagation techniques and domain reductions in (Moore 1966) (Davis 1987) (Faltings 1994) for real constraint variables and in (Garrido, Onaindia et al. 2008) for enumerated and integer constraint variables. Over the past years a variety of solving methods has been developed, which enable fast computation of CSP, and supply the user with intervals ensuring to contain all solutions of the CSP. ILOG Solver® provides complete methods for solving CSP problems. The technique used by ILOG Solver is widely known as branch & bound.

CSP and design problem

During the design process, designers use and manage design rules, tables, abacus, relations… All these structures could be modeled as constraints (mathematical relations between variables). Yannou et al. in their works (Yannou and Harmel 2004; Yannou and Awedikian 2005; Canbaz, Yannou et al. 2011) present a Plug-And-Contract Mechanism implemented by constraint programming techniques (evolved interval arithmetics) that immediately contracts the performance and design variable domains to provide an outer approximation of the solution (or design) space.

Yvars (Yvars 2008; Yvars 2009) (Canbaz, Yannou et al. 2011) considering the design process as a constraint satisfaction problem. They propose to extend the functions of CSP modeling or resolution, which has proved its efficiency within the framework of single-designer design, to the context of multi-concept design of the same artifact.

✧ **Constraint programming technique in relation to this research**

Since the product design problem is indeed a Product Satisfaction Problem, with the constraints from technical, production and requirement (marketing) issues, the constraint programming technique is a powerful and efficient tool for solving this thesis model proposed in the following section.

During the case study and model resolution phases, domain based variables and inter-variables' causal loop are emerged. In order to address such problems, the constraint programming techniques is deployed to simulate the performances of given products in regard of personalized usage scenarios.

2.7. Conclusion

This part of the thesis covers the fundamental theoretical background that forms the basis of the research work. It has described the main areas: marketing research in design engineering and multiple products development. The existing product family assessing methods and advance calculation techniques are described and analyzed.

The marketing research combining with engineering design is essential for new product development and evaluation processes. Analytical Target Cascading gives us a good solution from marketing aspect, while it neglects the usage diversity in the marketing study even though the research concerning the usage itself and the usage context exist in marketing study for centuries.

The design engineering research field is the basic starting point for the whole work as the thesis research background within that area. The section presents the general theories and perceptions of products that are relevant to the work.

Multiple products development stresses the importance and potential of making decisions about product families instead of making decision about single products. Decision-making at product family level is necessary if achieve the benefits from commonality effects when deriving the desired product variety in considering with usages variety in the targeting market.

The actual usage model development and detailed aspects applied in the process of product family design/redesign assessment are based on and benchmarked against the existing methods listed, which are chosen with regards to the model requirements and limitation established in above sections.

Chapter III

3. Usage coverage model for product family assessing

3.1. Introduction

A product family is the concept that is designed for a market but caters for the individual wishes of customers by introducing variety within a defined product architecture and within a defined manufacturing process. The assessment of product family can be based on cost savings performance improvements, utility to the company, etc.

Our objective is to deliberately put the emphasis on the adequacy of a set of product usage scenarios with given products. We call this fitting or adequacy the usage coverage (Yannou, Chen et al. 2009). In this section, we present the concept of usage model and an inference mechanism for determining the usage coverage of a product regarding a set of expected usage scenarios.

3.2. Usage context model and usage coverage concept

3.2.1. Nomenclature

The following illustrates the principal notations used in this thesis.

$U - usage\ context\ scenario$

$k - index\ for\ the\ kth\ product\ in\ the\ family, k = 1, \dots, K$

$i - index\ for\ the\ ith\ user, i = 1, \dots, M$

$j - index\ fot\ the\ jth\ usage\ context\ scenario, j = 1, \dots, N_i$

$N_i - total\ usage\ context\ scenario\ for\ user\ i$

$E_{ij} - jth\ usage\ context\ attributes\ for\ user\ i$

$w_{ij} - jth\ usage\ relative\ weight\ for\ user\ i$

$C_s - performance\ related\ customer\ attributes$

$X - porudct\ design\ variables$

$Y - engineering\ performance$

$Pr - price\ of\ the\ product$

The example of the expected usage "to cut wood sticks and boards of defined materials and dimensions" is deployed for illustration purpose. Indeed, this is a technical domain for which the definition of the expected usages is very important and the subjective (sensorial, aesthetic, perceptual…) expectations are minor for an experienced handyman or craftsman. In addition, a number of saw categories may deliver an expected cutting service with different effectiveness, efficiency and comfort results. Let us mention the main categories: jigsaws, bow saws, panel saws, knife saws, circular saws, miter saws, chain saws, band saws. These tool categories are more or less adapted to a given cutting usage. Moreover, when considering a set of cutting usages (situations), one tool of a given category might cover more or less successfully the entire set of expected usages. For instance, a conventional jigsaw can primarily cover the whole set of expected cutting usages providing the thickness dimension is lower than 4.5 cm – i.e. it relates to the traditional length of cutting blades for jigsaws -. In other usage situations – beyond 4.5 cm of wood thickness -, a jigsaw is inadequate; only a band saw may exceed this dimension but, as a consequence, it is not well adapted to any type of wood. Imposing the use of a unique saw results in a partial coverage of cutting usages.

In general, the results of product usage by a customer may depend upon his/her degree of skill, let us say the $\mathrm{C_s}$ vector. For instance, a novice handyman may fail to cut a thick wood board of hard wood. This notion is rarely taken into account when building customer demand models.

$\mathrm{C_s}$ are user-related parameters that affect performances.

Moreover, the definition of the acceptability threshold of a performance is also customer dependent. For instance, a demanding customer may reject a board cut with insufficient accuracy or a peeling or jagged cut. Every customer has his/her own opinion on acceptable performance thresholds or bounds that he/she is willing to tolerate. Let us call C_b these acceptable bounds.

C_b are user acceptable bounding constraints of service performances.

Finally, within these acceptable bounds, the obtained performances are considered acceptable and a usage can be completed. But, the customer may express some preferences about the degree of service quality perceived. Let us call C_p the customer preferences.

C_p are user preferences of performance.

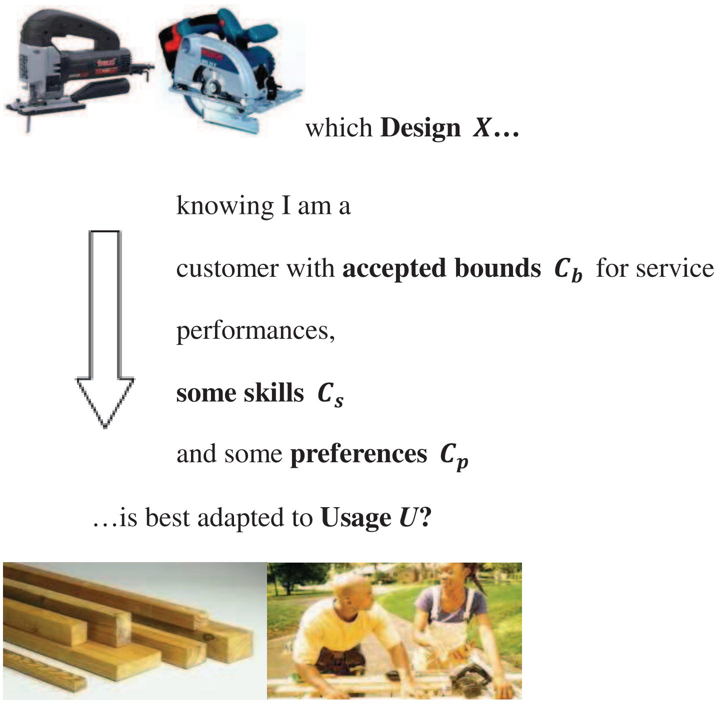


Figure 3-1 Objective of a design product : to be adapted at best to a given set of usages U

We determine that the performances of the service provided by a given product X handled by a user with skill C_s are acceptable when performances respect the bound C_p and, in that case that the perceived service quality depends on some preferences C_p. Finally, let us call S the user-related parameters that influence acceptable performance bounds and preferences and, consequently, the design choice. It should be noted that there is not a strict partition between C_s and S. For example, gender belongs to C_s and S vectors since it may influence the performance achieved (C_s vector) and it may also influence how products are viewed in a choice situation (S vector). *S are customer demographics which influence choice behavior (He, Hoyle et al. 2010), which is not involved in this research.*

In the following, we prefer to **consider a product as a service provider to realize some expected usage**. This choice has several strong advantages. First, it allows us to consider not only a physical product but a mix of products-services; second, the usage context surrounding products is made more apparent when viewed in this way. Let us propose a series of structuring definitions, starting by the one of a service

A service consists in transforming an initial state of the customer environment into a final state, the discrepancies between the initial and the final stages being mostly desirable.

The initial state is the part of the environment that will be transformed by the product use (e.g., the board to cut). The final state is what has been changed (e.g., the board cut into two parts and, unfortunately, some sawdust). Let us note that what has been changed is not necessarily desired like sawdust. This representation of a service as a transformation allows a clear definition of service performances and a useful distinction between these performances.

Service performances Y are of two kinds: they feature the results of the transformation by the service and they feature the transformation conditions.

Let us call Y_r the first kind of transformation *results* characteristics and Y_t performances characteristics of the *transformation* conditions. Then, the entire performance vector is:

$$Y = (Y_r, Y_t) \tag{3-1}$$

The Y_r vector represents the measures of the end performances of the resulting service.

Examples of Y_r for the "cutting wood" problem include the *precision* or the *planarity*. The performances related to the transformation conditions must not refer to any resulting design characteristics but rather to the manner in which the transformation (design use completion) occurs.

The Y_t vector represents the measures of the performances related to the way the service is delivered.

Examples of Y_t include the $linear\_speed$ or the $noise$. Transformation conditions may be enumerated after the TEMIF acronym – Time, Energy, Material, Information, Flows -. Flows correspond to any other type of flow (forces or perceptions like safety, comfort, noise…). They may be considered as performances if a customer has related specifications or preferences.

The so-called transformation occurs in a *service environmental context* E which is common to both initial and final states and influences the service performances. More generally, it includes the description of the conditions of an elementary service to deliver. For instance, an environmental context of the "to cut a wood board" service may be the wood type, the cut instruction (e.g. length, thickness), the presence of a workbench, the location of the cutting operation, etc.

Variable set E *represents any variables that describe the conditions under which the product is used to provide the service.*

3.2.2. The usage model: general model

In the present usage coverage model, performances Y depend both on the design solution considered X, the usage context U and the customer skills C_s. It is expressed by:

$$Y = f(X, U, C_s) \quad (3\text{-}1)$$

Functions f are called *performance equations* since they, most of the time, define explicitly the service performances from physics models or empirical studies (virtual or real design of experiments that lead to performance metamodels (Simpson, Peplinski et al. 2001)). The elicitation of theses equations is of the utmost importance as soon as we want to study the mapping between given usages and a given product design X.

The performance bounds C_b and the performance preferences C_p are dependent on user-related parameters S.

It is now time to define what a usage is. We first provide the definition of a *usage need*. Then, we propose three definitions of effective usages given a product design X: *feasible usage*, *acceptable usage* and *preferred usage*, ranging from the less to the most constraining definition of a usage.

A usage needed is a set of expected usage contexts E_i *associated with a usage frequency* w_i.

This usage frequency w_i is the number of times the product is yearly used for the given usage context E_i. A usage needed is then expressed by:

$$U_{needed} = \{(E_i, w_i)\} \tag{3-2}$$

An example of a *usage needed* set is provided in Table 3-1, where a given customer expects to successfully cut w_1 wood sticks and w_2 wood boards per year. It is interesting to note that, in practice, the usage contexts are themselves value sets since they are defined as Cartesian products of domains.

Table 3-1 Example of a usage needed set composed of two usage contexts of different usage percents

Usage contexts	Usage frequency
$E_1 = \left\{\begin{matrix} material = \{wood\}, \\ thickness \in [5,40], \\ length \in \{5,60\}, \\ workbench = \{no\} \end{matrix}\right\}$	w_1
$E_2 = \left\{\begin{matrix} material = \{wood\}, \\ thickness \in [10,30], \\ length \in \{20,1000\}, \\ workbench = \{yes\} \end{matrix}\right\}$	w_2

A feasible usage is the subset of needed usage contexts that can be fulfilled by a given design X.

It means that we look at accomplishing the minimal service so as to be feasible, i.e. effectively cutting a wood board or stick defined by E_i without any user requirement neither on the quality of the resulting performances Y_r – e.g. the $precision$, nor on the preferences on the service processing Y_t – e.g., the $linear\_speed$ or the $noise$. It can be expressed by:

$$U_{feasible}(X, U_{needed}, C_s) = \left\{\begin{matrix} (E_i^*, F_i), such\ that \\ (E_i^*, F_i) \in U_{needed} \\ and\ E_i^* \subseteq E_i \\ and\ Y_{r_i} = f_r(X, E_i^*, C_s)\ is\ feasible \end{matrix}\right\} \tag{3-3}$$

A "feasible performance" in the aforementioned formula means for instance that cutting the board is possible whatever the linear speed and the cutting quality. For cutting the board, the linear speed must be strictly positive, which requires a minimal value of horizontal force and may be impossible by the user ability (C_s vector).

Figure 3-2 graphically represents the calculation of the feasible usage $U_{feasible}$ from the needed usage U_{needed}. For each needed usage context E_i it amounts to shrink its domain values to its feasible part E_i^*; this domain reduction being expressed by $E_i^* \subseteq E_i$. As soon as one domain of E_i^* becomes empty, the initial usage context E_i cannot be fulfilled, even partially, i.e., with certain value ranges.

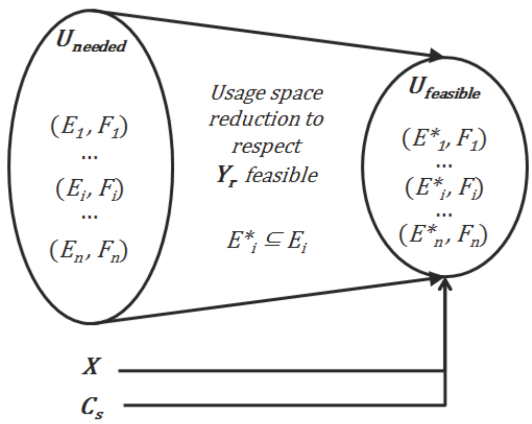


Figure 3-2 Calculation of the feasible usage set $\mathrm{U_{feasible}}$ from the needed usage set $\mathrm{U_{needed}}$

An acceptable usage is the subset of a usage need that is fulfilled by a given design X and which is compliant with the required quality level of the service results.

It can be expressed by:

$$U_{acceptable}\left(X, U_{feasible}, C_s, C_b\right) = \left\{ \begin{array}{c} (E_i^*, F_i),\ such\ that \\ (E_i, F_i) \in U_{feasible}(X, U_{needed}, C_s) \\ \text{and } E_i^* \subseteq E_i \\ \text{and } C_b\left(Y_{r_i}\right) with\ Y_{r_i} = f_r(X, E_i^*, C_s) \end{array} \right\} \quad (3\text{-}4)$$

The expression $C_b(Y_r)$ meaning that the bounding constraints C_b on performances Y_r are respected. For instance, a cutting service may be acceptable if and only if the $precision$ and the $planarity$ of the cutting surface area is sufficient. Otherwise, the customer would reject the service and throw or recycle the processed wood parts.

A preferred usage is the possible subset of a usage need that is fulfilled by a given design X and which is compliant with the required quality level of the service results as well as with the maximum level of comfort, safety and pleasure during the service processing.

It can be expressed by:

$$U_{preferred}\left(X, U_{acceptable}, C_s, C_b, C_p\right) = \left\{ \begin{matrix} (E_i^*, F_i), such\ that \\ (E_i, F_i) \in U_{acceptable}\left(X, U_{feasible}, C_s, C_b\right) \\ \text{and } E_i^* \subseteq E_i \\ \text{and } C_p\left(Y_{t_i}\right) \\ with\ Y_{t_i} = f_t(X, E_i^*, C_s) \end{matrix} \right\} \quad (3\text{-}5)$$

For instance, a cutting service is preferred if and only if the $precision$ and the $planarity$ of the cutting surface area is sufficient and the $comfort$ and $safety$ conditions are satisfactory.

Figure 3-3 may summarize the principles of our usage model.

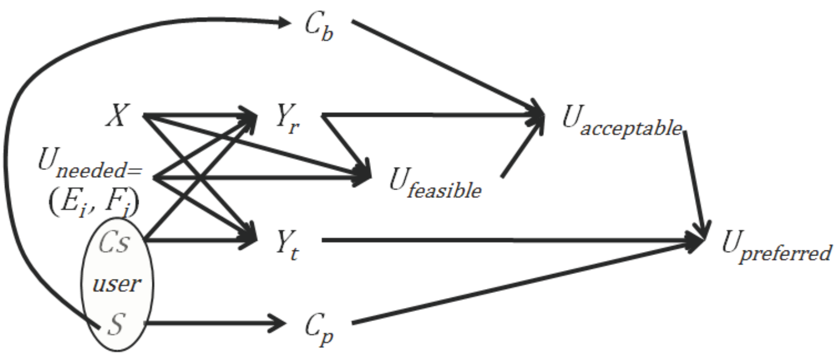


Figure 3-3 Principles of the usage coverage model

The major usefulness of such a Usage Coverage Model (UCM) is to be able to choose among several parameterized designs and to optimize it, starting from a targeted set of usage needed. On an analysis point of view, we want to get a graphical image of the need coverage of a given product or a given product family, in comparison with other competing products or product families. We also want to be able to take the different psychological and behavioral customer profiles into account in terms of quality requirements concerning both the service performance results Y_r and the service processing conditions Y_t. From the adopted definitions (eq. 3-3, 3-4, 3-5) and the set-based modeling of the usages, it follows that:

$$U_{preferred}\left(X, U_{acceptable}, C_s, C_b, C_p\right) \subseteq U_{acceptable}\left(X, U_{feasible}, C_s, C_b\right) \subseteq U_{feasible}(X, U_{needed}, C_s) \subseteq U_{needed} \quad (3\text{-}6)$$

Table 3-2 Graphical representations of the 4 different usage sets

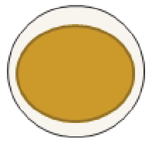
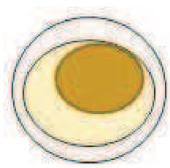
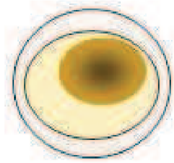
Usage type	Graphical representation of the usage set
U_{needed}	
$U_{feasible}$ (X, U_{needed}, C_s)	
$U_{acceptable}$ $\left(X, U_{feasible}, C_s, C_b\right)$	
$U_{preferred}$ $\left(X, U_{acceptable}, C_s, C_b, C_p\right)$	

Table 3-2 summarizes the different usage sets we might get when using the usage coverage model. We might be able to figure out the shrinking ratio of the usage needed set when the service must be fulfilled by a given product-service design X: $U_{feasible}(X, U_{needed}, C_s)$ (see row #3 of Table 3-2). As soon as the customer requires that the service results be of a certain quality level, the effective usage set acceptable for a given design X is further shrunk into $U_{acceptable}\left(X, U_{feasible}, C_s, C_b\right)$ (see row #4 of Table 3-2). If, in addition, the customer wants to get these results with a quality of the service processing, this $U_{preferred}\left(X, U_{acceptable}, C_s, C_b, C_p\right)$ usage set may be considered as a mathematical fields of preferences.

Our ultimate goal is to develop *usage-oriented choice models* for narrowing down the choice alternatives for each person to only those which meet his/her requirements. Or, from a product point of view, to assess the competitive advantages of a given product among a set of preexisting competing products defined by slightly different design parameters.

3.3. Definition of Usage Coverage Index (UCI)

3.3.1. Usage Coverage Index for single usage

In order to apply computation, the former typological variables describing the usage context must be reinterpreted as intermediate value variables via several correspondence tables. For the usage context aspect, when collecting usage context and user information through a questionnaire (He, Hoyle et al. 2010) or when interpreting intermediate variable, uncertainties are generated because of linguistic ambiguity. In appendix, a usage context information collection process and a questionnaire for jigsaw cutting wooden board usage are shown for a precedent research attempt {WANG, 2010 #401}. A set-based modeling method is used to model the subsets of usage and user contexts. These subsets are modeled by domain variables: discrete sets or continuous intervals.

As illustrated in Figure 3-4 below, for a potential usage target market segment, the usage context scenario can be identified as ($\boldsymbol{U}_{needed}$, $\boldsymbol{C_s}$); this can be represented as a domain in a Cartesian space formed by the variables defining the usage context ($\boldsymbol{E_1} \times \boldsymbol{E_2}$) for illustrative purposes). Given a product design $\boldsymbol{X}$ combined with demographic variables $\boldsymbol{C_s}$, its capable usage context can be mapped by a physical-based performance prediction model.

To identify these variables $\boldsymbol{U}_{needed} = \{(\boldsymbol{E}_i, w_i)\}$ which define the usage context space, several attempts are carried out during this thesis research. Wang, He et al. (He, Hoyle et al. 2010; WANG and Yannou 2010) are using questionnaire survey and clustering analysis method to figure out these decisive variables for a particular product usage context. Throughout this thesis, we suppose that the usage context space is pre-defined by these methods and we apply directly in this space a usage coverage mechanism illustrated as Figure 3-4.

We can also consider the target market as an initial usage context domain. An implemented product design $\boldsymbol{X}$ serves as a set of constraints for the initial usage context domain, because of the limited feasibility and even user exigency on cutting speed and comfort. This initial usage context domain can therefore be considered as a feasible usage context domain: in Figure 3-4, it is the overlap between initial usage context domain and a given product's capable usage context domain. Alternatively, if we consider the problem in a product design variables space ***X***, the initial usage context variables identified in the target market can serve as constraints to reduce the product's design variables domain.

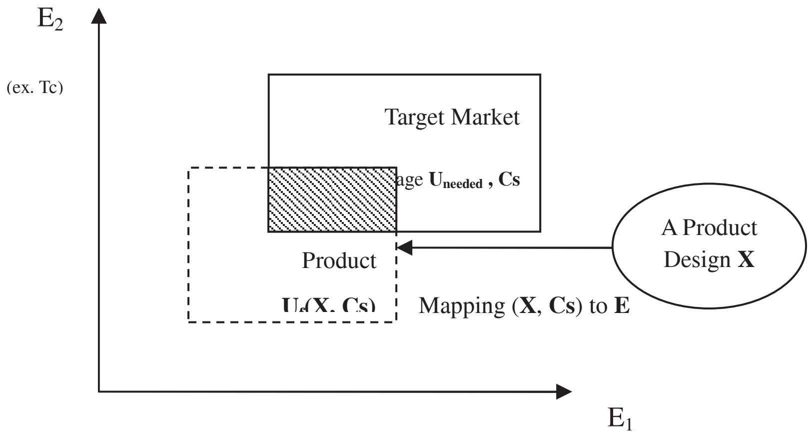


Figure 3-4 Usage coverage mechanism in usage context space for single usage

This coverage mechanism cannot be solved properly by mathematical programming, because of the existence of a causal loop in the relation constraints identified in the appendix **Fig.** 2. In addition, these variables must be computed in the form of value domains. For these reasons, the usage coverage model forms a Constraint Satisfaction Problem which can be solved by constraint programming techniques.

For our usage context based design problem, the usage context variables ***E*** and design variables ***X*** are *constraint variables*, with their initial domains. The constraints are all these physical constraints, feasible constraints, and users' performance exigencies/demands.

After using a constraint programming technique to shrink the intervals of initial usage variables, a possible Usage Coverage Index is defined as the ratio of the final widths of the contracted interval of usage context variables and those of their initial domains, as given in formula (3-7). The feasibility variable is a Boolean variable, which means whether the required usage can be succeeded under basic performance criteria – e.g. a non-null advance cutting speed with no exigency on result quality or comfort in cutting process, for a wooden board cutting usage.

$$UCI_{single-usage} = feasibility \times \frac{|E_{final}|}{|E_{initial}|} \times 100\% = \frac{\prod i|usage\_context\_varaiable|_{final}}{\prod i|usage\_context\_variable|_{initial}} \times 100\% \quad (3\text{-}7)$$

3.3.2. Usage Coverage Index for multi-usages

In daily life, one product may be used in several different situations. Especially for durable products, their usage context can be multiple. We model this situation of multi-usages as a weighted combination of single usage.

We suppose that user *i* has a set of *j* usage context scenarios for a given product. The different usage context scenarios of the user are weighed with a relative importance w_{ij}, which can be interpreted as a percentage of occurrences of such usage context. As described above, the UCI of each single usage scenario can be calculated. For a given user *i* with a given product *k*, the UCI of his/her multi-usage context can be calculated using formula (3-8), which is a weighted sum of all single usages. A more detailed example of multi-usages for jigsaw case is illustrated in section 4.5.

$$UCI_{multi-usages} = \sum_{j=1}^{N_i} \left(UCI_{ijk} \cdot w_{ij}\right) \text{ for user } i \text{ with } N_i \text{usages} \quad (3\text{-}8)$$

3.3.3. Consumer buying decision criteria

Therefore, based on the marketing proposition of consumer's expectations and product's perceived performances; we define consumer criteria for buying decision. One criterion is based on the measurement of the adequacy between usage and product. Consumers can make *coverage – efficient compromised choice* with the index which increases with perceived performances and adaptation of their expectation, and decreases with the product price. The values of the performances and price are normalized by the formula (3-9). This normalization will have a value between [0, 1]: X_{Max} is the greatest value of X from all the studied usage context scenarios.

$$|X| = \frac{X}{X_{Max}} \quad (3\text{-}9)$$

The normalized user's decision index CI is given by formula (3-10) below. It takes the value

[0, 1] and reflects a compromise decision between expectations, adequacy and economy. The product from all the P_i $(i = 1, .., K)$ alternatives that produces the maximum CI is the most adapted product for the given usage context and the given user.

$$CI = \frac{|UCI| \times |Performance|}{|Price|} \tag{3-10}$$

$$\text{EfficientCh}(User) = max_{P_i}(CI) = max_{P_i}\left(\frac{|UCI| \times |S_{a\,max}| \times |P_{com\,min}|}{|Price|}\right) \tag{3-11}$$

3.4. Conclusion

In the above sections we presented the generic concept and principles of usage context model, usage coverage model and the indices to measure it. The terms, variable definitions and classes as well as relation classes are proposed. Four kinds of usage sets are defined.

This chapter intends to represent a more thorough marketing model for products and services in which the contextualization of usage is fundamental. The given usage coverage model attempts to accomplish this by embodying a paradigm in which customers are understood as product employers and products as service providers. This method of quantifying individuals' performances during product usage is new; it offers the advantage of linking with user experience to introduce the perceived quality of a product's service, as well as to consider particular service delivery conditions. In this way, the usage coverage model is able to distinguish between the performance of the product's service results and the quality of the product's service delivery process.

In the next chapter, this generic usage coverage model and the new indices are applied to a jigsaw product family case. The contributions of proposed method are revealed during the experiments and case studies.

Chapter IV

4. Assessing approach for jigsaw family case

4.1. Background of redesign context

In this section, we apply the usage coverage index to check if a given jigsaw product family matches the target usage market well. The expected usage is “to cut wooden boards of different density and dimensions”.

First of all a brainstorming is carried out among design team members to identify the important usage context variables. Brainstorming is well-known for generating a flood of new ideas, in which a group of open-minded designers from different spheres of life bring up any thoughts that are related to usage context variables of a given product. These variables can describe properly the conditions under which the product is used to provide the service. Meanwhile, several experiments were carried out to verify the defined usage context variables as shown in Figure 4-1.

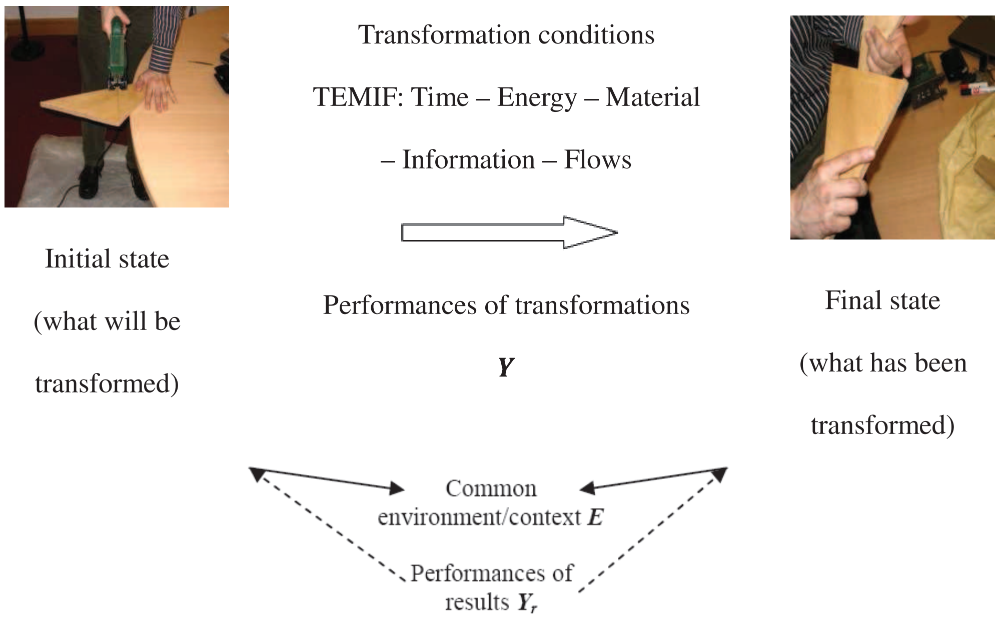


Figure 4-1 Experiments and cutting wooden boards usage context

The intervals of the context variables are identified by interviews with experts: here design team members discuss the usage context information one single customer at a time. The interviewed customers are chosen to be "experts" on the product usage. They can estimate the importance of each context variable and its possible interval value. The interviews are held in the customer's environment, where the customer uses the product. The design team records the customer responses.

Power tool - jigsaw family

We start with the issue of an existing scale-based family of 4 Bosch jigsaws (from P1 i.e. PST 650 to P4 i.e. Bosch PST900 in Table 4-1), each with increasing power, weight and price. However, their dimensional parameters are the same as shown in Table 4-2.

Table 4-1 The products in Bosch jigsaw family

	P1	**P2**	**P3**	**P4**
Models	PST 650 	PST 700 PE 	PST 800 PEL 	PST 900 PEL 
Power (P_m):	120W	180 W	200 W	250 W
Weight (m):	1.5 kg	1.8 kg	2 kg	2.2 kg
Price (Pr):	50 €	80 €	100 €	130 €
Tunable stroke frequency (f): 8.4 – 45 s^{-1}				

Table 4-2 Jigsaw dimensional design parameters (same values for all products P1 to P4)

Variables		**Value**
A	Blade translation	0.018 m
H_w	*Wrist* position *height*	0.22 m
L_w	*Wrist* position *length*	0.09 m
O_s	*Slider origin* position	0.03 m
L_s	*Slider length*	0.13 m
n	Number of teeth	18

O_t	*Teeth origin* position	0.015 m
L_t	*Teeth length*	0.068 m
H_t	*Teeth height*	0.002 m
W_t	*Teeth width*	0.0012 m
s	*Step* between two teeth	0.004 m
α	Rake angle of teeth	18°

The variables cited in Table 4-2 above can be discerned clearly in **Fig. 1** in the Appendix. The relations are established between performances Y and X, E and C_s through a series of intermediate variables which in this case are mainly forces, torques and speeds. The usage coverage model of the jigsaw design issue is represented in Figure 4-2 below. A physics-based analysis of these variables is detailed in the Appendix.

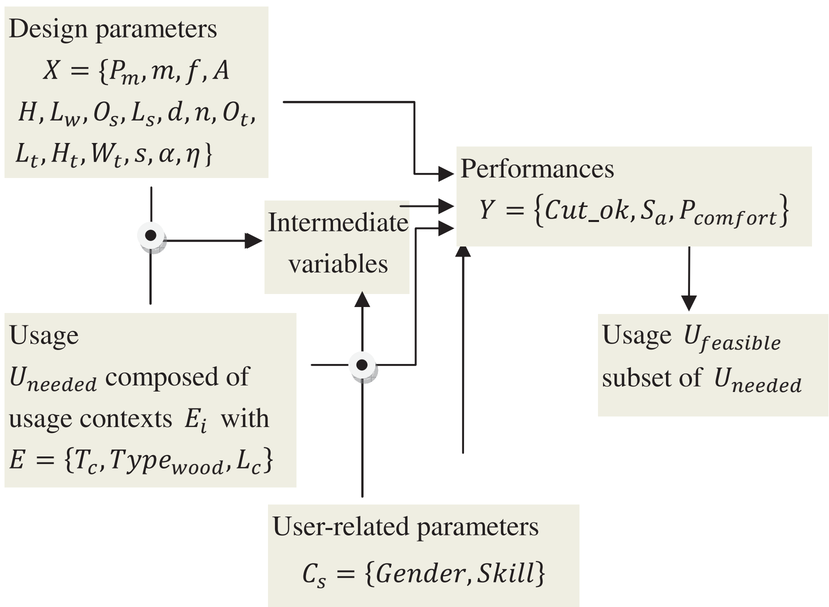


Figure 4-2 Variable screening for the jigsaw usage coverage modeling problem

4.2. Usage context model and usage coverage index

Jigsaw cutting wood usage example

As an example of illustration, a physics-based performance estimation model for jigsaw is used as shown in appendices. Different categories of variables and detailed list of intermediate variables for jigsaw design problem are illustrated and interpreted. Below certain important variables for cutting wood board usage are cited for simplicity:

$$E = \begin{cases} T_e - \text{Thickness of the wood board} \\ \rho_w - \text{Density of wood} \end{cases} \tag{4-1}$$

In practice, the usage context variables in (4-1) that influence the performance of cutting wood service are composed of the thickness of wood board and its density.

$$C_s = \begin{cases} Gender - \text{Gender of the saw user} \\ Skill - \text{Skill of the user for cutting wood with a tool X} \end{cases} \tag{4-2}$$

We consider two demographic variables $C_s = \{Gender, Skill\}$ which are user-related parameters that affect performances. These two variables define the maximal allowable bounds $F_{i\,max}$ - the translation force, $F_{p\,max}$ - the pressure force, and $M_{w\,max}$ - the torque the user wrist may deliver to the jigsaw. As a result, we have assessed these bounds with ergonomic analysis and a correspondent Table 4-3 is obtained.

Table 4-3 Correspondence table between the gender values and maximal force and torque admissible values

Gender	**Skill**	$F_{t\,max}$	$F_{p\,max}$	$M_{w\,max}$
Female	*Basic user*	45N	90N	20N.m
	Medium	80N	130N	40N.m
	Professional	110N	170N	60N.m
Male	*Basic user*	70N	105N	30N.m
	Medium	100N	150N	50N.m
	Professional	130N	195N	70N.m

We consider two most concerned performances for this service of "to cut wood boards". The first one is the mean advance speed; especially an advance speed non null signifies the saw tool is able to complete this service (feasible). The second one is the comfort during the cutting wood operation.

$$Y = \begin{cases} S_a - \text{Mean advance speed of cutting} \\ P_{comfort} - \text{Degree of comfort in the user's wrist} \end{cases} \quad (4\text{-}3)$$

The comfort of cutting with a jigsaw is mainly due to the wrist torque which must not exceed a maximal value the user can afford. It can be expressed by:

$$P_{comfort} = 1 - \left|\frac{M_w}{M_{w\,max}}\right| \in [0,1] \quad (4\text{-}4)$$

For the jigsaw use case, the Usage Coverage Index is defined as

$$UCI_{single-usage} = Cut_{ok} \times \frac{|T_c|_{final} \times |\rho_w|_{final}}{|T_c|_{initial} \times |\rho_w|_{initial}} \quad (4\text{-}5)$$

4.3. CSP for single product and single usage problem

In this section, for illustration we present in detail the CSP mechanism to solve single product – single usage coverage problem for jigsaw cutting wooden board service.

We suppose for a problem that a family is wondering which saw is well adapted to the usage needs of any of its members: the two parents and three teenagers. They have the project to restore a wooden cottage all together. They are more or less skilled with the use of saws. Seven usage contexts for cutting wood have been planned depending on the assigned tasks to the family members (see Table 4-4). Here, usage contexts are defined by given values of $(type\_wood, thickness)$ like $(\{oak\}, \{0.02\})$ instead of intervals like $(hard\ wood, [0.015, 0.035])$; the reason being only the simplicity of a first example.

Table 4-4 Usage contexts for cutting wood with different users

		Daughter	Mother	Father	Son #1		Son #2	
		a	b	c	d	e	f	g
Usage contexts E	$type\_wood$	oak	oak	$plywood$	$plywood$	fir	fir	fir
	$thickness$	0.025	0.025	0.03	0.05	0.04	0.04	0.035
User-related variables U	$gender$	$female$	$female$	$male$	$male$	$male$	$male$	$male$
	$skill$	$basic\ user$	$medium$	$professional$	$medium$	$medium$	$basic\ user$	$basic\ user$

Their stake is to buy a saw that fulfill at best the different needs, we prefer to say "that cover at best the usages needed". The jigsaw Bosch PST 650 is a candidate they envisage to purchase. The three performances are considered as objectives, no preference constraint is put on them. Table 4-1 and Table 4-2 show the design parameter values corresponding to the Bosch PST 650 jigsaw with the large value domain for the stroke frequency f between 8.4 and 45.0 $round/s$. Indeed, an electronic variator may address a range of frequencies at the detriment of the cut force F_c for a given fixed engine power P_m. This possible variation of f is directly modeled as a value interval in our CSP system.

The simulation results show in Table 4-5 that with a Bosch PST 650 jigsaw we can cover the $\{b, c, e, g\}$ subset of the $\{a, b, c, d, e, f, g\}$ initial set of usages. The failure analysis reveals that:

- For usage context a: The thickness (2.5 centimeters of oak, a notable hard wood) is too important for a $basic\ female$ user.
- For usage context d: The thickness is too important for a jigsaw tool.
- For usage context f: The cutting operation is impossible for a $basic$ user with this thickness of 4.0 centimeters of fir.

For the other feasible usage contexts $\{b, c, e, g\}$, the CSP computation brings the information of the maximal allowable advance speed and the minimal comfort ratio. For instance, for usage contexts $\{b, c, e, g\}$, the advance speed is between $\{1.1, 4.1, 2.2, 1.3\}$ millimeters per second, which is quite a good advance speed. The most tedious operations (advance speed around 1 millimeter per second) are for usage contexts b and g, which correspond to non-experienced people facing a wood piece of a practical thickness. Usage context e corresponds to a more medium-experienced male and then, the advance speed may reach 2.2 millimeters per second since it directly depends on the maximal forces $F_{t\,max}$ and $F_{p\,max}$ that the user may deliver.

The maximal advance speed of 4.1 millimeters per second is reached for usage context c which corresponds to a $male$ user with a $professional$ skill cutting $plywood$ which is in general less dense than oak. It is not surprising to note that the maximal amount of comfort follows the same order than the advance speeds. We got for usage contexts $\{b, c, e, g\}$, the maximal comfort ratios $\{80\%, 97\%, 91\%, 84\%\}$. The $professional\ male$ is more comfortable in usage context c since his wrist is less sollicitated relatively to the maximal allowable wrist torque.

Another interesting result from the CSP computation is the maximal allowable stroke frequency which is strongly limited to 12 rounds per second, far from the technical possibility of 45 rps. The reason must be that, beyond this value of 12 rounds per second, the translation force F_t applied to the wood section becomes insufficient to get a given positive scob height H_d. It denotes a non trivial interaction of physics equations. This notion of minimal translation force F_t is well illustrated by the existence of non-zero lower bound of F_t variable. This phenomenon of a minimal translational force to exert so as to start the advance is easy to notice as soon as the cutting operation is not that easy.

Table 4-5 CSP results for the {a,b,c,d,e,f,g} usage needed set

	a	b	c	d	e	f	g
Cut_ok	**0**	**1**	**1**	**0**	**1**	**0**	**1**
$S_a\ (m/s)$		[0.00100000, **0.00111064**]	[0.001, **0.00405477**]		[0.00100000, **0.00221003**]		[0.00100000, **0.00133189**]
$P_{comfort}$		[**0.779321**, 0.796168]	[**0.811661**, 0.966039]		[**0.806973**, 0.908946]		[**0.764855**, 0.835711]
$f\ (round/s)$		[8.4, **12.31**]	[8.4, **10.4778**]		[8.4, **9.36761**]		[8.4, **10.7535**]
$F_t\ (N)$		[**37.3677**, 80.00]	[**45.9523**, 130]		[**53.3138**, 100]		[**44.4207**, 70]
$F_{t\ max}\ (N)$		80	130		100		70
$F_p\ (N)$		[0, 130]	[0,195]		[0, 150]		[0, 105]
$F_{p\ max}\ (N)$		130	195		150		105
$H_d\ (m)$		[0.0000090260, 0.0000248901]	[0.0000106045, 0.0000429988]		[0.0000118612, 0.0000262136]		[0.0000103325, 0.0000137619]
$\rho_w\ (kg/m^3)$		[590.000, 864.640]	[575.000, 650.001]		[480.600, 535.961]		[480.600, 589.302]

For this first experiment, the Bosch PST 650 jigsaw is able to cover 4 usage contexts out of 7. And for these 4 usage contexts, the performance S_a and $P_{comfort}$ are more or less satisfactory.

In a second experiment, we support the family shift the jigsaw Bosch PST 650 to PST 700 PE, which is more powerful. The same CSP computations are performed, leading to the results of Table 4-6. Then, the usage coverage is extended since usage contexts $\{a, f\}$ are made feasible.

Table 4-6 Results for the {a, b, c, d, e, f, g} usage needed set for a jigsaw PST 700 PE

		a	b	c	d	e	f	g
Performances	Cut_ok	**1**	**1**	**1**	**0**	**1**	**1**	**1**
	$S_a\ (m/s)$	[0.001, **0.00111064**]	[0.001, 0.00371680]	[0.001, 0.00546453]		[0.00100000, 0.00298814]	[0.00100000, 0.00180478]	[0.00100000. 0.00180478]
	P_{com}	[0.955401 ,0.975332]	[0.826927 , 1]	[0.815168 , 1]		[0.84026 , 1]	[0.886381 , 1]	[0.886381 , 1]
Other variables	f	[**14.8785, 16.5246**]	[8.40000, 16.5246]	[8.40000, 14.0815]		[8.40000, 12.6013]	[10.8791, 12.6013]	[8.40000, 14.4491]
	$F_t\ (N)$	[33.9387, 45]	[33.9387, 80]	[41.2246, 130]		[47.4047, 100]	[39.9315, 70]	[39.9315, 70]
	$F_{t\ max}\ (N$	45	80	130		100	70	70
	$F_p\ (N)$	[0, 5.30622]	[0, 130]	[0, 195]		[0, 150]	[0, 105]	[0, 105]
	$F_{p\ max}\ (N$	90	130	195		150	105	105
	$H_d\ (m)$	[0.00000672398, 0.00000746787]	[0.00000672398, 0.0000249917]	[0.00000789061, 0.0000431185]		[0.00000881746, 0.0000263479]	[0.00000768985, 0.0000138785]	[0.0000076898, 0.0000138785]
	$\rho_w\ (kg/m$	[590.000, 619.255]	[590.000, 930.001]	[575.000, 650.001]		[480.600, 608.701]	[480.600, 525.040]	[480.600, 608.701]

Each Usage Coverage Index is calculated as defined in formula (4-5). Then, an overall degree of coverage is computed through the formula (4-6):

$$UCI_{total} = \sum_{j=1}^{N_i} \left(UCI_{ijk} \cdot w_{ij} \right) \text{ for } N_i \text{usages} \tag{4-6}$$

Table 4-7 provides the values of this usage coverage index for the 7 usage contexts. We can observe a significant improvement of the degree of usage coverage from 44% to 63% when increasing the engine power. But usage contexts *a* and *f* remain hard to fulfill in case of particular dense wood material.

Table 4-7 Usage coverage for the {a,b,c,d,e,f,g} usage needed sets for the two jigsaw

	a	b	c	d	e	f	g	UCI_{total}
$P = 150\,W$	0	0.808	1	0	0.432	0	0.849	$\mathbf{0.44}$
$P = 200\,W$	0.086	1	1	0	1	0.347	1	$\mathbf{0.63}$

4.4. Generic usage context space for cutting wooden board usage

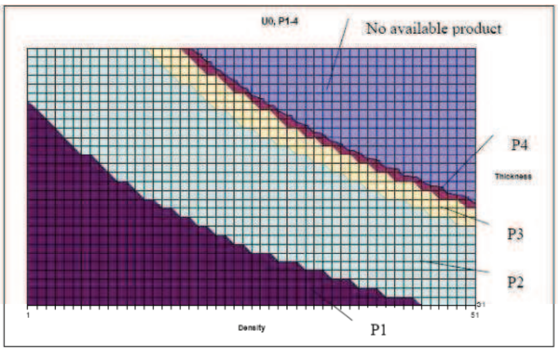
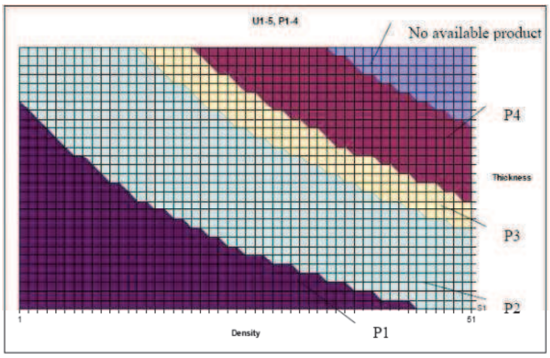
The difficulty of succeeding the cutting wooden board usage increases as the density and thickness of wooden board increase, in usage context variable space (T_c, ρ). In this section we supposed that the users can probably have a usage of cutting wooden board with density between $[400, 900]$ kg/m^3, which is an interval of current natural wood densities. And typical board thicknesses lie within $[0.02, 0.05]$ m. This space can be named as generic usage context space. The given jigsaw products P1, P2, P3, P4 have different performances for a given user type.

We suppose that in the target market there are 6 types of typical users: *Female Beginner (U0), Female Medium (U1), Female Professional (U2), Male Beginner (U3), Male Medium (U4)*, and *Male Professional (U5)*. Each user type may not know exactly what kind of usage situation he/she would encounter when cutting wooden board. So, the calculation is based on the entire possible usage context space – in this case, $[400, 900] \times [0.02, 0.05]$.

4.4.1. Product family assessment under UCI criterion

Under the usage coverage index, value increases as the class of product increases. For the above usage context space, a process of discretization is applied. The process takes the granularity steps of 10 kg/m for density and of 0.001 for thickness.

The graphic of coverage is shown in Figure 4-3 after calculation of the UCI index.

Female Beginner User (*U0*)	Other User (*U1-U5*)
	

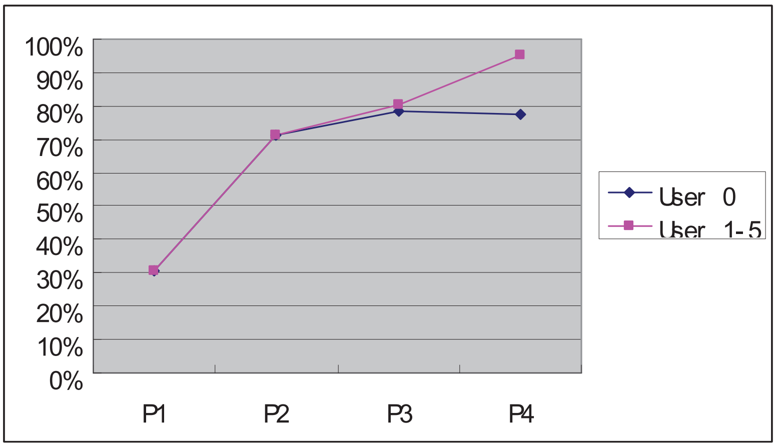


Figure 4-3 Illustration of usage context coverage increase with the power capacity of the product family

For example, from the above curve in Figure 4-3 and data of Table 4-8, it can be seen that product P1 covers 30.41% of the usage contexts of given user types. This value increases to 71.17% for product P2. However, products P3 and P4 see respectively increases of around 10% and 15% compared to their predecessors, P2 and P3. For a *female beginner* user in particular, the maximum forces that she can deploy are already at their maximum and thus limit the usage context coverage, which means that she would not be able to succeed in the extremely difficult usage scenarios even with a more powerful product. So the UCI of the most powerful product P4 does not increase at all compared to P3. So under UCI criteria, for most user types, product P2 can satisfy most of their usage contexts. For skilled users, the increasing UCI by product P3 to P2 adds little for that by P4 to P2.

Table 4-8 UCI values for 6 user types and 4 products

UCI	**Female**			**Male**		
	User0 **Beginner**	***User1*** **Medium**	***User2*** **Prof.**	***User3*** **Beginner**	***User4*** **Medium**	***User5*** **Prof.**
P1	30.41%	30.41%	30.41%	30.41%	30.41%	30.41%
P2	71.17%	71.17%	71.17%	71.17%	71.17%	71.17%
P3	78.26%	80.29%	80.29%	80.29%	80.29%	80.29%
P4	78.44%	95.00%	95.00%	95.00%	95.00%	95.00%

Although some of the UCI values are identical for a given product with different user types, the other performances, such as the maximum advance speed which can be attained by the user, are not identical. For example, the maximum advance speed $S_{a\,Max}$ with product P1 is shown below for the 3 types of female user. Even if the UCI stays the same, S_a (m/s) performance varies.

User Type 0, P1 User Type 1, P1 User Type 2, P1

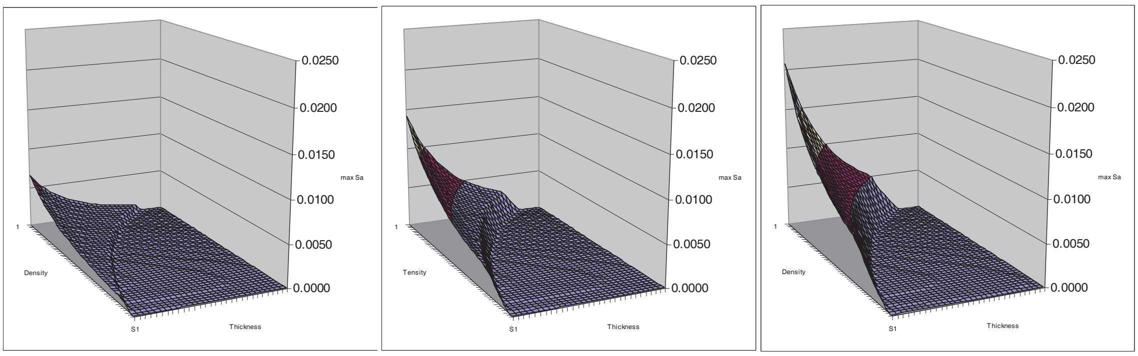


Figure 4-4 Variation of maximum advance speed S_a (m/s)

4.4.2. Product family assessment under consumer choice

The decision index CI value of a user type *Male Professional* with a jigsaw P1 is illustrated in Figure 4-5.

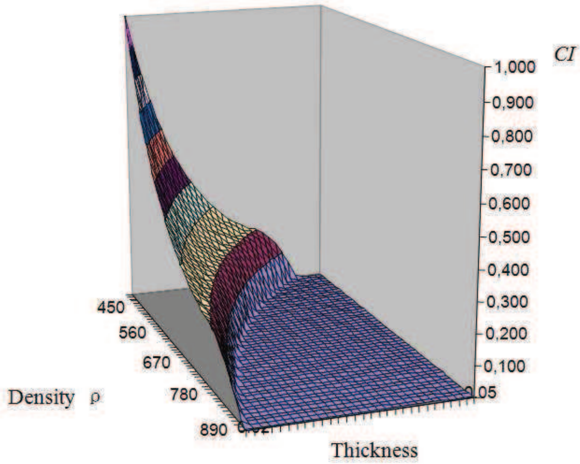


Figure 4-5 Decision index for entire usage context space – Male professional user and jigsaw P3

The typical users' decision to choose an appropriate jigsaw of a given product family is based on an average value of the decision index CI , as shown in formula (4-5), from their entire possible usage context space as shown in Figure 4-5 above. We refer to this as the *Density-Thickness* space. In formula (4-5), all decision index CI's on discrete usage scenarios in usage context space are integrated – under a hypothesis of equal weight for normalized usage context space, since here we consider that the micro usage scenarios are not discriminated by user type.

$$CI_U = \frac{\int_\rho \int_{T_c} CI \cdot dT_c d\rho}{\int_\rho \int_{T_c} dT_c d\rho} = \frac{\int_{400}^{900} \int_{0.02}^{0.05} CI \cdot dT_c d\rho}{500 \times 0.03} \tag{4-7}$$

Table 4-9 User decision index (CI) for 6 user types in target market

CI_U	Female			Male		
	User0 Basic	**User1 Medium**	**User2 Prof.**	**User3 Basic**	**User4 Medium**	**User5 Prof.**
P1	0	**0.0157**	0.0653	0	**0.0372**	0.0856
P2	0	0.0123	**0.0763**	0	0.0340	**0.1057**
P3	0	0.0109	0.0677	0	0.0301	0.0947
P4	0	0.0104	0.0644	0	0.0288	0.0908
Choice	*no*	**P1**	**P2**	*no*	**P1**	**P2**

Under the integrated decision index values, the most adequate products to target user types are listed in Table 4-9. No product among the given product family is appropriate for the two beginner user types.

For the two types of beginner user (User0, User3), these is no choice under usage coverage, performance and economic tradeoff criteria, because the maximum torque in a user's wrist is always attained if maximum advance speed is desired.

4.4.3. Conclusion of the two assessments

According to the assessment from 4.4.1, the given product family is not well positioned in relation to the 6 types of user in the market. Product P3 may be excluded from the family, because the gain of usage context coverage by P3 to P2 is less significant by that of P4 to P2. P1, P2, P4 serve the target market well. And P4 is especially useful for skilled users.

Concerning perceived performances and the economic factors, discussed in 4.4.2, the 6 types of user would prefer products P1 and P2 for their generic usage context.

4.5. Simulated panel of users with usage context scenarios

In this section, the user's usage context scenarios are represented as discrete domains, for example a panel of users with different usage context scenarios, facing K products in a family which perform the same service with minor distinctions between them. This representation reveals a potential target usage market.

These typical usages in the market are represented as a structure of usage context map. Each user is defined by a set of usage context scenarios. Users are supposed to be representative of the market. The usages for each user are weighted with a relative importance w_{ij}, which can be interpreted as a percentage of occurrences of such usage context. Table 4-10 gives an example of M users; each one gets N_M usage scenarios.

Table 4-10 Consumers' Usage Context Scenario Map

User Id	$Usage_{i,1}$	$Usage_{i,2}$	…	$Usage_{i,Ni}$
User 1	E_{11} (w_{11})	E_{12} (w_{12})	…	E_{1N_1} (w_{1N_1})
User 2	E_{21} (w_{21})	E_{22} (w_{22})	…	E_{2N_2} (w_{2N_2})
User 3	E_{31} (w_{31})	E_{32} (w_{32})	…	E_{3N_3} (w_{3N_3})
…				
User M	E_{M1} (w_{M1})	E_{M2} (w_{M2})	…	E_{MNM} (w_{MNM})

The numbers of different usages N_i for a use $i = 1, \dots, M$ may vary for the different users i. And the relative weights of each usage context should respect equation (4-8).

$$\sum_{j=1}^{N_i} w_{ij} = 1, with\ i = 1, \dots, M \quad (4\text{-}8)$$

For each Product P_k and user i, a series of N_i user decision indices (CI) and usage context coverage indices (UCI) is then calculated. And a total CI, UCI for user i's multi-usages N_i by a product P_k can be calculated using formula (4-9).

$$CI_{ik} = \sum_{j=1}^{N_i} (CI_{ijk} w_{ij}), with\ i = 1, \dots, M \quad (4\text{-}9)$$

For example: If a Female Basic User wants to cut a hard wooden board (such as oak) of 0.035m thickness, a medium wooden board (such as pine) of 0.050m thickness, and a soft wooden board (such as plywood) of 0.015m thickness, each usage scenario will be given relative weighted importance. She has 4 Bosch jigsaws listed in table 4 to choose from.

If we consider these 3 usage scenarios with relative importance w_1, w_2, w_3, then this user will choose the product with a maximum composite decision index CI, defined by formula (4-10).

$$\text{Choice}(P_k) = max_{P_i}\left(\sum_{j=1}^{3} (CI_{jk} w_j)\right), with\ k = 1, 2, 3, 4 \quad (4\text{-}10)$$

4.5.1. Results and conclusion of simulations

For experimental illustration, we randomly generate a panel of 100 users from 6 different types, using a combination of gender and skill in C_s variables as listed in section 3.2. Each of the users has at most 6 usages with different weights. The usages are also generated with 3 types of wood (soft, medium, hard) and with a thickness which is uniformly distributed in the interval [0.010, 0.060] m. A user-usages map is generated randomly.

The user's decision to choose an appropriate jigsaw for his/her potential composite usages is based on the index shown in section 3.3.3.

The given Bosch Jigsaw product family, whose features were listed in Table 4-1 is used as a reference in Table 4-11 - 100% of power, weight, and price. We can see that, for a generally uniform-distributed usage scenarios case, the given jigsaw product family corresponds to the target usage market well: P1 takes 30% of the market share, P2 41%, P3 6%, and P4 17%, with only 6% of users unable to find an appropriate jigsaw for their specific usage scenarios. Products P1, P2, and P4 take in total 88% of the market share, while P3 is redundant, which was the prediction in section 4.4.3

Table 4-11 Products' usage market share estimation

	Power, Weight, Price	*50%*	*100%*	*150%*
P1	Average Decision Index (CI)	0.022	0.141	0.164
	Average Usage Coverage Index (UCI)	0.035	0.300	0.522
	User Choice	**3**	**30**	**61**
P2	Average Decision Index (CI)	0.099	0.156	0.158
	Average Usage Coverage Index (UCI)	0.166	0.522	0.698
	User Choice	**24**	**41**	**32**
P3	Average Decision Index (CI)	0.101	0.141	0.138
	Average Usage Coverage Index (UCI)	0.211	0.574	0.732
	User Choice	**3**	**6**	**0**
P4	Average Decision Index (CI)	0.117	0.137	0.123
	Average Usage Coverage Index (UCI)	0.321	0.671	0.755
	User Choice	**54**	**17**	**4**
X	Users do not choose	*16*	*6*	*3*

For illustrative purposes, we generate two fictive product families, scaled down or up respectively by 50% and 150% of the power, weight and price of the given Bosch Jigsaw product family. They can be considered as competing or alternative jigsaw product family compositions. The former consists of less powerful and less expensive products. The latter is, conversely, more powerful and more expensive. For the given target usage market – represented by the user panel - the question is whether the Bosch Jigsaw family composition is well composed or not.

For a less powerful product family (scaled down by 50%), the percentage of users whose usage scenarios have no adaptive choice in the family increases from 6% to 16%. The given panel of users shifts for more powerful products P2, P4 as shown in Figure 4-6. For the case of more powerful product family (scaled up to 150%), firstly, the increase of no choice users is less significant; secondly, the more powerful products P3 and P4 are less preferred due to their higher price.

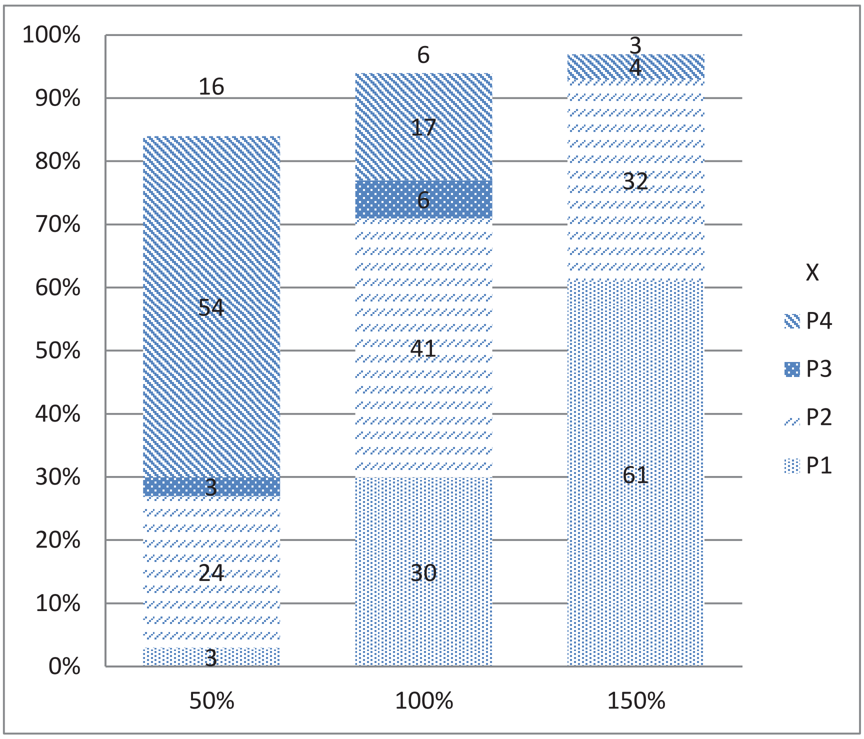
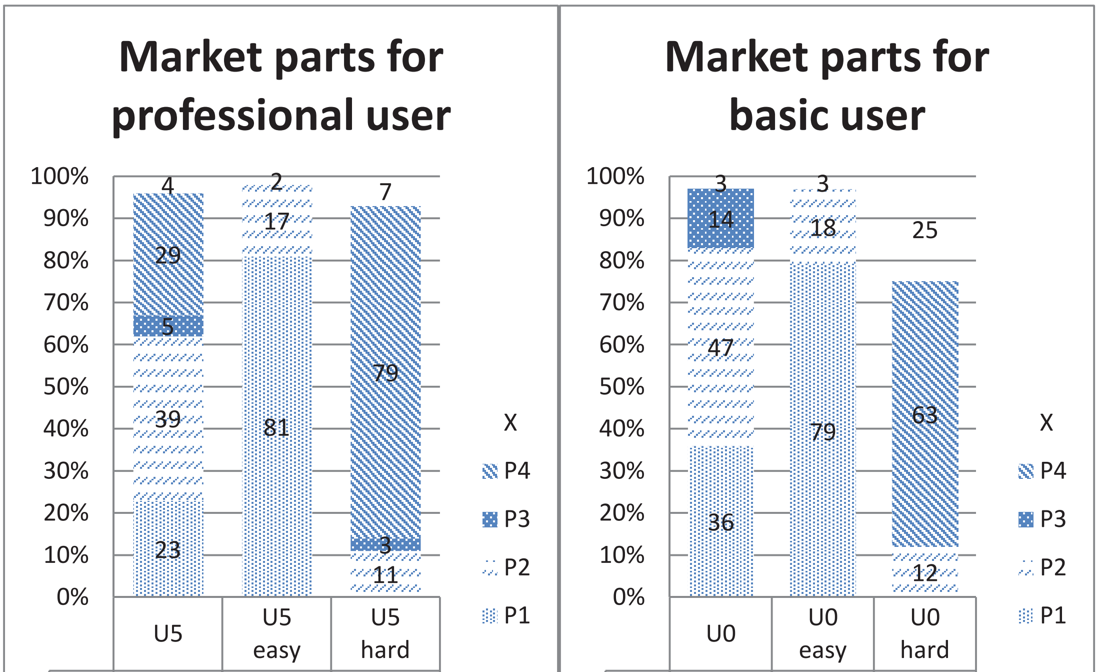


Figure 4-6 The usage market shares for the jigsaw families

The above comparison reveals that the Bosch Jigsaw family studied covers the target usage market quite well; however, since the product P3 is too close to P2 and P4's performances (similar specification) and P2 has better usage coverage and performances for its price, and since P4 is more powerful for extremely hard usages, product P2 and P4 cannibalize the market part of P3. A better composition of products in the family can be further studied in regard to the target usage market.

Similarly, we take the extreme cases – User type 5 (male professional user) and User type 0 (female basic user); each user type will face easy wooden board cutting usage scenarios (wood type 0 or 1, thickness drawn uniformly from [0.01, 0.03]) and hard wooden board cutting usage scenarios (wood type 1 or 2, thickness drawn uniformly from [0.03, 0.06]). The choice of products of a randomly generated group of 100 typical users with composite usage scenarios is shown in Figure 4-7.



	U5	U5 easy	U5 hard
X	4	2	7
P4	29	0	79
P3	5	0	3
P2	39	17	11
P1	23	81	0

	U0	U0 easy	U0 hard
X	3	3	25
P4	0	0	63
P3	14	0	0
P2	47	18	12
P1	36	79	0

Figure 4-7 The market parts for the products in Bosch product family

for professional/beginner user

In the left-hand chart, we can see, for professional users cutting wooden board usage, they prefer P4 for their difficult usage scenarios, and P1 or P2 for their easy usage scenarios. This justifies the existence of product P4. A professional user with all the range of usage scenarios (column 1) may choose any of the three products P1, P2, or P4.

For the basic users in the right-hand chart, products P1and P2 are the most preferred. 25% of difficult usage scenarios cannot be served by any product in the family. P3 can also be substituted by either P2 or P4.

4.6. Conclusion

In this chapter, it has been accounted for how to apply the proposed usage coverage model and indices described in chapter 3 to a case-study. For experimental reasons, we take a usual power tool family – Bosch Jigsaw product family – as a validation case-study.

First of all, the background of the given product family is presented and modeled. Certain useless product attributes details are not modeled. A single jigsaw product and a family cutting wooden board usages example is used to show how CSP technique works with interval variables and domain reducing. The single usage coverage index shows well the degree of adequacy for the consumers with different usage contexts.

And then a generic cutting wooden board usage context space is built. The entire jigsaw family is compared in the sense of usage coverage.

Furthermore, a panel of consumers with different usage contexts is simulated to represent multi-usage scenarios. Towards such target usage market, the given product family is assessed for its adequacy, efficiency and economical properties. Interesting re-design propositions are drawn from the results. A product in the family is too close to the others, and thus leads to a cannibalization. However, in total, the given product family covers well the usage requirements from the market, by comparing with two constructed competing product families.

Chapter V

5. Conclusion

This chapter recapitulates the results of the research work including giving answer to the research objectives and summing up the contribution and limitation from this thesis research work. Finally, several future research directions are shown to reveal the potential of this research.

5.1. Conclusion on the research objectives and contribution

Although the concept of usage model and usage context information is not new in marketing research, its use in design engineering, especially in helping product family design is relatively void. The presented usage coverage model successfully combines the two aspects of product design process: engineering and marketing researches. The advantage compared to traditional demand estimation in marketing research is to reduce the complexity of survey and data analysis. The objectives defined in section 1.4.1 are achieved in certain degree: we developed a process and models that can support designers while analyzing and diagnosing a product family by several objective indices and visual charts and hereby support decision-making about re-design of the products with the intention to rationalize the product family composition.

As the research approach described in section 1.4, this thesis first presents a survey research on product family design and evaluation methods and recent advances in the usage-based product design. The sub-objective of defining the usage context model and usage coverage model is fulfilled, which is the core concept of this research work.

The concept of Usage Coverage Index is applied to composite usage scenarios. UCI metric is then extended to a given product family in the form of a matrix. To measure the quality/price tradeoff of users, we propose a user's decision index CI. A constraint programming technique is applied in the process of UCI calculation and performance estimation. Simulations with a jigsaw family for cutting wood usages are implemented in the case of a product family redesign.

The experimental results in chapter 4 show that the proposed indices help to evaluate the adaptability, for a given scale-based product family, to diverse usage context scenarios in a target market. Interesting redesign suggestions can be drawn from the given indices and charts: designers can rely on the results to eliminate redundant units in the family. Scale-based configurations of the products can be rapidly simulated and compared to find out an appropriate series. This study clearly demonstrates the usefulness of a usage coverage model based approach to assess the composition and configuration of a product family design.

5.2. Limitation and perspectives

Even though the thesis work has certain contribution to the product redesign research field, some of the limitation must be revealed and considered.

First limitation of the present product family assessing process is that a well-established physics-based product model is required for the purpose of individual performance calculation. Nonetheless most products can be studied in sufficient detail as shown in the Appendix, using a physics-based model or a heuristics-based (or human appraisal) model (Hoyle 2009) (He, Hoyle et al. 2010). Yannou et al and Moghaddam et al (Yannou, Simpson et al. 2003) (Moghaddam, Wang et al. 2006) also tried to solve partially this problem by first metamodeling physics-based performances before using these metamodeled performances into a constraint programming frame. Relations between usage contexts and performances delivered by a product in these contexts can then often be successfully established.

Second limitation of the given assessing process is that not all the product attributes and sub-functions are included in the models. The design variables' variation is limited. This is just the case-study and time limitation, since the product family redesign and redesign process are highly case dependent, not all the product attributes and sub-functions should be considered in one time. The concept of usage coverage mechanism to assess product family design is appropriate.

Nevertheless, the concept of using usage model and usage coverage model to combine marketing and engineering research is pertinent and potential. The importance of modeling product usage in product design and redesign is non-trivial as mentioned in all precedent academic research and industrial application (see section 1.2 & 1.3). To reduce the presented limitation and extend this thesis research, several perspectives of research are appealing and worth further developments:

- Only scalable variations in the product family have been here considered so far. More dimensional variations and functional variations should be currently studied.

- Moreover, it is possible to add a performance quality index in the decision indices. The constraint programming technique is based on a set-based concept. A sensitivity analysis with the subsets may clarify the quality of the redesign suggestion.

- Finally, a user interactive product selection platform might be helpful for customers when looking for the best adapted product or service in a store, Figure 5-1, in which several products are compared.

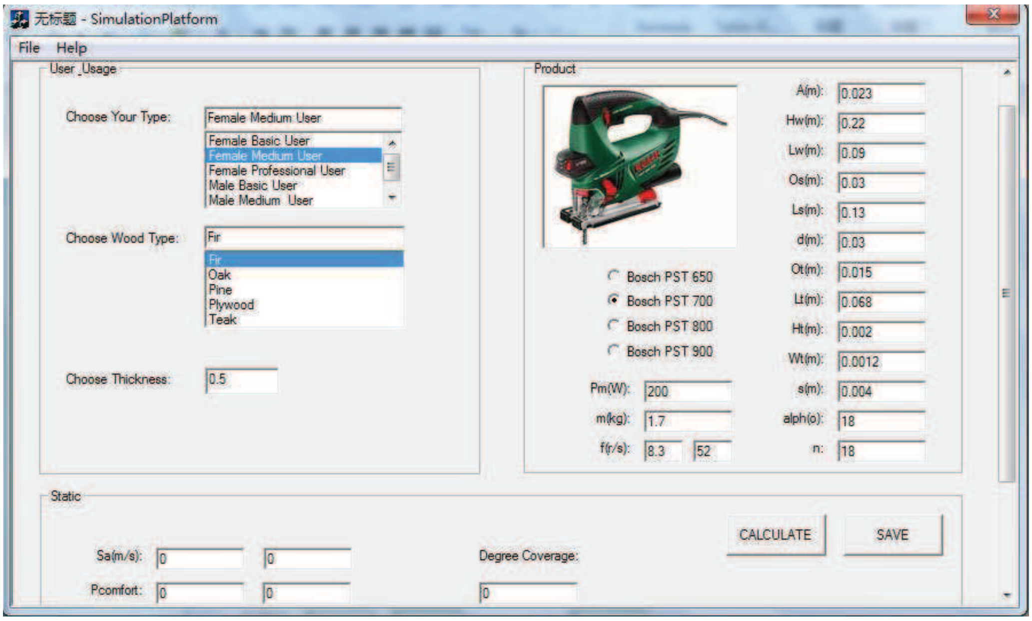


Figure 5-1 Screening of possible usage-oriented helping buyer interface.

Personal publication

Wang J.L., Yannou B., Alizon F., Yvars P.-A., “A usage coverage based approach for assessing product family design”, submitted to Engineering with Computers

Wang J.L., Yannou B., “Explicit product family indicators based on a CSP simulation of usage coverage”, International Conference on Research into Design (ICoRD'11), Bangalore - India, 10-12 January, 2011.

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Appendix

1. Jigsaw parameterization

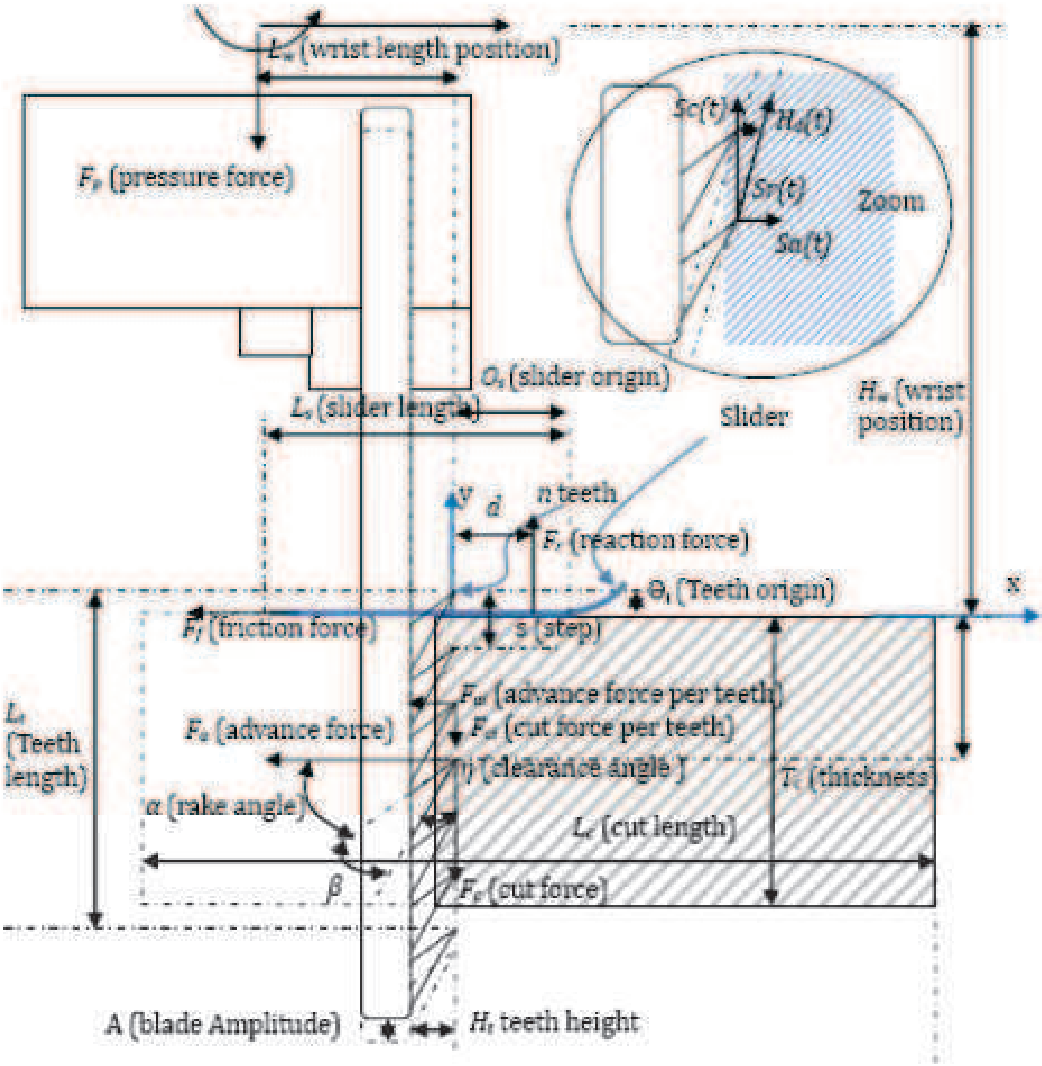

Fig. 1 The jigsaw parameterization: dimensions, forces, torques, speeds

2. Intermediate variables for the jigsaw modeling

INTERMEDIATE VARIABLES (Forces, Speed)	
ρ_w (kg/m3)	Wood density
μ (no unit)	*Friction* factor between the *steel* and *wood*
F_t (N)	*Translation force*
$F_{t\,max}$ (N)	Maximal *translation force* that can be delivered by the given user defined by C_s vector
F_p (N)	*Pressure force*
$F_{p\,max}$ (N)	Maximal *pressure force* that can be delivered by the given user defined by C_s vector
M_w (N·m)	*Wrist torque*
$M_{w\,max}$ (N·m)	Maximal *wrist torque* that can be delivered by the given user defined by C_s vector
F_r (N)	*Reaction force* between slider and wood
F_f (N)	*Friction force* between slider and wood
F_a (N)	*Advance force*
F_{ai} (N)	Elementary *advance force* on tooth *i*
F_c (N)	*Cut force*
F_{ci} (N)	Elementary *cut force* on tooth *i*
H_d (m)	*Height* of scobs
N_m	Mean number of teeth cutting wood at any moment
S_c (m/s)	Mean *cutting speed*
$S_c(t)$ (m/s)	Instantaneous *cutting speed*
$S_a(t)$ (m/s)	Instantaneous *advance speed*

3. Other relations for the jigsaw physics

3.1. The geometrical relations

In the upper position of the blade, the upper tooth is always above the slider is expressed by:

$$O_t > 0 \tag{1}$$

The lower tooth in the upper position is below the lower wood stick plane (teeth are cutting all along the thickness at any moment of the cutting period):

$$t \in \left[\frac{1+2n}{2f}, \frac{n+1}{f}\right], n \in N \Rightarrow L_t - O_t \geq T_c \tag{2}$$

The useful length of the blade L_t, is proportional to step s and the number of teeth n minus 1:

$$L_t = (n - 1) \cdot s \tag{3}$$

3.2. The statical relations

All the forces are non-negative (by construction on **Fig. 1**). And the slider is always touching the wood surface. Then:

$$F_r \geq 0, F_a \geq 0, F_f \geq 0 \tag{4}$$

The forces F_t and F_p delivered by the user onto the jigsaw tool can be modeled as intervals of possible values which are bounded by the maximum allowable translation force F_{tmax} and pressure force $F_{p\,max}$ a user can afford:

$$F_t \in [0, F_{t\,max}], F_p \in [0, F_{p\,max}] \tag{5}$$

As previously seen with Table 1, these maximal allowable bounds are dependent from the user gender and the user skill.

The horizontal force equilibrium (advance acceleration is neglected) is expressed by:

$$F_a = F_t - F_f \tag{6}$$

In the following, we assume that F_t may be considered as a constant entry force, imposed by the user.

The friction force between the jigsaw slider and the wood is expressed by:

$$F_f = F_r \cdot \mu \tag{7}$$

The vertical force equilibrium is expressed by:

$$F_p + m\,g + F_c = F_r \tag{8}$$

The momentum equilibrium at wrist position provides the expression of the wrist torque:

$$M_w = F_a\left(H_w + \frac{T_c}{2}\right) + F_c L_w + F_f H_w - (d + L_w)F_r \tag{9}$$

In the same manner, the torque in the user wrist M_w is bounded by a maximal allowable torque the user may support expressed in table 1.

$$M_w \leq M_{w\,max} \tag{10}$$

The position of the reaction force of the slider must stay inside the slider surface area so as to avoid for the jigsaw tool to flip:

$$d \in [O_s - L_s, O_s] \tag{11}$$

3.3. The cutting technological relations

The minimal teeth number for a successful cut is 3:

$$Tc > 3s \tag{12}$$

The mean number of teeth cutting wood at any moment is expressed by:

$$N_m = \frac{T_c}{s} \tag{13}$$

The elementary advance force F_{a_i} on a tooth i is provided by:

$$F_{ai} = \frac{F_a}{N_m} \tag{14}$$

This equation means that F_{ai} is constant. During the cutting phase, when the blade is ascending, a cutting relation exists between the elementary advance force $F_{a_i}(t)$ on a tooth i and the scobs height $H_d(t)$. As F_{ai} is constant, then H_d is constant when the blade ascends and the relation is:

$$t \in \left[\frac{1+2n}{2f}, \frac{n+1}{f}\right], n \in N \Rightarrow F_{ai} = W_t \rho_w (H_d A_2 + A_2) e^{A_1(35-\alpha)} \quad (15)$$

This equation was found based on experimental measures of H_d for different types of wood and teeth (i.e., different values of W_t, ρ_w, H_d, α). The three A_i coefficients have been found experimentally:

$$A_1 = 0.01, A_2 = 272000, A_3 = 0 \quad (16)$$

Finally, we obtain from (15) and (16) the following relation between H_d and F_{ai}:

$$H_d = \frac{F_{ai}}{272000 W_t \rho_w e^{0.01(35-\alpha)}} \quad (17)$$

As well, a constraint should be:

$$H_d \leq s \quad (18)$$

During the descending phase, the scobs height is zero:

$$t \in \left[\frac{n}{f}, \frac{1+2n}{2f}\right], n \in N \Rightarrow H_d(t) = 0 \quad (19)$$

The Elementary cutting force on a tooth during the cutting - ascending - phase is:

$$F_{ci} = W_t \rho_w (60000 H_d + 20) e^{0.01(35-\alpha)} \quad (20)$$

This equation has also been found experimentally. In the same manner, the cutting force is not dependent of time.

During the descending phase, the cutting force is primarily due to the friction between the teeth and wood:

$$F_{ci} = -F_{ai} \cdot \mu \quad (21)$$

The resulting cut force is given by:

$$F_c = F_{ci} \cdot N_m \quad (22)$$

3.4. The kinematic relations

The mean cutting speed for a forth and back of the blade (i.e. A) is:

$$S_c = 2\mathrm{Af} \quad (23)$$

The instantaneous cutting speed has a sinusoidal form:

$$S_c(\mathrm{t}) = 2\mathrm{Af}\sin(2\pi\mathrm{ft}) \quad (24)$$

It can be inferred that the maximal cutting speed is:

$$S_{c\,max} = 2\pi\mathrm{Af} \quad (25)$$

The instantaneous advance speed during the descending phase is null:

$$t \in \left[\frac{n}{f}, \frac{1+2n}{2f}\right], n \in N \Rightarrow S_a(t) = 0 \quad (26)$$

The instantaneous advance speed during the cutting - ascending - phase is (see similar triangles on Figure I):

The mean advance speed during one time period is:

During

$$t \in \left[\frac{n}{f}, \frac{1+2n}{2f}\right],$$

(28)

we get

$$S_a = \frac{2H_d f A}{s}$$

3.5. The power relations

During the cutting phase, the power provided by the engine and the hand must be enough to cut the wood, then:

(29)

$$P_m + \left(F_t - F_f - F_a\right) \cdot S_a(t) \geq F_c(t) S_c(t)$$

Given that $\mathrm{F_t} - \mathrm{F_f} - \mathrm{F_a} = 0$ (advance acceleration neglected), then we obtain:

$$P_m \geq F_c(t)S_c(t) = F_cS_c(t)$$

And consequently,

$$P_m \geq F_c max(S_c(t))$$

leading to:

$$P_m \geq F_c \cdot 2\pi Af \tag{30}$$

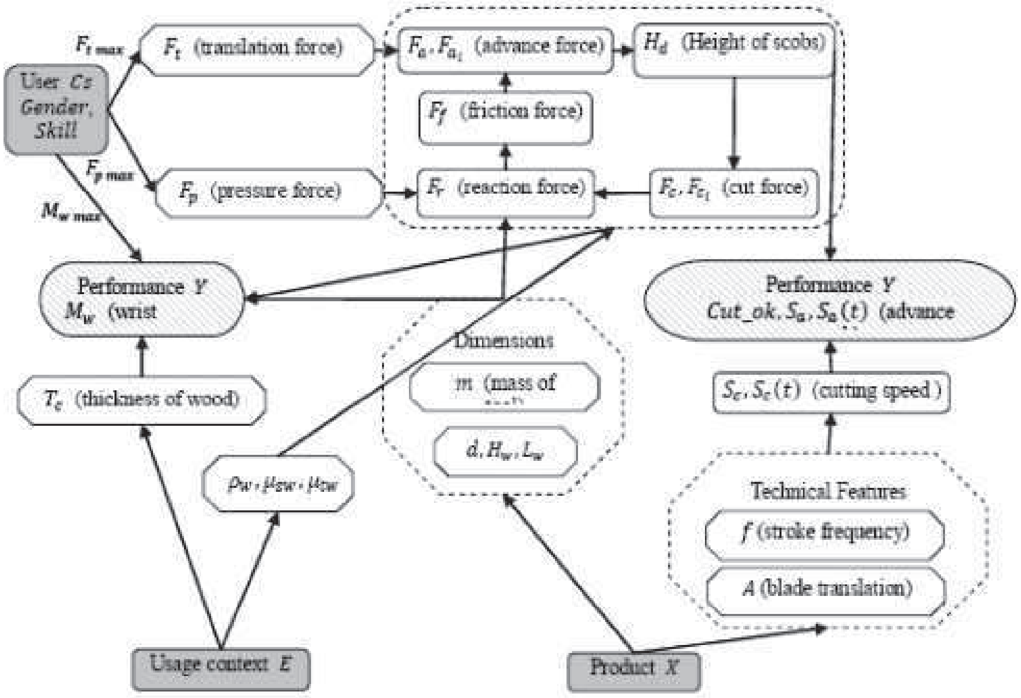

Fig. 2 Causal relations between the variables of the usage coverage modeling issue of a jigsaw

4. Process of usage context information collection

The process of usage context information collection is very crucial for the whole usage context based market segmentation process. Because the kind of contextual information collected and its quantity play an important role in the following clustering process. Figure 1 reveals the principal stages of this process.

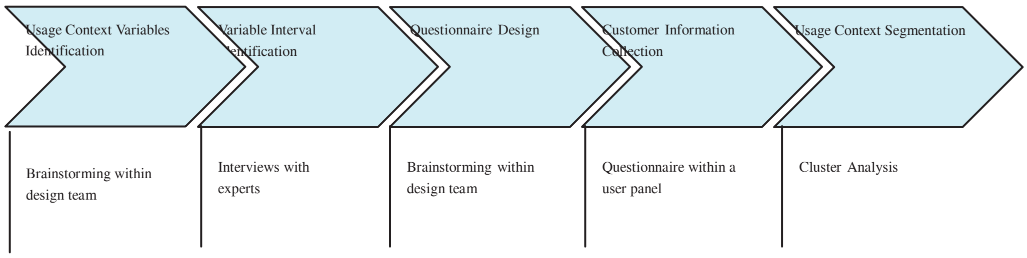

Fig. 3 Process of Usage Context Information Collection

5. Sample survey questionnaire to identify E, Cs {WANG, 2010 #401}

Assume that you are given a jigsaw BOSCH as shown in the picture. What is your most usual usage context when you cut a piece of wood? Pleas answer the following questions:

1. Please tell us a little bit about yourself:

o Are you:

□,. male □,. female

o What is your skill level in terms of saw usage?

□,. Beginner □,. Intermediate □,. Experienced

o What is your monthly income?

□,. Low (<1000€) □,. Medium (1000€~3000€) □,. High (>3000€)

2. Please tell us about your typical saw usage situation:

o What kind of wood hardness do you mostly cut with a jigsaw?

□,. Soft wood □,. Intermediate □,. Hard wood

o What kind of size do you usually cutting with a jigsaw?

□,. Small size □,. Intermediate □,. Large size

o What thickness of wood do you mostly cut with a jigsaw?

□,. Thin □,. Intermediate □,. Thick

o What type form of wood do you mostly cut with a jigsaw?

□,. Board □,. Stick

o Where do you live in?

□,. Apartment □,. House

o Is there lighting system when you are doing your saw job?

□,. Yes □,.No

o Do you have a workbench while you cutting wood?

□,. Yes □,.No