An Intelligent Hybrid Model for Customer Requirements Interpretation and Product Design Targets Determination

by

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A Doctoral Thesis

submitted in partial fulfilment of the requirements for the award of

The Degree of Doctor of Philosophy of Loughborough University

February, 1997

This Ph.D. thesis is dedicated
to those people who care
for and stand by
me throughout
the years

Acknowledgements

This research was carried out on a part-time basis at Loughborough University. First of all, I would like to thank the Department of Manufacturing Engineering and Engineering Management at City University of Hong Kong where I work for sponsoring this Ph.D. programme.

I am very grateful to Dr. Keith Popplewell, my supervisor for his guidance, encouragement and help in the past five years. Although most of the time we have to rely on E-mails to exchange ideas, Keith always manages to give me his prompt instructions and comments clearly and categorically, particularly during the final stage of preparing this thesis. Besides being a good advisor, Keith is also a very patient and open-minded listener. I still have a lot more to learn from him.

I would like to extend my gratitude to Professor Shouju Ren, Dr. Jinxing Xie of Tsinghua University, Beijing and Dr. Jurgen Bode of Leipzig University, Germany for their inspirations and valuable advice on the research topics during our numerous discussions both in Hong Kong and Beijing over the years.

Thanks are also due to all the engineers and designers from various local manufacturing companies who have provided me with the product data and technical advice during the preparation of the case study for this thesis. Their professional opinions on the functionality of the hybrid model proposed in this research have also helped significantly enhance and polish the approach.

The supports and assistance from my student helpers Angela, Dave and Edmund in customer data capture and analyses are very much appreciated.

In particular, I owe my grandmother, my parents, my brothers and sisters, and all my close friends their love, thoughts and continuous supports. They have helped me in many different ways in completing this Ph.D. work.

Abstract

The transition of emphasis in business competition from a technology-led age to a market-oriented era has led to a rapid shift from the conventional "economy of scale" towards the "economy of scope" in contemporary manufacturing. Hence, it is necessary and essential to be able to respond to the dynamic market and customer requirements systematically and consistently. The central theme of this research is to rationalise and improve the conventional means of analysing and interpreting the linguistic and often imprecise customer requirements in order to identify the essential product features and determine their appropriate design targets dynamically and quantitatively through a series of well proven methodologies and techniques.

The major objectives of this research are:
a) To put forward a hybrid approach for decoding and processing the Voice of Customer (VoC) in order to interpret the specific customer requirements and market demands into definitive product design features, and
b) To quantify the essential product design features with the appropriate technical target values for facilitating the downstream planning and control activities in delivering the products or services.

These objectives would be accomplished through activities as follows:
- Investigating and understanding the fundamental nature and variability of customer attributes (requirements);
- Surveying and evaluating the contemporary approaches in handling customer attributes;
- Proposing an original and generic hybrid model for categorising, prioritising and interpreting specific customer attributes into the relevant product attributes with tangible target values;
- Developing a software system to facilitate the implementation of the proposed model;
- Demonstrating the functions of the hybrid model through a practical case study.

This research programme begins with a thorough overview of the roles, the changing emphasis and the dynamic characteristics of the contemporary customer demand with a view to gaining a better understanding on the fundamental nature and variability of customer attributes. It is followed by a review of a number of well proven tools and techniques including QFD, HoQ, Affinity Diagram and AHP etc. on their applicability and effectiveness in organising, analysing and responding to dynamic customer requirements. Finally, an intelligent hybrid model amalgamating a variety of these techniques and a fuzzy inference sub-system is proposed to handle the diverse, ever-changing and often imprecise VoC. The proposed hybrid model is subsequently demonstrated in a practical case study.

Keywords: ***Customer Attribute, Product Attribute, QFD, HoQ, AHP, VoC Target Value, Fuzzy Logic, Fuzzy Inference, Hybrid Model***

Contents

Chapter 1
Introduction

1.1 Preamble

At a time when supply of products and services has overtaken demand, the market competition is getting increasingly intense by days. An organisation can no longer be guaranteed a steady growth nor survival if it solely relies on a set of self-defined technical specifications, design guidelines and quality standards. Researches believed that the reactive, technology-led mass production or "economy of scale" approaches of running a business have been outdated. They were only applicable at a time when the markets were less discriminating and "value for money" was one of the few deciding factors for choosing a certain product among many others. However, as the markets become more sophisticated with time, customers' perceptions towards "value" has also changed over the years. Nowadays, in addition to competitive pricing, products with a higher performance / price ratio and outstanding market-driven features are equally important. However, irrespective of the product or activity, contemporary manufacturing ought to be operated as a value adding and producing process. The "economy of scope" approach, which allows a wider variety of products or services to be offered economically, is more preferable and more readily accepted by the market. It has rapidly become a major selling point in many business sectors (Frazelle, 1986) (Blois, 1986) (Bennett et al., 1992 &1993).

This shift of emphasis marks the transition from a product-oriented age to a market-focused era. A company has to actively go out to the market and try to understand the customers' "needs" and "wants" in order to duly address the issues that bother or interest them most. In the context of this research, the "needs" represent the critical customer requirements that have to be satisfied if a product is to stand any chance of success in the market, whereas the "wants" are those desirable features that are nice to have and are less essential in the eyes of the customers.

Apart from conforming to its internal standards, a forward looking enterprise must be alert to the market factors by offering the quality and values perceived and appreciated by the customers at a level at least compatible to if not more superior than that of the competitions. Hence, aligning the people, processes and products in a company closely in line with the evolving needs of the market are among one of the first steps towards securing customer satisfaction.

The term "Customer Attributes" is used in a general sense in this research to encompass both the customer requirements on a given product as well as the characteristics of the respective customer groups, perhaps classified by age, income bracket or areas of interest, etc. The components of requirements in customer attributes will be analysed and mapped against the appropriate product design features in the proposed hybrid model, whilst the relevant customer groupings will be taken into account during the design of the market surveys and the compilation of the questionnaires for customer interviews.

The journey of gaining satisfied customers begins with effectively capturing, analysing and understanding what they really need. To support subsequent enterprise planning and control activities, specific design targets for the product features have to be determined with respect to given customer attributes. However, these customer attributes or Voice of Customer (VoC) are often expressed in linguistic and sometimes non-technical terms. Therefore, it may be difficult for the designers and engineers to translate the VoC into definitive product specifications for various product features which are often referred to as Product Attributes. The concepts of Quality Function Deployment (QFD) have been widely adopted for customer attributes analysis in various business sectors (Cohen, 1995) (Bossert, 1991). It was originating from Japan in the 1960's, and became increasingly popular world-wide in the 1980's. With the QFD approach, the VoC is analysed, categorised and transformed into technical terms to facilitate subsequent downstream activities by engineers at every stage of design and manufacture including materials planning, process planning and production planning, etc. Such a multi-stage process can be described by a number of inter-connected matrix-like structures, each of which is called a House of Quality (HoQ). A typical HoQ consists of several basic building blocks (Hauser and Clausing, 1988) holding entries of customer and product attributes, as well as representations of their relationships, planning, correlation and technical data as illustrated in Figure 1.1.

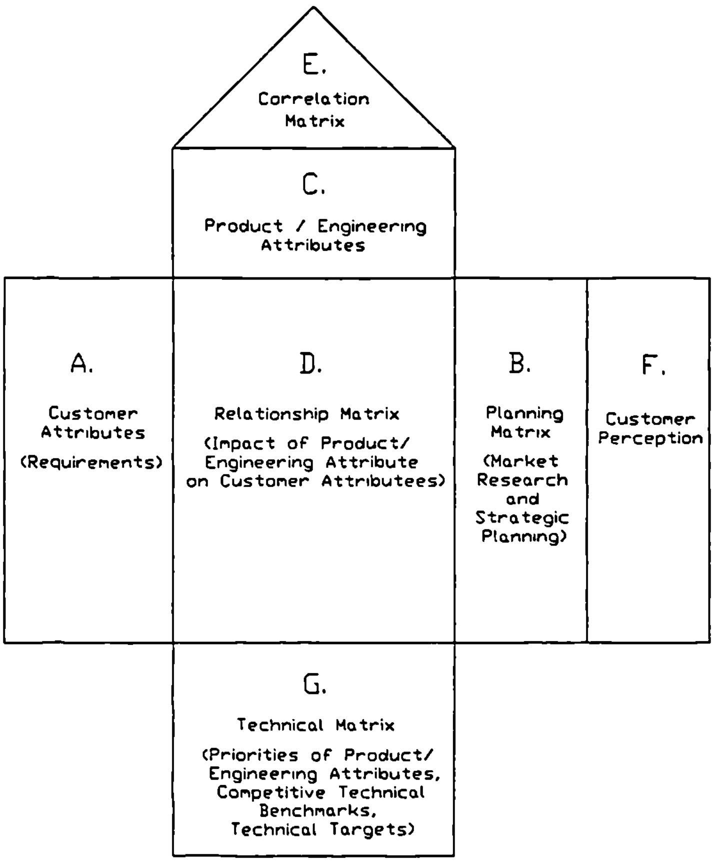

Figure 1.1: The Basic Functional Building Blocks of an HoQ

Although HoQ is a convenient tool for mapping customer attributes onto product attributes, the details held in the HoQ can become so congested that the key issues might be over-shadowed and the attentions get side-tracked when dealing with a more complex product. Besides, the interpretation of the market-perceived quality and values into the appropriate technical actions also requires well organised team effort.

It is not uncommon to find that various departments or divisions within an organisation, such as marketing, research & development, engineering, and manufacturing alike may not necessarily have the same perceptions and ideas of what product quality and values they are to offer. Similarly, as the number of trading partners increases, the consumers and the service providers will be even less likely to be in any better agreement (Garvin, 1988). For instance, manufacturing may see product quality and customer values as the degree to which a specific product can conform to a set of design specifications (Gilmore, 1974), whilst marketing might be more concerned about how well a product can fit the patterns of customer preferences (Edwards, 1968), but after all the consumers themselves might decide their choice of product simply from the viewpoint of fitness for use (Kuehn and Day, 1962). Garvin (1988) suggested that quality of a product or service can be considered to possess eight dimensions covering aspects of performance, features, reliability, conformance, durability, serviceability, aesthetics and customer perceived quality. The spectrum of product quality can be further extended to encompass other considerations, such as variety, maintainability, timeliness and responsiveness (Bennett and Forrester, 1993).

In addition to the aforementioned conceptual variations and multi-dimensional ramifications of product quality and customer perceived values, the process of interpreting and satisfying customer attributes is often further complicated by the inherent ambiguity and imprecision innate in the VoC. These ambiguities and imprecision might be due to different reasons, such as:

- insufficient understanding or knowledge on the product design or the technology employed;
- inexactness in the description of a problem or a set of requirements;
- distortions or misinterpretations of messages somewhere along the line;
- insensitivity and complacency on the part of the service providers to detect or decode the VoC, etc.

Owing to a combination of these properties, the categorisation, prioritisation and interpretation of the linguistic VoC into some definitive and quantitative product attributes probably involve some complex transformation processes which might well be non-linear in nature.

The Central Theme of this Research is to:

- **Rationalise and improve the conventional means of analysing and interpreting the linguistic, often vague and imprecise customer attributes, and**
- **Establish a generic routine to support more dynamic and consistent product design and specification in response to given customer attributes.**

1.2 Research Objective and Activities

The prime objective of this research is to put forward an intelligent hybrid approach for:

- Decoding and processing the VoC, and interpreting the resulting customer attributes into definitive product design features, and

- Determining the corresponding technical design targets for driving subsequent downstream planning and control activities in order to supply a product or service that can satisfy the customers.

The research objective will be accomplished through the following activities:

- Investigating and understanding the fundamental nature and variability of customer attributes (requirements);
- Surveying and evaluating the contemporary approaches in handling customer attributes;
- Proposing an original and generic hybrid model for categorising, prioritising and interpreting specific customer attributes into the relevant product attributes with tangible target values;
- Developing a software system to facilitate the implementation of the proposed model;
- Demonstrating the functions of the hybrid model through a practical case study.

1.3 The Roles of the Proposed Hybrid Model in Market-Focused Manufacturing

The transition from a technology-led approach to a market driven strategy means that contemporary manufacturing enterprises need to have an organisational culture that promotes an orientation towards product and process quality supported by a more responsive and flexible production system.

A generalised product design methodology for market and environment, as shown in Figure 1.2, was introduced by Bennett and Forrester (1993). It can be seen that in this generalised model, signals and messages are captured from customers, competitors as well as through benchmarking assessment, market survey and direct interaction with the environment. Through analysing these data from various sources and origins, the corporate policy and mission can be determined and the appropriate product and market strategies can thus be identified to guide the downstream activities.

The hybrid model proposed in this research is primarily a market information analyser and a design targets projector which can process the customer and market data, prioritise the relevant attributes and mapping them onto the appropriate product features and characteristics. Furthermore, the corresponding technical design targets can be determined through the fuzzy inference engine in the model with reference to the corporate policy and mission which are reflected in the systems knowledge-base. By virtue of its functional capability, the proposed model can be incorporated as an integral part in the generalised design methodology so as to enhance its analytical power for practising market-focused manufacturing. This new addition to the generalised design methodology can be represented by the functional block enclosed in dotted line in Figure 1.3. With this analytical and intelligent tool, the methodology will be empowered to exploit the data captured through different channels more thoroughly and systematically, and to respond to the market demands more dynamically and consistently. As a result, the VoC can be better understood and more accurately interpreted so that more realistic product and market goals can be set with due considerations of the competitive advantages in a company.

1.4 The Structure of this Thesis

In Chapter 2, the multi-dimensional characteristics of customer attributes is considered. It describes the fundamental nature of product quality and reveals its contribution towards product performance as perceived by the customers. The aspects of understanding and interpreting the needs and wants of customers, and satisfying the market demand will also be discussed.

In Chapter 3, an overview of the contemporary methodologies in managing the VoC is given in order to set the scene for the introduction of the non-conventional approach in the hybrid model proposed in this research. The principles of the tools and techniques adopted in the model are outlined. The merits, limitations and potential areas of improvements in applying the traditional QFD and HoQ will be explored.

Chapter 4 defines the scope of this research and outlines the framework and functional features of the proposed hybrid model.

In Chapter 5, the concepts of Fuzzy Set Theory, which support the inference process in the proposed model, will be introduced in order to facilitate subsequent specification and explanation of the fuzzy inference process in the proposed model. This inference process is an essential mechanism for tackling the possible inexactness and imprecision intrinsic in the VoC and determining the technical design targets of a product.

Chapter 6 expounds the architecture and construction of the hybrid model. The functional characteristics of individual systems building blocks will be fully described. Comparisons of the proposed approach with the conventional means of customer requirements management will also be made.

In Chapter 7, the functional and mathematical modelling of the fuzzy sub-system will be explained and illustrated with the help of some practical examples. The features and the roles of various model components will be discussed. The technical issues in specifying and developing the software system to support the implementation of the hybrid model will also be addressed in that chapter.

Chapter 8 presents a detailed case study illustrating the functional and operational features of the hybrid model in interpreting, analysing and mapping specific customer attributes onto the design and engineering characteristics of a selected range of household hi-fi equipment. It describes how the market trend and the VoC can be captured, filtered, categorised, prioritised, and subsequently projected onto the quantitative technical targets for the relevant product attributes. The functional behaviour of the sub-systems in the hybrid model will be expounded through real-life scenarios. The general critiques and comments from manufacturing professionals on the approach taken to tackle the problems in the case study will also be quoted.

The conclusions in Chapter 9 give a thorough overview of the research activities. The strengths and limitations of the hybrid model for managing customer requirements are recapped.

Finally, in Chapter 10 the potential areas of improvement and enhancement to the proposed hybrid model are discussed, and the possible extensions of the current work are outlined. Some of the recommended topics are tied in with the ongoing government funded research projects in Loughborough University.

1.5 Summary

This chapter highlights the transition of emphasis in business competition from a technology-led age to a market-oriented era. Hence, "economy of scale" is rapidly replaced by "economy of scope". The necessity and importance of being able to respond to the dynamic market and customer requirements systematically and consistently are discussed. The prime objective and major activities of this research are stated. The possible roles of the proposed hybrid model in a generalised product design perspective are considered, and finally the contents of each chapter in this thesis are outlined in this introductory chapter.

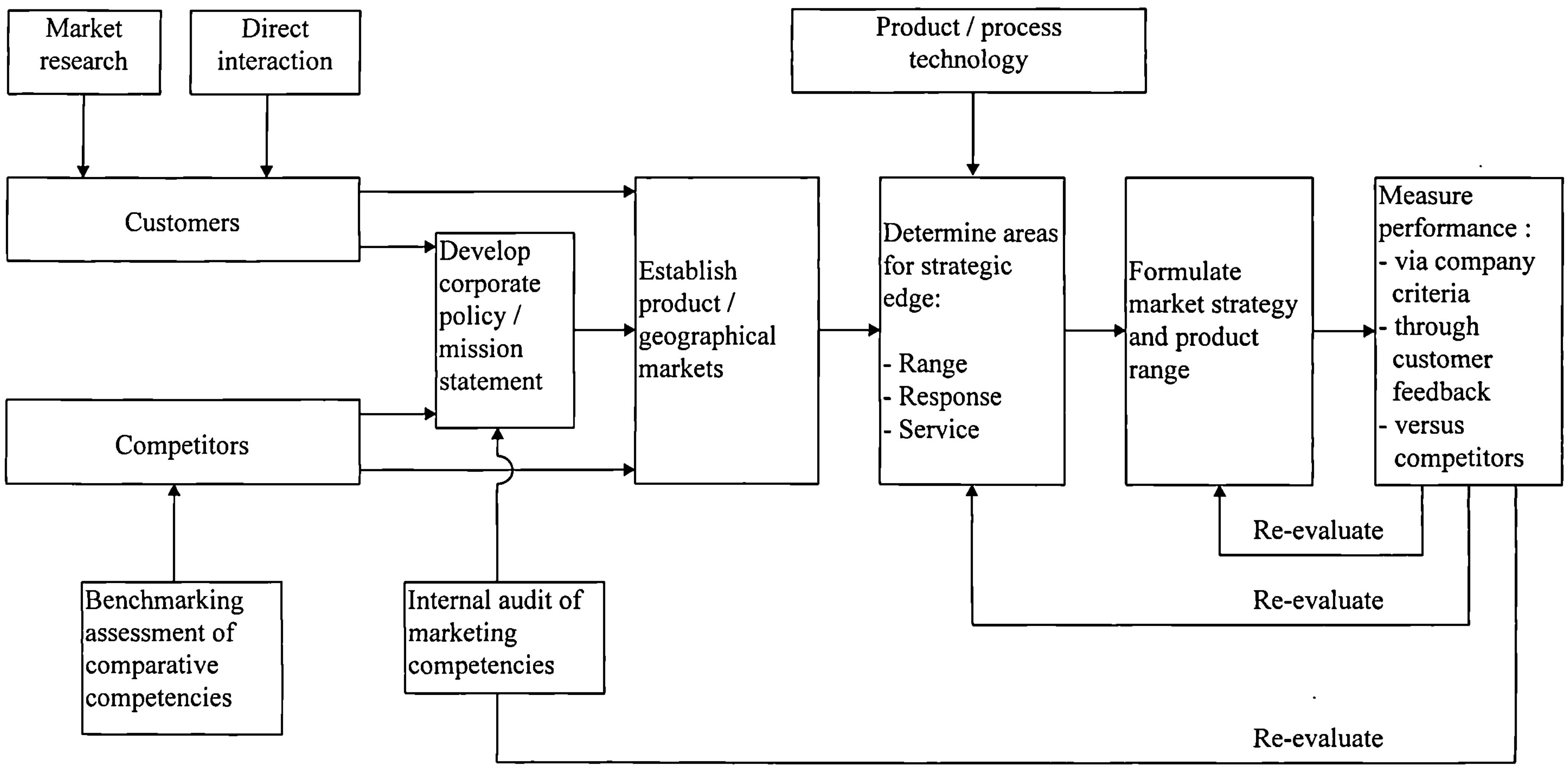

Figure 1.2: A Generalised Market- Focused Product Design Methodology
(Adopted from Market-Focused Production System, by David Bennett & Paul Forrester;
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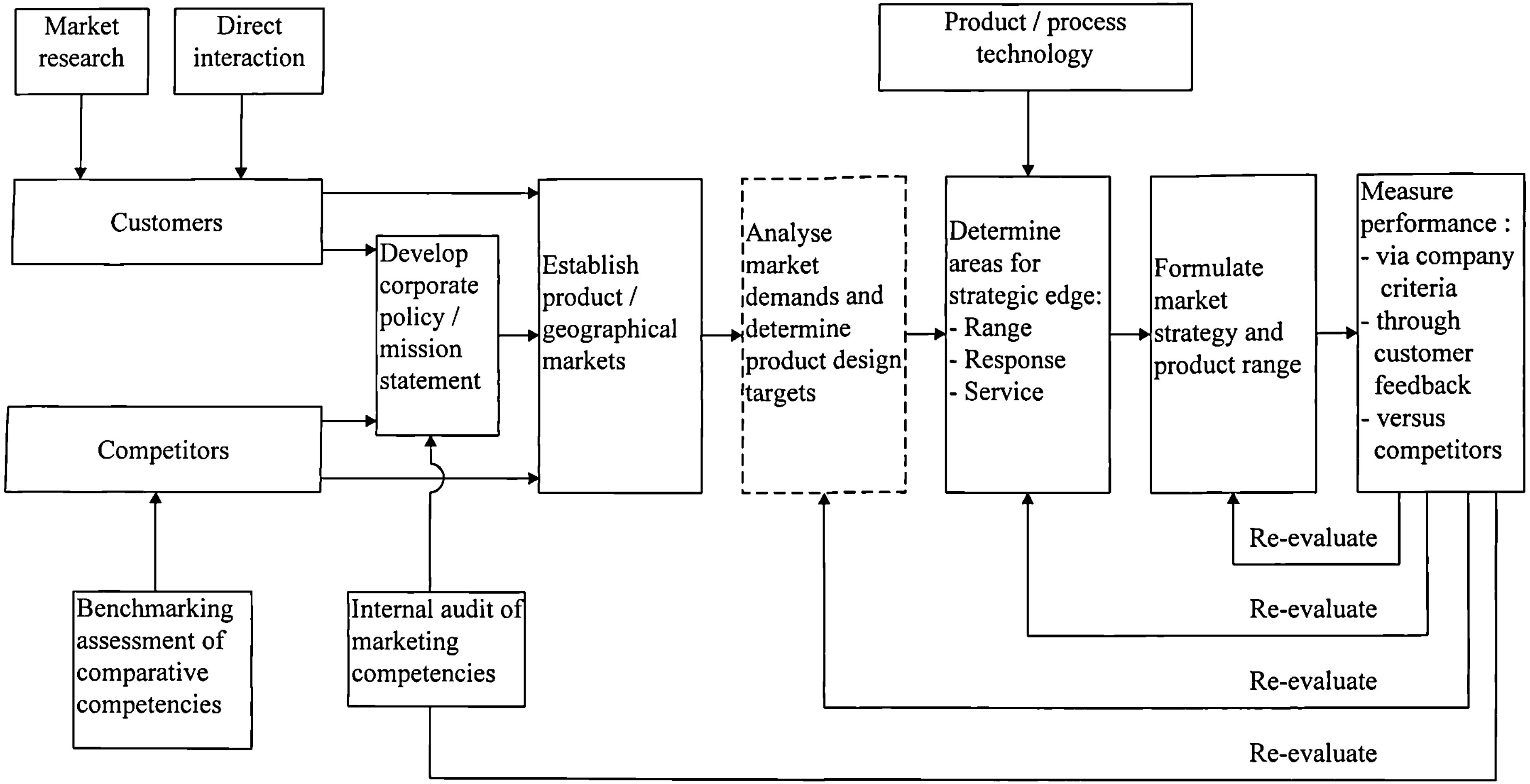

Figure 1.3: A Modified Generalised Market- Focused Product Design Methodology
(Modified from Market-Focused Production System, by David Bennett & Paul Forrester;
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Chapter 2

The Significance of Customer Attributes and Product Performance

2.1 Introduction

Customer Attributes are normally expressed by customers in the form of statements of the features or benefits they get, could get or might get from a product or service (Cohen, 1995). Ideally, these benefits should be stated in a generic way independent of any specific make of the product, although it is not always feasible due to customer's previous knowledge, experience or pre-conceptions on certain products. In this research, the term customer attribute is used in a general sense to encompass any requirements and expectations voiced by the customers when they are specifying or selecting a product as well as the characteristics of individual customer groups.

The focuses and emphases of customer attributes vary with fashion trend and market economy. For instance, in the early 1950's when most nations were recovering from the Second World War, the demand for almost all types of commodities was very high. At that time, consumers' expectation on the goods they bought tended to be rather fundamental and less critical as long as the basic and essential requirements could be met within a reasonable and affordable price bracket. However, as the supply and demand started to even out, consumers began to enjoy a much wider freedom of choices from the products and services they get. As a result, being a product or service provider of today, in addition to meeting the basic needs of performance and specification, a company has to offer certain outstanding features in their products in line with the values perceived by the customers in order to gain the market acceptance and improve business competitiveness. In a market driven economy, the willingness and ability of a company to offer distinctive and customised product attributes have become the prerequisites and critical success factors for gaining competitive advantages, profitability and security for all its stake holders (Dale, 1994).

2.2 The Impact of Customer Attributes on Product Competitiveness

Market demands have been recognised a major driving force for continuous improvements in product functionality, quality consistency and reliability of timely and uninterrupted supply of service / goods, all available at a competitive price. In order to achieve such diverse performance targets, the entire chain of activities starting from product conception through design, engineering, materials planning, process planning, production, distribution as well as after-sales support have to be effectively co-ordinated. Customer-centred commitments are usually categorically spelt out in the corporate policies of successful enterprises world-wide. "The Customer always come first", "Customers are too good to lose, ... let's keep them happy", etc. are among the popular slogans. It is also apparent that the customer requirements are becoming increasingly rigorous and dynamic to the extent that they sometimes behave like moving targets. However, it is beyond any doubt that being able to effectively capture the genuine needs and wants of the customers, and being able to understand and respond to them promptly are the gateway to satisfying the customers and meeting their expectations.

Studies showed that most successful companies believed that the best way to conduct new product development was to go out to potential markets and seek the view of the end users and field engineers. The areas to be explored typically include what they feel about the competing products available in the market, what bothers them, what features they will expect from future offerings, and what is required to satisfy their needs, expectations, as well as realising their imaginations and desires. A thorough understanding of these customer and market related messages will help formulate the features and characteristics of the product which will be found more charming, attractive and distinctive than the competitions.

2.3 The General Perceptions of Product Quality Performance

Quality is one of the essential measures of product performance, and it can be a rather abstract term in itself. "Fitness for use / purpose" (Juran, 1974), "Conformance to Requirements" (Crosby, 1979), "Quality consists of the capacity to satisfy wants ...", "Quality is the degree to which a specific product conforms to a design or specification" (Gilmore, 1974), etc. are among some of the differing views on product quality.

Some researchers treat quality in a more liberal or less exact way. Pirsig (1974) suggested that quality should be considered neither mind nor matter, but a third entity independent of the two ... even though it could not be defined, people seem to know what it is. Tuchman (1980) suggested quality as a condition of excellence implying fine quality as distinct from poor quality, and he further elaborated that quality could be viewed as reaching for and achieving the highest possible standard as against being satisfied with the sloppy or fraudulent.

On the other hand, product designers / engineers incline to take a more practical view that differences in quality amount to differences in the quantity of some desired ingredient or attribute (Abbott, 1955). In other words, to meet certain customer requirements, one has to reflect them in some quantitative product specifications and tangible technical targets. While some customer attributes are more explicitly stated, others might have to be implicitly revealed through the features offered (Edwards, 1968). Taking the financial aspects into consideration, Feigenbaum (1961) suggested that quality should mean best for certain customer conditions including the actual use value as well as the selling price of the product. The importance of the latter was reinforced in (Leffler, 1982) in which quality is deemed to refer to the amounts of unpriced attributes contained in each unit of the priced attribute. Broh (1982) described product quality performance as the degree of excellence at an acceptable price and the control of variability at an acceptable cost.

Furthermore, Garvin (1988) took an elementary view at product quality performance and put forward a framework of quality which consists of eight major dimensions, i.e. Performance, Features, Reliability, Conformance, Durability, Serviceability, Aesthetics and Perceived Quality.

These differing views from various experts and quality gurus reflect the general beliefs as well as certain professed biases of the researchers on how this seemingly abstract yet unavoidable issue of providing a quality product can best be addressed. After all, in the ultimate analysis of the marketplace, the quality of a product depends on how well it fits the patterns of consumer preferences (Kuehn & Day, 1962). Hence, at the end of the day, it is how the products or services are received by the market and customers that matters. In fact, having a good quality performance and having satisfied customers are almost synonymous. All the same, individual customers may have their own perception on quality which can well be reflected in their agenda of needs and wants in a product. Therefore, adopting a scientific approach for mapping the dynamic VoC onto some tangible product features and technical targets represents a positive move towards gaining the acceptance of customers on a product.

2.4 Understanding Customer Satisfaction

Almost all companies claim that they value their customers, and their customers come first, etc. However, it is not uncommon to find that a fair number of them are just paying lip service, and they are in fact underestimating and losing touch with their customers without whom their business is destined to suffer (Snyder et al., 1994). For instance, in 1993, a story in the Wall Street Journal on the computer industry described how the "Big Blue", IBM made a loss of nearly five billion US dollars in the previous year mainly due to the fact that they lost touch with the users' demand by refusing to react promptly to their evolving desire and preferences for small computer networks.

It has long been recognised that customers are too good to lose, and customer satisfaction is one of the prerequisites for business success. Customer satisfaction can be defined as the state in which customer needs, wants and expectations are met or exceeded, resulting in repeated orders and continuing loyalty. Typically, a problem in a product will cause on average a 20% decrease in loyalty to the vendor, i.e. one in every five customers who are not happy with a company's product will choose another supplier next time. In fact, further studies indicated that less than 5% of the dissatisfied customers will complain to the manufacturer direct, instead they will tell ten others that how a given product falls short of their expectations (Goodman, 1989). Therefore, the exact magnitude of the impact of poor product performance may well be very much larger than what appears on the surface which may be just the tip of an iceberg.

Customer satisfaction does not come about overnight or by accident, it requires careful planning and execution. Roberto Goizueta (1989), the chairman of the Coca-Cola Company said, "Coca-Cola might be the most valuable trademark in the world, but the value of any trademark is merely a reflection of the degree of consumer satisfaction it brings about". Owing to the supreme importance of customer satisfaction, it will be necessary to have some ways of assessing or measuring its degree or extent of achievement. In recent years, customers, suppliers, and survey practitioners have different views on assessing and measuring customer satisfaction because the approach and emphasis might vary in different market sectors (Hayslip, 1994), dependent upon the individual product types and commercial considerations, such as:

- the size of the customer populations;
- the volume of purchase;
- the complexity of the products or services;
- the knowledge of the customers on the products; and
- the state of vendor-customer relationships; etc.

The weights on these parameters are not always identical for different companies and business sectors. Normally, in the consumer markets, survey of customer satisfaction can be conducted over a larger population, whereas in the commercial markets, the results rely more heavily on the responses of a relatively small number of co-operative and consistent respondents.

2.5 Converting Customer Attributes into Product Strategies

As customer attributes can vary both in dimensions of emphasis as well as individual perception and expectations, it will be necessary to capture the relevant customer data and convert them into appropriate actions.

The process of satisfying customers or outperforming their expectation starts with effectively understanding their genuine needs. Treating "the customer" as a single person, a group or a rigid set of product specifications might not be able to address their needs and expectations. Hence, an organisation has to establish some effective means of capturing and interpreting the VoC because ordinary consumers may not have the required technical or professional know-how to categorically define their needs and preferences on a product in a sufficiently precise and unambiguous fashion. Typical ways of capturing customers' opinions include the use of general or specific questionnaires or comment cards for different focus or target customer groups. Sometimes, on-site visits or interviews to selected customers can also be used to encourage more open dialogues and help reveal their major concerns.

Besides, appropriate analytical techniques can be applied to assist thorough understanding and realistic prioritisation of the customer attributes (Lu et al., 1994) (Wasserman, 1993). Through applying the relevant techniques, individual departments in a company will be able to gear up their way of thinking in line with the customer's expectations. As a result, enhancements and new features can be established and built into the existing and future products. In other words, the company can then live in the customer's shoes and assess the performance of their business in the eyes of the customers (Snyder & Dowd Jr., 1994).

Quality Function Deployment (QFD) (Akao, 1990) (Hauser & Clausing, 1988) (Clausing & Pugh, 1991) and the Seven New QC Tools (Mizuno, 1988) (Bossert, 1991), including the Relation Diagram, Affinity Diagram, Systematic Diagram, Matrix Diagram, Matrix Data Analysis Method, Process Decision Programme Chart and Arrow Diagram, are amongst the methodologies and mechanisms commonly employed. They can help clarify and co-ordinate both the subjective and objective customer attributes and transform them into product / design attributes as well as the relevant manufacturing activities. This knowledge interlinking the customer demands and the relevant responses is essential for formulating the marketing and corporate strategies of an organisation.

This research offers a novel approach with the view to helping satisfy customers by responding to their dynamic requirements with the relevant product features, quality and performance targets.

2.6 Summary

This chapter considers the nature and characteristics of customer attributes, and it reveals the roles of these attributes in the making of a competitive product in the market. The multiple views and dimensions that affect the quality performance of a product are discussed. The importance of customer satisfaction towards the survival and success of an organisation has been spelt out. The journey of satisfying the customers begins with capturing their essential requirements and understanding their major concerns. Both technical and commercial considerations are required in setting the standards for product quality performance with the application of appropriate analytical tools. Some well proven techniques and methodologies applicable to customer requirements management will be discussed in Chapter 3.

Chapter 3
Analysing and Mapping Customer Attributes

3.1 Introduction

It is beyond doubt that capturing, analysing and responding to the demand of customers are essential prerequisites for offering good quality products and ultimately gaining customer satisfaction. Some quality experts and practitioners expressed the concerns that with customer opinions of products being so diverse and unstructured, customer satisfaction can hardly be measured as rigorously as the conformance of products to specifications. Others might argue that the VoC tends to be so subjective and biased that it can hardly be used to guide strategic decision making and drive a business (Gale, 1994).

In order to make use of customer feedback and opinions effectively, proper selection and application of some appropriate tools and techniques will be necessary. There are numerous methods that can facilitate the analysis of the VoC in order to assist a company to understand their customers, markets, competitions, technologies and processes better than their competitors. Successful selection and adoption of some of these techniques can bring about improved business performance and increased competitiveness in the marketplace. This chapter introduces the techniques which will be employed or referred to in the hybrid model proposed in this research.

3.2 Techniques for Pre-Processing and Analysing Customer Attributes

The management of customer requirements begins with effective capturing and pre-processing the messages or the VoC from various sources prior to submitting them to more detailed analyses. Some of the simple tools and charts commonly used for processing the VoC, as introduced in Gale (1994), include:

- The Market-Perceived Quality Profile,
- The Relative Price Profile,
- The Customer Value Map,
- The Orders Won / Lost Analysis,
- The Head-to-Head Area Chart,
- The Key Events Time Line and,
- The What / Who Matrix, etc.

Their general characteristics and functional features can be outlined in the following sub-sections.

3.2.1 The Market-Perceived Quality Profile

The Market-Perceived Quality Profile reveals the competitive position of a company relative to their rivals in each of the major business segments, identifying their key selling points, relative weights of importance, and performance scores.

The market-perceived quality profile can be established through the following steps:

a) Obtain from a group of customers in a targeted market the factors, namely the quality attributes, that influence their decision in choosing a given product other than the price consideration.
b) Ask the customers to weigh or prioritise the various quality attributes.
c) Seek the view of the experienced customers on how the different competitors have been performing against the various quality attributes.
d) Determine for each attribute the performance ratio of one product against another, and multiply the ratio by the corresponding priority obtained in b).

e) The overall market-perceived quality score can be obtained by summing up the values obtained in d) for all the quality attributes.

In essence, the market-perceived quality score is an objective indicator of the overall performance of a product in the targeted market among the key competitions.

3.2.2 The Relative Price Profile

The Relative Price Profile of a product is similar to the Market-Perceived Quality Profile described above except that instead of the factors affecting the customers' perception on quality, the factors affecting their perception on its cost will be considered. In this case the price attributes, such as the purchase price, trade-in allowance, resale value, etc. will be investigated. This exercise is useful for determining the pricing policy on a product. A company has to ensure that the prices being charged are compatible to the quality performance perceived by the customers on their products.

3.2.3 The Customer Value Map

The Customer Value Map shows the market-perceived quality score of the competing products versus their relative price ratios in a given market segment. In essence, this map combines the scores obtained in Sections 3.2.1 and 3.2.2 for each competing product and expresses the information in a chart as illustrated in Figure 3.1.

It can help uncover any products that are receiving premium prices that are not fully supported by their perceived quality. In this case, something has to be done to improve the market-perceived quality to justify its premium price. On the contrary, remedial actions may also be needed on some products which might have been over-priced because they are perceived by the customers as possessing a higher quality performance and customer value.

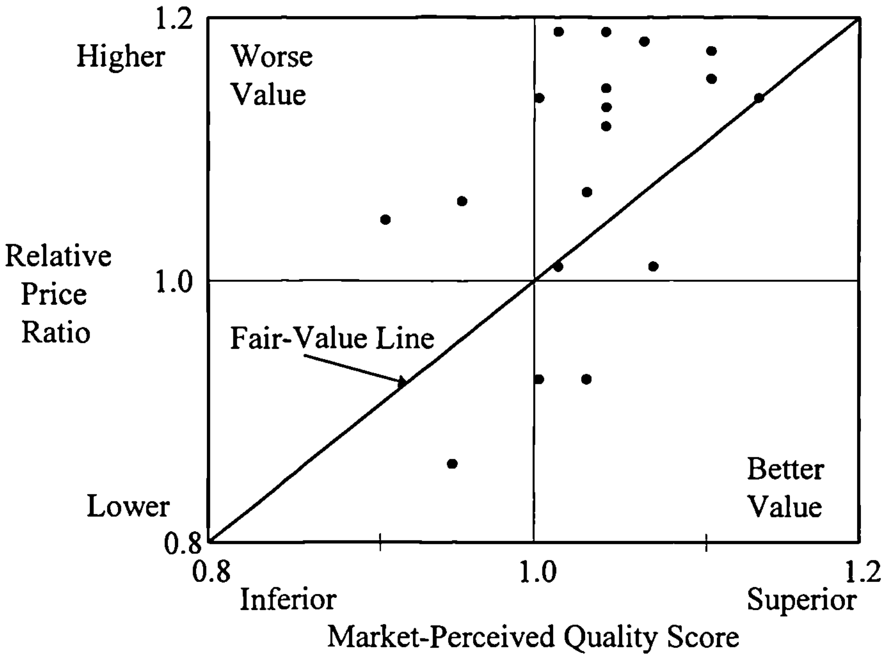


Figure 3.1: A Customer Value Map Pinpointing the Strengths and Weaknesses of a Business

(Adapted from the PIMS Principles, by Robert D. Buzzell & Bradley T. Gale; Copyright © 1987 by The Free Press.)

3.2.4 The Orders Won / Lost Analysis

This technique shows the recent sales won from or lost to the competitions with an explanation of why each order was won or lost. It can be used to analyse the outcome of the major competitive confrontations and help formulate the company's future game plan. Winning or losing is only the consequence of what one did or did not do, it does not necessarily give a direct or absolute indication of success or failure of our company or products. Under certain circumstances, one may choose to lose a few sales battles to the vanishing competitors who mat be operating below the survival level just to struggle to stay in business. On the other hands, lessons can also be learnt from the success stories of the competitors.

The Won / Lost Analysis is particular useful when the market is relatively young, and there may not be sufficient data to allow a reasonably reliable market-perceived quality profile to be established. This technique is also applicable for evaluating the performance of existing as well as impending threats from a new competitor in the market. It reveals why customers decided to switch to the new comers, and equally importantly why they decided to stay with or return to us.

3.2.5 The Head-to-Head Area Chart

The Head-to-Head Area Chart, as illustrated in Figure 3.2., is a graphical tool showing where a company is doing well (as indicated by a Customer Value Performance Ratio greater than 1.0) and where they are lacking (as indicated by a ratio less than 1.0) against a given competitor. In addition, the thickness of each of bands of product feature in the chart indicates its relative weight of importance as perceived by the customers It is useful for identifying the areas where improved performance will be needed and for determining how resources can best be deployed in order to focus on the areas which favour the company. In many markets, the competition is centred around the top two or three players, hence their competing tactics in the markets can be rather decisive. The swings of competitive power can easily be revealed on a head-to-head area chart. More details can be represented in these charts than just considering the position of any two competitors as in the case of a customer value map.

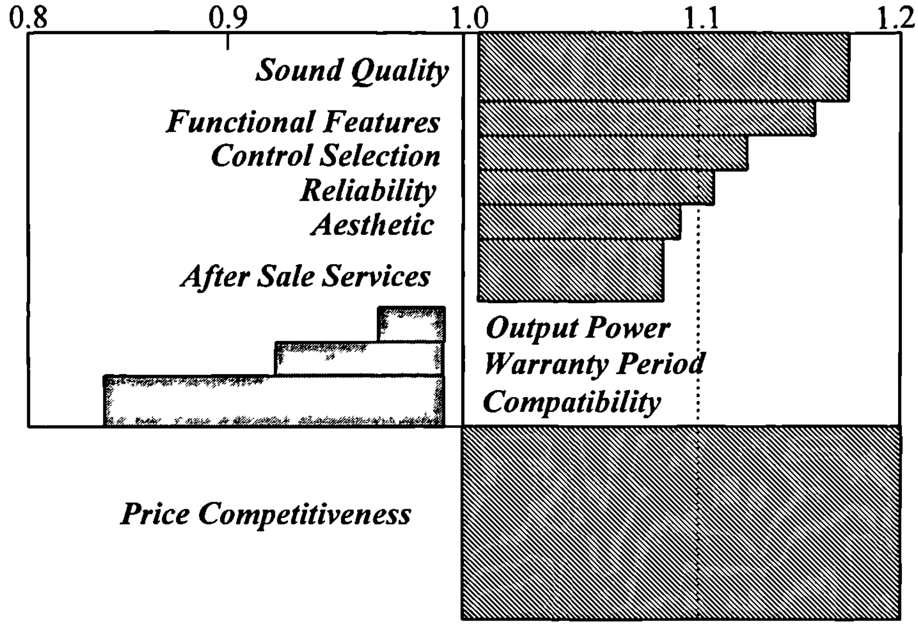


Figure 3.2 : A Head-to-Head Area Chart showing the Customer Value Performance Ratios between two competing hi-fi products

3.2.6 The Key Events Time Line

A Key Events Time Line is a record of the actions taken by a company to improve on their customer perceived position against competitions, showing their relevant effects. It gives a historical account of what you and your competitors did, such as new product launches, changes in pricing or customer / product attributes, shifts in customer service policies, etc., have managed to change the market's perception of performance on the major quality attributes and have shifted their relative priority.

3.2.7 The What / Who Matrix

A What / Who Matrix links the major quality attributes to the business processes that drive performance on those attributes and identifies the corresponding "process owner" who will be responsible for co-ordinating the various processes and functions required to improve performance against competitions. It tracks who is responsible for the actions that contribute to outstanding performance for each quality attribute, and it also helps identify where company resources should be deployed to allow certain aspects of performance to be strengthened. A typical example of a what / who matrix can be shown in Figure 3.3.

Quality Attributes	*Designing*	*Assuring Conformance*	*Manufacturing*	*Selling & Servicing*	*Distributing*	*Marketing*
Trouble free	X	X	X	X	X	
Comfort	X	X				
Safety	X	X	X	X		
Driveability	X	X				
Service				X	X	
Aesthetics	X					X
Brand image	X			X		X

Figure 3.3: What/Who Matrix for the Design of a Motor Car
(Adapted from Managing Customer Value, by Bradley T. Gale;
Copyright © 1994 by The Free Press.)

3.3 Quality Function Deployment

The traditional tools and techniques introduced in Section 3.2 are relatively simple to understand. Having been successfully applied in a wide variety of problems in managing customer value, these tools have also influenced and contributed towards the contemporary development in market-focused manufacturing. Among these techniques, Quality Function Deployment (QFD) is a relative recent methodology which offers a more in-depth analysis and investigation into the handling of customer requirements by projecting the design features and managerial strategies.

3.3.1 Background of QFD

QFD is generally believed to be originating from Japan. However, there have been different versions of when and by whom the technique was first introduced. Some experts believed that the initial ideas of QFD were first put forward by Yoki Akao in 1966, the idea was further complemented when Nishimura and Takayanagi introduced the concepts of quality charts in 1972 (Kogure and Akao, 1983) (Akao, 1990).

Clausing & Pugh (1991) reckoned that the basic concepts in the development of QFD have their roots in value analysis as advocated by its founder, Lawrence Mile in the 1950's. Some believed that QFD, at least by that name, was most likely introduced via Japan (Wolfe, 1994) into USA and put into useful practice by dedicated users, such as the American Supplier Institute of Dearborn, Michigan and GOAL/QPC of Methuen, Massachusetts (Eureka & Ryan, 1988) (Hauser & Clausing, 1988). Schubert (1989) acknowledged Mizuno's contribution in developing QFD, despite Akao first advocated the concept in 1966. However, most people tend to take the view that the first version of QFD in its present form was introduced and put into practice at the Mitsubishi Heavy Industries Kobe Shipyard in 1972 (Wasserman, 1993).

Irrespective of its origin or process of development, QFD is acknowledged as a versatile methodology whose scope of applications has been extended beyond the original intent of just transforming the VoC into product attributes. It has become a standardised tool for mapping customised needs, which can be technical biased, production or process related, or business oriented, into strategic decisions that can be acted upon by an organisation. New applications are being found and continuous improvements are constantly made to the technique. This research represents one of such attempts to help extend the horizon of QFD in a quantitative fashion to facilitate the design, engineering and management of a product.

3.3.2 The Principles of Quality Function Deployment

In simple terms, Quality Function Deployment can be described as a methodology for breaking down the customer requirements on a product into discrete functional specifications and matching them up with the relevant product and engineering features. This approach can facilitate better understanding of the real needs and wants of the customers and enable the relevant product and design features to be engineered in accordance with customer perceived quality standard in a much shorter development time span. QFD can be viewed as a tool for interpreting and developing the VoC into quality and technical characteristics and building such attributes into the finished product. The tasks are meant to be accomplished through systematically deploying the relationship between the demands and the characteristics starting by considering the quality performance of each part and process (Akao, 1990). The overall quality of the product will be constructed through the established network of relationships. QFD can also be described as an overall concept that provides a method of translating customer attributes into the appropriate product attributes for each stage of product development and production (Sullivan, 1986).

When QFD is working to all its intents and purposes, each customer attribute will be looked after by the relevant design / engineering characteristics, and that no design features will become part of the final product attributes unless they are required by the customers. It can be a powerful tool for validating the goals of customer requirement management and identifying the corresponding technical issues required to guide subsequent operational activities and improvements.

The Voice of Customer (VoC) can be captured through survey and interviews in accordance with the company's quality policies and the customer-perceived quality profile as discussed in the previous sections. With QFD, product attributes can be defined interactively with the design and engineering constraints, the company's planned performance, the sales points and other operational preferences and limitations. In the end, a practicable service strategy acceptable to and affordable by both the customer and the company can be formulated.

The transformation process described by QFD can be represented graphically in a matrix-like configuration commonly known as the House of Quality which will be discussed in depth in the following sections.

3.4 House of Quality and its Construction

A House of Quality (HoQ) can be viewed as a conceptual map which provides the means of inter-functional planning and communications for customers and service providers. It helps work out a set of mutually acceptable product features and design characteristics by referring to patterns of evidence on the house grid (Hauser and Clausing, 1988). The building blocks in a basic HoQ can be shown in Figure 3.4.

A number of HoQ's can be applied in turn to guide decision making throughout the entire product development and manufacturing cycle. The tasks can be described by interrelated matrices of what's and how's, i.e. <u>what</u> customers want and need from the product; and <u>how</u> the company can meet the what's through different operations in various departments and units. This concept of interlinking the matrices of what's and how's can be illustrated in Figure 3.5.

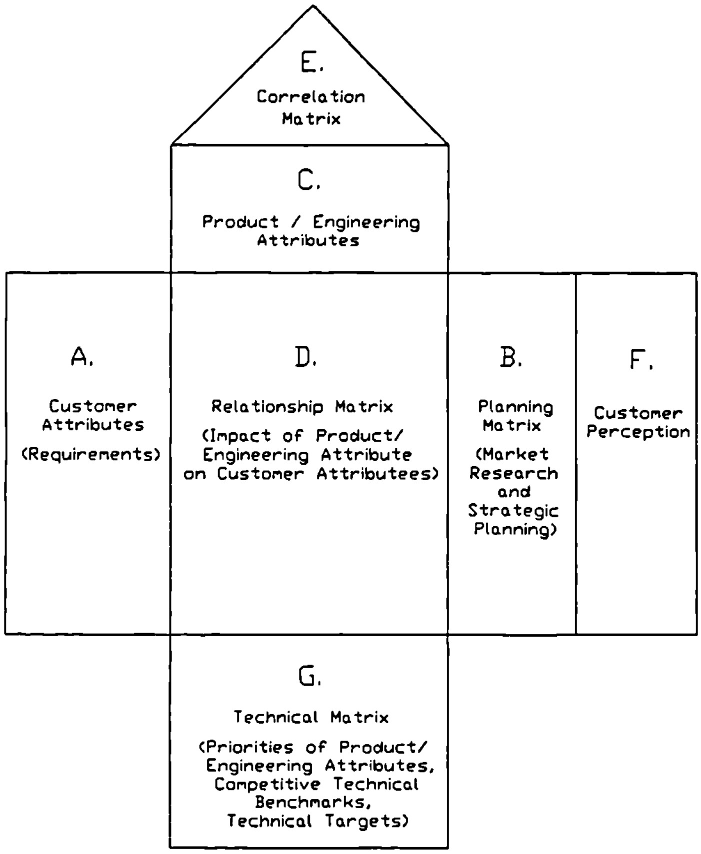


Figure 3.4: The Basic Functional Building Blocks of an HoQ

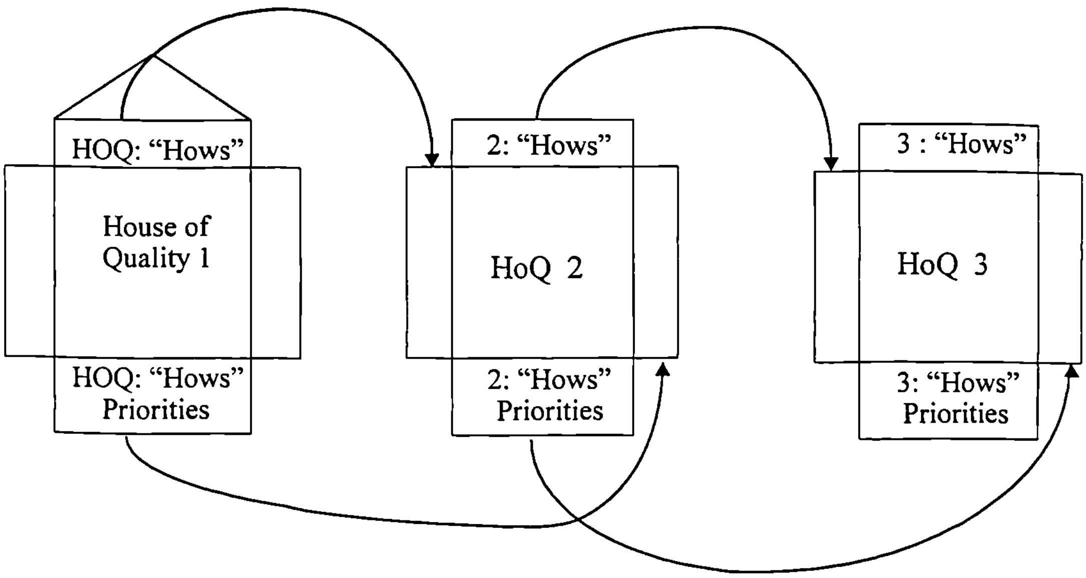


Figure 3.5: Interrelated Matrices of QFD

For simplicity, the interactions of the what's and how's shown in Figure 3.5 propagate from one HoQ to the next (i.e. from left to right). In practice, the flows of information between the HoQ's are bi-directional. When it is necessary, messages from later analyses can be fed back to the previous HoQ's in order to adjust and refine the earlier decisions. Structurally speaking, HoQ is a framework consisting of several matrices attached to each other. To construct a HoQ, first of all one has to solicit the customer requirements through surveys and interviews, and the findings will be represented in the **Customer Attributes** section on the left hand side of the house. The **Planning Matrix**, usually situated on the right hand side of a HoQ, is normally the next section to be constructed. The building block immediately below the triangular attic of the house holds the **Product / Engineering Attributes** which can be viewed as a set of product or design characteristics expressed in technical terms. These technical issues are sometimes referred to as the Voice of Designer (VoD). The **Relationship Matrix** situating in the centre of the house is usually the most complex block which requires a great deal of efforts to establish. The **Relative Weight of Importance** and the **Target Value** for each product attribute are calculated from the entries in the Planning and Relationship Matrices, and they are entered into the bottom part of the house. Finally, the **Correlation Matrix** showing the inter-relationship between each pair of product attributes is placed at the attic the HoQ. An example showing the constructs of a typical HoQ can be found in Figure 3.4. The detailed constructs of each building block will be discussed in the following sections.

3.4.1 The Customer Attributes

Listening to the customers and capturing their needs is almost always the first step in gaining customer satisfaction. Customer Attributes are usually expressed in statements of benefits that a customer gets, or could get, or might get, from a product or service (Cohen, 1995). They may take different forms, such as complaints, suggestions through different channels such as interviews, questionnaires, market survey, etc. Hence, they might not be structured in a format directly suitable for a QFD exercise. The customer attributes are then sorted and structured into different categories as shown in Figure 8.3. in order to facilitate their subsequent analysis, interpretation and mapping against the relevant Product Attributes.

3.4.2 The Planning Matrix

The Planning Matrix is an integral part of the HoQ that reveals the policies and targets of product performance of a company. It combines the business priorities of a company with the preferences of the customers to help set policy and goal for the development of a product and guide other downstream design and engineering activities. Thus, the Planning Matrix holds the resulting quantitative strategic decisions and company policies primarily established through market survey. In other words, these strategic decisions are made through comparing the performance of a company against that of its competitors in terms of how well a given customer attribute is fulfilled. A typical Planning Matrix contains the following columns of data:

- **Relative Customer Priority** – this represents the priority indicated by customers on each customer attribute, and it is usually normalised and expressed in percentage. Besides, the Relative Customer Priority for each category or individual attributes within a category can also be determined and expressed in a HoQ.

- **Company's Own Rating** – this represents the customer's rating (customer satisfaction rating) on a company's performance on a specific customer attributes.

- **Planned Level** – this is the target of performance on a given customer attribute that the company plans to achieve.

- **Improvement Ratio** – this is the ratio of the Planned Level and the Company's Own Rating for each customer attribute, i.e.

$$Improvement\ Ratio = \frac{Planned\ \ Level}{Company's\ \ Own\ \ Rating}\ .$$

- **Sales Point** – this characterises the relative sales potential that can be generated against a given customer attribute, if its target performance is fulfilled. It is normally expressed quantitatively according an arbitrary scale, such as:

  1.0 -- No Sales Potential;

  1.2 -- Average Sales Potential; and

  1.5 -- High Sales Potential.

- **Weight of Importance** – this represents the quantitative weight on each of the customer attributes by consolidating the corresponding customer's view, company's performance target and marketing policy for guiding the company's emphases as given in the following equation:

  The Weight of Importance for a given customer attribute

  = (Relative Customer Priority) * *(Improvement Ratio)* * *(Sales Point)*.

- **Relative Weight of Importance** – this is the normalised value of the above Weight of Importance for each customer attribute expressed in percentage so that the sum of them for all customer attributes will be equal to 100%.

- **Customer Perception** – this takes the form of a graphical chart showing the customer's view on the performance of some competing products on each of the customer attributes.

3.4.3 The Product Attributes

Product Attributes represent the design and technical specifications of a product. They purport to offer the features suitable for meeting the market demands identified from the customer attributes. They can be collectively called the Voice of Designer (VoD), representing the organisation's internal and technical language of communications for the product designers and engineers. The Product Attributes can be expressed in qualitative terms and entered above the Relationships Matrix as shown in Figure 8.3 later in the Case Study. Through further analyses and investigations including AHP and fuzzy inference process adopted in this research, the Product Attributes are prioritised, and their target values can be determined quantitatively.

3.4.4 The Relationships Matrix

The entries in the Relationship Matrix indicate the extent to which a given product / engineering attribute contributes towards fulfilling the customer attributes of a product. It is a direct way of showing the strength of impact of a product attribute on a given set of customer attributes. In a conventional HoQ, the relationships are usually described by symbols, such as space, Δ, O ..., etc. each of which is assigned a numerical value on a selected scale, such as the 1-3-9 scale. In this case, zero stands for "not related", 1 for "possibly related", 3 for "moderately related" and 9 for "strongly related". Alternatively, other scales, such as 1-5-9, are used sometimes. The appropriate scale of relationship is chosen to facilitate the later calculation of the Weight of Importance for each product attribute. Instead of symbols, quantitative values can be assigned to the cells as illustrated in the proposed model to give more precise representations of the relationships. Strictly speaking, when a given product attribute happens to adversely affect the fulfilment of certain customer attributes, negative entries should be assigned. These negative elements can complicate the QFD computation. In most QFD exercises, only the positive entries figure in the relationship matrix mainly for the sake of simplicity. To have a more satisfactory analysis, the product attributes responsible for the negative relationships have to be replaced by other alternatives which will improve the overall orthogonality and independence of the set of attributes.

The entry into each cell of the matrix along with the Relative Weight of Importance of individual customer attributes can be used to project the contribution of a given product attribute to the overall customer satisfaction performance. When all the contributions have been worked out, those product attributes having higher scores and hence more significant impacts on customer satisfaction can be identified to help plan resources deployment.

3.4.5 The Correlation Matrix

At the attic of the HoQ, there stands the Correlation Matrix (or strictly speaking just a correlation triangle) which reveals the inter-relationships and inter-dependencies among the product attributes. It allows a clearer understanding and insight into the design and development of a product. The entries into this matrix can be represented symbolically according to some selected scales in a similar fashion as in the Relationship Matrix, or simply by ticks, crosses or blanks depending on whether they are positively, negatively or simply not related to each other as illustrated in Figure 8.3. These items of correlation are normally assumed to have bi-directional properties, however for precise representations, the directions of impact should also be indicated because one attribute may have a strong impact on another but the converse does not necessarily follow.

An alternative method of describing the correlation is to use Relationship Network Diagram in which product attributes are expressed in circular nodes and the correlation are indicated by ticks or crosses alongside the directional arrow joining any two related attributes (Belhe, Kusiak, 1996). A more sophisticated version of this type of network, the Interpretative Structural Model was proposed (Warfield, 1994) for products of higher complexity.

Irrespective of the form in which correlation is represented, the attributes inter-relationships essentially show the extent to which design features are affecting one another, and identify the existence and nature of the possible conflicts. As a result, product design and development efforts can be planned to resolve or alleviate these dilemmas perhaps through improved communications and team work.

3.4.6 The Relative Weight of Importance of a Product Attribute

The Relative Weight of Importance of a product attribute represents the total contribution of the product attribute towards the overall fulfilment of a given set of customer attributes. It is calculated based on the Weight of Importance of each customer attribute established in the Planning Matrix and the numerical entries in the corresponding column of the Relationships Matrix. The sum of the results under each column of product attribute will give the total contribution. The Relative Weights of Importance for the product attributes are the corresponding normalised contributions expressed in percentage in a row below the Relationships Matrix as shown in Figure 8.3. The larger the weight, the more influential the product attribute will be on overall customer satisfaction, and the more enterprise resources ought to be deployed to assure its intended performance and prompt delivery.

Normally, the QFD exercise in most companies terminates at this point, and the priorities of the product attributes revealed by their Relative Weights of Importance are taken as a guideline or an urgency indicator for planning the downstream design and manufacturing activities.

3.4.7 The Target Values

For the more dedicated and committed QFD applications, setting the Target Values for the product attributes will represents a big step forward in extending the product planning horizon. These target values define the goals for product development and planning activities. To determine the target values, knowledge on the related attributes as well as their inter-relationships have to be considered simultaneously. The findings from the analyses conducted in preceding stages of QFD are called upon, and the process is traceable because most of the parameters affecting the work are clearly specified in respective sections of the HoQ.

A simplified approach for setting the targets can be similar to that for determining the Importance Weights in the Planning Matrix. Starting with the highest ranking product attribute, determining the emphasis of design with reference to that of the competitions. The targets can be set with the view to excelling the strengths of the design team in those product attributes that matter most to the overall customer satisfaction. These values are normally entered at the bottom of the HoQ under the column of the corresponding product attributes.

In this research, a non-conventional approach based on fuzzy set theory is proposed to infer on available knowledge and experience on customer demands, product features and their inter-relationships systematically and quantitatively with the view to determining product design targets more responsively and consistently.

3.4.8 Limitations and Potential Improvements in a Basic HoQ

HoQ is a conceptual map and a robust tool that allows every department in a company to work together in planning and designing a product. The actual roles of an HoQ depend on how it is implemented. A fully established HoQ is a complete structured representation of the knowledge from the market and a detailed plan of how a product can be better designed in a much reduced time span on par with those high-performing world-class competitions. In fact, the concepts of QFD and those of HoQ can be applied further a field. Strategic planning for the future prospects of product within a product family, organisational planning in a company, cost deployment against a number of tasks, and many other unbounded applications are among the potential candidates in the manufacturing and service industries (Noda, Ogino, 1988) (Akao, 1990).

All the same, the conventional HoQ does suffer from certain limitations. As a product becomes more complex, the details held in the HoQ can get too congested to the extent that it fails to display the full details of the problem domain, and certain key issues may get overlooked in the over-sized matrices. Furthermore, HoQ is sometimes classed as a "one-shot" tool for facilitating communication among marketing, engineering, and manufacturing during the design phase of a new product, and it does not lend itself to continuous product improvements. There has been suggestions that the conventional HoQ ought to be augmented with other customer value analysis tools, such as those introduced in Section 3.2 of this chapter to offer a "Dynamic House of Quality" (Gale, 1994).

Hitherto, the Correlation Matrix has been the least exploited section in the HoQ, probably because there is usually a lack of options for either strengthening or avoiding the attribute relationships. Most companies accept design conflicts as being natural and inevitable in real life, and are quite prepared to live with the situations through compromises.

Simple multivariate mathematical models and algorithms have been suggested to approximate the customer satisfaction performance as a function of the target value of a given product attribute (Cohen, 1995). However, this approach is far from perfect because it cannot cope with the possible non-linear properties which exist in the relationships between a product attribute and its performance towards customer satisfaction.

Although HoQ provides a strategic mapping of customer and product attributes in a compact form, it could be further enhanced by other tools and techniques and continually enriched with additional knowledge from business experience, engineering and technical know-how. The ability to cope with the ambiguity, vagueness and imprecision commonly innate in the semantics of VoC will also be essential.

This thesis puts forward an hybrid model which incorporates a number of analytical tools including Affinity Diagram, Analytic Hierarchy Process, and a

Fuzzy Inference Sub-System in order to overcome the hurdles in target setting and extend the applicability of the QFD methodology.

3.5 Affinity Diagram

An Affinity Diagram is a tool suitable for coping with a large volume of data: some of which might be qualitative or linguistic, such as requirements, opinions, comments, etc. It can be considered as a largely creative rather than logical process (Bossert, 1991). It organises the data into categories or a hierarchy of structured ideas according to the natural relationship between the items from the bottom up without any pre-conceived preferences or biases. The resulting categories of customer attributes of a given range of hi-fi systems after clustering using an Affinity Diagram can be shown in Figure 3.7.

The relationships between the ideas are derived from the intuition of the development team from their "gut" feeling rather than intellectual or logical thinking. This technique is particularly applicable for sorting out complex and sometimes chaotic issues for which a new way of thinking might offer a good alternative. The grouping and categorisation of the primarily qualitative VoC is a typical task that can be handled by the Affinity Diagram. Similarly, it can also be used for organising other types of non-numerical data, such as product features and technical characteristics.

In the context of customer requirements management, the initial data for constructing an Affinity Diagram can be obtained through interviewing the customers. This facts finding exercise can be further supplemented by internal brainstorming sessions within the development team. Having capturing the ideas that represent their current understanding of the problem domains, the team will then be better placed to decide which problem requires more attention and where additional data are still required.

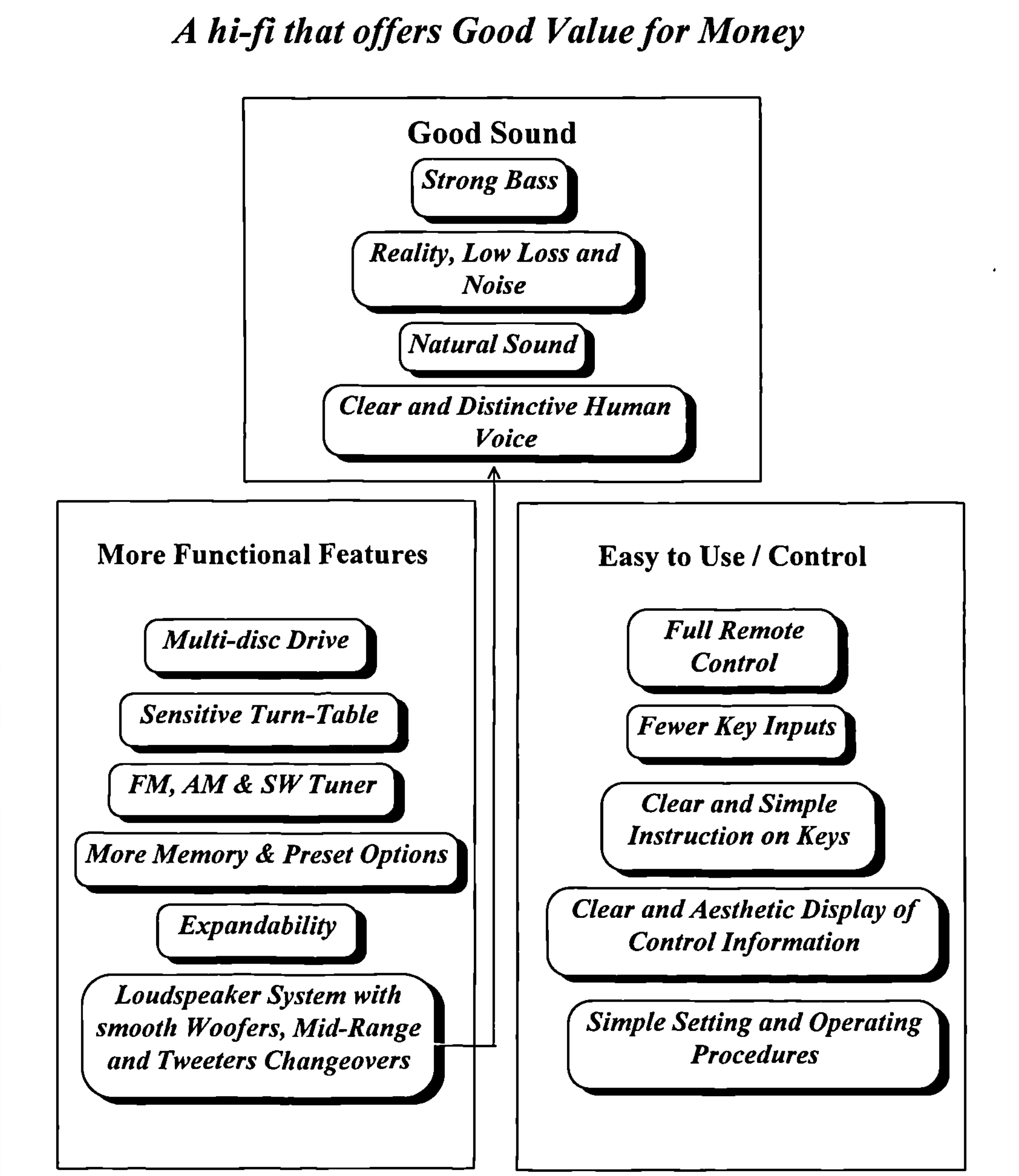


Figure 3.7: An Affinity Diagram showing the Customer Attributes for a new hi-fi system after clustering

3.5.1 The Construction of an Affinity Diagram

An Affinity Diagram working group is typically made up of members who have knowledge in different dimensions of the problem. The conventional steps of constructing an Affinity Diagram can be explained as follows:

- Each team member is required to state the problem to be tackled in simple terms without detailed explanation in order to avoid any prejudice towards existing methods or conventions.
- The statements made by the team members are then recorded onto separate cards in exact wordings as they were stated in order to capture the essence of the thought.
- The cards are then mixed and spread randomly on a large table.
- Groupings are formed for those cards which seem to relate to one another.
- In each group, a card which can capture the central theme of the group is chosen and put on the top of the group as the header. If such a card cannot be found, one must be written.
- The detail on each card is then transferred onto paper with lines around each cluster of groupings, and the related clusters can be bundled together as shown in Figure 3.7.

The steps outlined above described the conventional approach of constructing an Affinity Diagram. With the help of a simple computer programme supported by a relevant database, an Affinity Diagram can in fact be constructed much more interactively and comprehensively.

The resulting groupings need to be regularly reviewed and updated, such as the transfer of attributes between categories when necessary as illustrated in Figure 3.7 in order to reflect the up-to-date groupings.

The concept of Affinity Diagram has been adopted in the proposed hybrid model for grouping the customer and product attributes into related categories in the HoQ to facilitate subsequent analyses and attributes mapping.

3.6 Analytic Hierarchy Process

The Analytic Hierarchy Process (AHP) is a multi-criteria decision-making technique initially put forward by Thomas L. Saaty in the 1960's. It is an analytical tool having an architecture which can take care of both the quantitative and qualitative aspects of a decision making process. An AHP provides a simple model capable of tackling both structured and non-structured problems through establishing an effective hierarchy using ratio scales for relative judgement on a single criterion (Saaty, 1980). The use of hierarchical ordering has always been a natural human instinct both in our conscious and sub-conscious mind (Whyte, 1969 (a) & (b)). Saaty (1994) suggested that a better way of approaching a problem with hierarchy is to seek understanding of the problem at the highest level from the interactions of the various levels of the hierarchy rather than directly from the elements of the same level. The technique allows the relative importance of a number of options or alternative elements to be determined with known consistencies through pairwise comparison judgements based on previous experience as well as personal preferences (Saaty, 1990 & 1994). It synthesises all judgements and identifies the factors that have a higher weight and will affect the final outcome of a problem more significantly.

The AHP has been successfully applied to help set priorities in a wide variety of problem areas, such as marketing strategies (Dyer & Forman, 1991) (Lu et al., 1994), manufacturing automation decisions (Madu & Georgantzas, 1991), information technology management (Madu et al., 1991), total quality management

(Madu & Kuei, 1993) and many other disciplines (Tummala & Wan, 1994). The immense scope of AHP applications is apparent because it can assist decision-makers in ordering experience, observations, entities and information during the classification of the related issues.

3.6.1 The Principles of Analytic Hierarchy Process (AHP)

The AHP offers a framework of logic and problem-solving, accepting opinions resulted from instant awareness through to fully integrated consciousness. It organises perceptions, feelings, judgements and memories into a hierarchy of criteria and alternatives to facilitate decision making. When the AHP is applied, individuals are required to exercise their personal judgements on the relativity of a number of alternatives or choices essentially through comparing them in pairs. As a result, ratios of a variety of dimensions both tangible and intangible are obtained. Hence, the AHP can be used to rearrange any list of related elements or entities into a specified order of preferences via basic reasoning and intuition. It breaks down a problem into hierarchies of components and sub-parts which will then be subject to pairwise comparisons in order to derive their relative priorities with respect to a pre-defined goal or a specific focus.

The complexity of the hierarchical structures depends on the nature of the problem as well as the knowledge available from the expertise of the people involved. One of the distinct advantages of AHP is that it encourages the individuals who understand and appreciate the problem to become actively involved in weighing the options and alternatives so as to guide the decision-making process. As a result, the participants will feel more at home with the outcomes of the investigation and will be more prepared to take the ownership in implementing them.

In this research, AHP is used for prioritising the customer and product attributes as well as for identifying the contributions of individual product attributes towards the fulfilment of each customer attribute in a Focused HoQ as discussed later in Sections 6.4 and 6.5 respectively. Further explanations on the application of AHP in the proposed hybrid model will be given in a case study in Chapter 8.

Although pairwise comparison is a relatively objective way of weighing a number of criteria, a certain degree of subjectivity and intransitivity is inevitable and is considered a natural phenomenon during the aggregation of preference patterns (May, 1954). Transitivity and consistency are the two major measures for assessing the accuracy and reliability of the resulting priority. Based on the results of numerous researches and experiments, Saaty (1980) concluded that any results from an AHP exercise having an Inconsistency Ratio (IR) less than 0.10 can be deemed reasonably acceptable. Studies on the mathematical theory of AHP, the determination of the priorities through solving the eigenvalues or characteristic roots of the relevant matrix, and the calculation of the Inconsistency Ratio are outside the scope of this research. More detailed explanation of the AHP can be found in (Saaty, 1980, 1990 & 1994).

3.7 Summary

This chapter discusses the ways how customer attributes can be analysed. It introduces the commonly used tools and techniques that are available for processing the customer attributes and interpreting the VoC.

Special efforts have been put on explaining the concept of QFD and the construction of the HoQ. Their strengths and weaknesses are discussed and the proposed areas of improvement, which will be dealt with in this research, have been outlined.

Overviews of the principles of Affinity Diagram and AHP, which form an integral part of the proposed hybrid model, have been given. The principles of fuzzy reasoning, which will be applied in the proposed hybrid model for determining the design targets for product attributes, will be further discussed in Chapter 5.

Chapter 4
Outline of the Research

4.1 Introduction

This research programme begins with a thorough overview of the roles, the changing emphasis and the dynamic characteristics of the contemporary customer demand with a view to gaining a better understanding on the fundamental nature and variability of customer attributes. A number of well proven tools and techniques including QFD, HoQ, Affinity Diagram and AHP, etc. are examined on their applicability and effectiveness in organising, analysing and responding to dynamic customer requirements.

The necessity and importance of effectively capturing, understanding and responding to the needs and wants of the customers to the survival and prosperity of an organisation has been discussed in some depth in the Chapters 1 and 2. Some of the well known contemporary techniques and methodologies for analysing and processing the customer attributes have been introduced in Chapter 3. The general approach and programme of work in this research in establishing an hybrid model is described in this chapter. The model amalgamates a variety of the proven techniques and methodologies for tackling the diverse, dynamic, often vague and imprecise VoC. Details of the interpretation of customer attributes and the determination of technical targets for the relevant product attributes will be outlined in the following sections.

4.2 Development Outline of the Hybrid Model

The major output of this research is an intelligent hybrid system which can be used for:

- Capturing, filtering, categorising, prioritising the customer attributes;
- Identifying the relevant product attributes;
- Representing the attributes in an HoQ;
- Extracting the highly weighted attributes into a Focused HoQ in order to perform more quantitative analyses and calculate the Relative Weights of Importance;
- Determining the technical Target Values for the key product attributes using a fuzzy inference process. Its routine will be mathematically modelled and coded into an object-oriented programme to facilitate the implementation of the proposed approach.

The road map for constructing the hybrid model will be unveiled in the following sub-sections.

4.2.1 Representing the Customer and Product Attributes in a Basic HoQ

The steps for constructing the basic HoQ are outlined as follows:

a) The process of product design and enhancement begins with tapping the sources of ideas primarily from the market. The customer requirements on a given product or service are captured through a multi-stage approach involving surveys, questionnaires, interviews with intermediate reviews, streamlining and re-focusing of the scope of the problem.

b) In order to categorise and prioritise the customer data captured, the Affinity Diagram and AHP are applied during the above multi-stage data capturing process. During this process, substantial customers and designers involvement and interactions are required.

c) The consolidated customer attributes are then entered into a HoQ based on the QFD principles.

d) In order to help determine the company's strategy on the product, the current and the planned performance levels as well as the sales point against each customer attribute are established through combined effort of the designers, product engineers and marketing personnel. The findings together with the performance of the major competitors are entered into the Planning Matrix of the HoQ.

e) Coupled with the entries of the sales points from the sales and marketing personnel, and the attribute priorities established earlier, the weight of importance of each individual customer attribute are calculated. Their Relative Weights of Importance can be worked out through a normalisation process in order to help determine subsequent deployment of design resources.

f) In order to meet the set of customer attributes, the corresponding product attributes in term of product features and technical specifications are suggested by the designers and product engineers. They are categorised using an Affinity Diagram in the similar way as with the customer attributes. At this point, the structural frame, i.e. the x-y dimensions, of the HoQ is fixed.

g) The relationships between the customer and product attributes are determined and expressed in a symbolic form in the Relationships Matrix in order to indicate the relevant contributions of each product attribute towards the fulfilment of the customer attributes. For illustration purpose, the 1-3-9 scale is used in this research to represent the strength of the attributes relationships. In fact, other suitable alternatives, such as the 1-5-9 scale, can also be adopted at the discretion of the end users in order to vary the ratings on specific ranges of attributes relationships.

h) The inter-dependencies among the product attributes as indicated in the Correlation Matrix may affect the effectiveness of the corresponding design features in satisfying the customer attributes. Too strong a correlation between two items may suggest that the attributes could well be combined for more focused attentions. On the other hand, should a significant negative correlation be present, alternative attributes might need to be sought in order to alleviate the possible conflicts of interest, and to improve the design effectiveness.

i) The Relative Weights of Importance for the product attributes can thus be calculated as described in Section 3.4.6 to help focus attentions and efforts in the product design and development process.

The bottom row in the basic HoQ is intended for the specification of the technical target values for the individual product attributes. These targets are traditionally determined heuristically based on the designers' experience and subjective judgements. One of the main objectives of this research is to develop a more scientific and consistent system for determining these target values. Further ground work will have to be done later this chapter to support the explanation of such a system. It is thus pre-mature to determine any meaningful target values at this stage, therefore the bottom row is intentionally left unspecified in the basic HoQ. The issues of determining the design targets will be addressed in full in the Focused HoQ.

4.2.2 Extracting the Essential Attributes into a Focused HoQ

In order to gain a more detailed and quantitative insight into the design problem, a Focused HoQ is introduced as described below:

a) Based on the first HoQ, individuals product attributes or certain categories of them having a higher score of Relative Weight of Importance are identified to support the formulation of the proposed hybrid model.

b) The selected product attributes and their related customer attributes are extracted from the first HoQ and put into a smaller structural framework called the Focused HoQ.

c) The Affinity Diagram can be applied again to regroup the selected customer attributes if the original categories of attributes have been fragmented in the process of data extraction.

d) A group of experienced customers are asked once again to express their preferences on the selected customer attributes using the AHP approach. As a result, a revised set of normalised Relative Weights of Importance for the customer attributes can be established.

e) Different from the basic HoQ, in the Focused HoQ the relative importance of individual product attributes are evaluated against one customer attribute at a time via pairwise comparisons using AHP. The contributions of product attributes towards the fulfilment of a particular customer attribute can then be worked out quantitatively.

f) The contributions of product attributes obtained from e) above are multiplied by the Relative Weight of Importance of the customer attribute concerned, and the results are entered into the relevant cells of the Relationships Matrix.

g) Repeating Step f) for all the selected customer attributes, in the end the entire Relationships Matrix in the Focused HoQ will be fully established.

h) The overall Relative Weight of Importance for each product attribute can be worked out by summing up the values in the cells under its own column in the Relationships Matrix.

4.2.3 Establishment of the Target Values

The Focused HoQ is thus nearly complete except for the entries to its bottom row, the Target Values. It looks a straight forward step to fill in this last row, but in reality a lot of QFD practitioners find the determination of these target values rather complex and choose to terminate their exercise at this stage. As it has been discussed in Sections 3.4.7 and 3.4.8, target values set the technical specifications and performance measures for the product attributes versus specific customer attributes. Substantial efforts in this research are devoted to developing and modelling a dynamic and intelligent approach to allow target values to be determined swiftly against any customer specifications.

4.2.4 Development of the Fuzzy Customer Requirement Inference System (FCRIS)

In order to decode with the inherent ambiguity and imprecision in the VoC and to cope with the changing customer specifications effectively and efficiently, a fuzzy inference approach supported by a mathematical model is developed. The structure of the Fuzzy Customer Requirement Inference System **(FCRIS)** is outlined here.

The **FCRIS** basically consists of three main building blocks, namely

- the User Interface,
- the Knowledge Base,
- the Inference Engine

with architecture as illustrated in Figure 4.1.

The working principles of the **FCRIS** can be explained as follows:

a) The first step in developing the **FCRIS** is to establish the Knowledge Base based on the opinions, experience and technical know-how of the customers and designers. This Knowledge Base can be continually revised and supplemented as the product becomes more mature, and more feedback and experience are cumulated. The knowledge base comprises three partitions, namely

   - **K-CR**, Knowledge on the Customer Attributes,
   - **K-PA**, Knowledge on the Product Attributes, and
   - **K-CR-PA**, Knowledge of the Relationships between the Customer Attributes and Product Attributes.

b) Both **K-CR** and **K-PA** are expressed in Fuzzy Sets with their relevant Membership Functions, while **K-CR-PA** contains a collection of Fuzzy Propositions / Rules.

c) As a given set of customer attributes is received and entered into the system through the users interface, the data are then fuzzified and submitted to the Inference Engine.

d) During the fuzzy inference process, the fuzzy rule base are evaluated against the fuzzified customer attributes.

e) The sub-conclusions from the evaluation process will be aggregated to yield a composite conclusion for each of the output domains (product attributes).

f) The composite conclusion described by the output fuzzy region is finally defuzzified to yield a crisp output which represents the Target Value for the product attribute concerned.

Details of the functional and mathematical modelling of the fuzzy inference process will be explained fully in Chapter 7.

4.2.5 Software Programming for the FCRIS

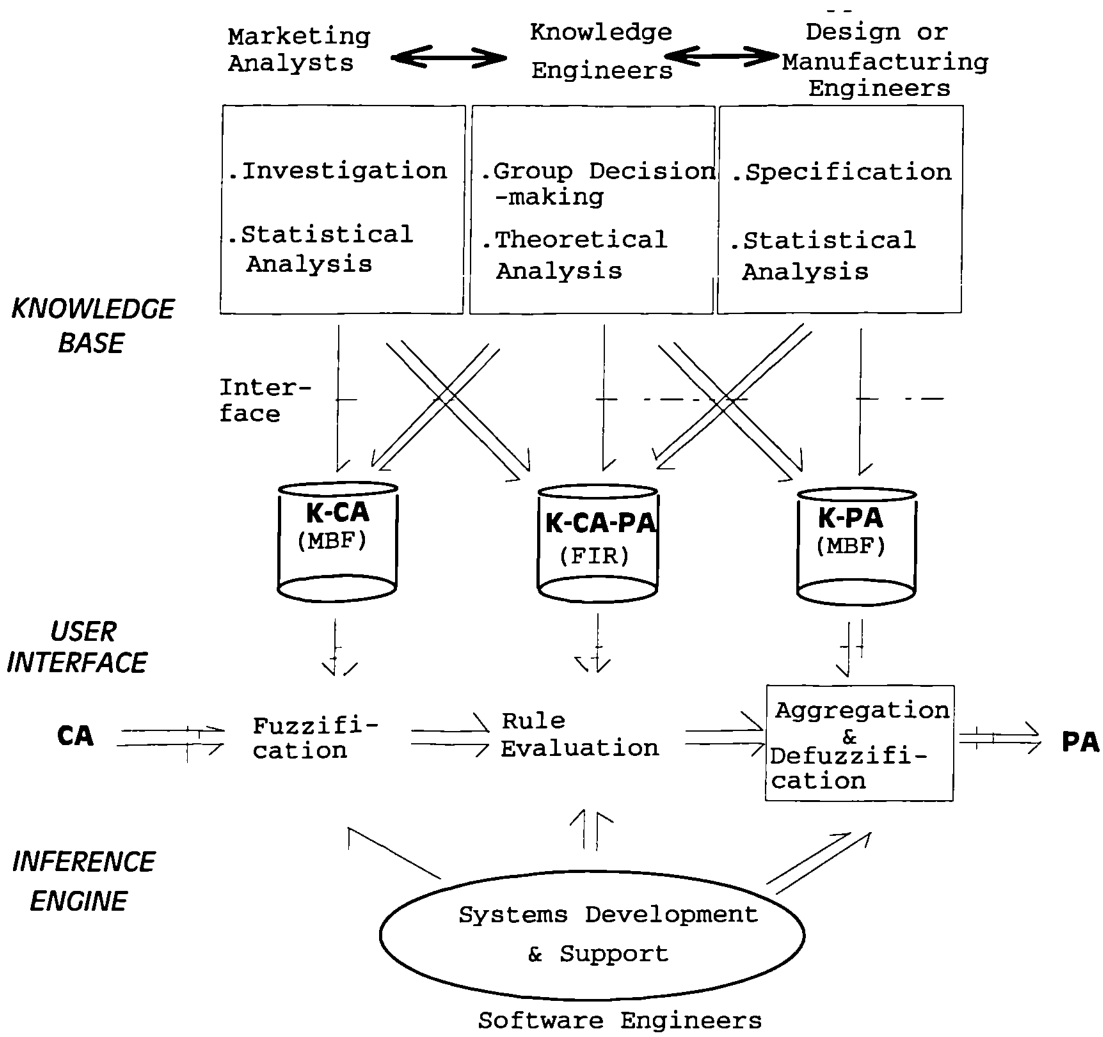
The processes and algorithms of **FCRIS** outlined in the last section are programmed into a software package using C++, an object-oriented language to ease the implementation and applications of the overall hybrid approach.

4.2.6 Development of a Case Study

In addition to the discrete examples given in this thesis, a case study giving a detailed account of the design and development process of a range of hi-fi equipment will be given in Chapter 8 to demonstrate the entire functions of the hybrid model.

4.3 Summary

This chapter describes the work required for developing the proposed hybrid model. The sequence of events at each stage of the model development process have been outlined. Supported by well proven techniques and methodologies, the proposed approach has been modelled mathematically and coded into a software programme to enable effective and consistent derivation of the target values for product attributes / design specifications quantitatively against any given sets of customer requirements. A case study demonstrating the entire operation of the model will be given later in this thesis.



CA : Customer Attributes / Customer Requirements (Inputs)
PA : Product Attributes / Engineering Characteristics (Outputs)
K-CA : Knowledge about Customer Attributes / Requirements
K-PA : Knowledge about Product Attributes / Characteristics
K-CA-PA: Knowledge about the Relationships between CA and PA
MBF : Membership Functions
FIR : Fuzzy Inference Rules / Propositions

Figure 4.1: Architecture of the Fuzzy Customer Requirement Inference System (FCRIS)

Chapter 5
The Basic Concepts of Fuzzy Reasoning

5.1 Introduction

The concepts of Fuzzy Logic, sometimes known as Fuzzy Sets, were initially conceived by Lotfi Zadeh in 1965. Fuzzy Logic is a class of multivalent, usually continuously valued logic having its roots originated from the principles of Continuous and Multi-Valued Logic put forward by Heracleitus, Lukasiewicz, Hilbert and Godel (Klir & Folger, 1988). In the foreword of the book "*Fuzzy Set Theory and its Applications*" (Zimmermann, 1991), Zadeh stated that the Theory of Fuzzy Sets is basically a theory of graded concepts, and he carried on to elaborate that fuzzy logic is a theory in which everything is a matter of degree or to put it figuratively, everything has elasticity.

Since its conception, the theory has been developed in different directions and has offered meaningful applications in many disciplines. In the past ten years or so, Fuzzy Set Theory has experienced tremendous growth with remarkable successes in artificial intelligence, control engineering, decision theory, expert systems, operational research, pattern recognition, robotics and not the least management science. This chapter gives an overview of the principles of fuzzy reasoning and explains the elements of fuzzy logic that can be applied to help understand, analyse and respond to the VoC which tends to be vague, imprecise and elastic at times.

5.2 The Fundamental Characteristics of a Fuzzy Reasoning Process

In one of his first publications on Fuzzy Sets, Zadeh (1965) described a fuzzy set as a class of continuum of grades of membership characterised by a membership function which assigns to each object a degree of membership ranging between zero and one. Therefore, instead of existing as a characteristic function which is binary having only two states, i.e. complete inclusion (1) and absolute exclusion (0) as in conventional Boolean (crisp) sets, fuzzy sets can be described by a membership function whose value varies from zero to one. In other words, partial membership is accepted in fuzzy sets.

Most of the phenomena in our daily life are not exactly dichotomous, instead they are to a certain extent imprecise in the description of their nature. A majority of the imprecision is attributable to vagueness rather than deficiency in the knowledge about the value of the parameter involved. Hence, fuzzy reasoning purports to offer the type of flexibility necessary to cope with the imprecision in real-life scenarios.

5.3 A General View of Vagueness, Uncertainty and Fuzziness

Scientists and engineers have been all along trying or contemplating to describe and tackle their day to day problems in a precise and definitive manner using conventional and crisp mathematical models. However, as a problem is getting more complex, the information contents of its model can become so much congested that those overwhelming mathematical equations may well be inadequate in representing the underlying process. Similarly, as the complexity of a system increases, the possibility of making precise and yet significant statements about its behaviour gradually diminishes until a threshold is reached beyond which precision, significance and relevance become almost mutually exclusive characteristics (Zadeh, 1973).

Schwarz (1962) suggested that an argument, which can only be convincing if it is precise, will lose all its strength and value if the assumptions on which it is based are slightly altered. On the other hand, an argument which is convincing but imprecise may well be relatively stable under small perturbation of its underlying axioms.

A majority of the problems encountered in real life are in fact equivocal, vague and ambiguous at times, and therefore they can hardly be fully understood or precisely described in a discrete, crisp and dichotomous (i.e. yes-or-no, true-or-false) fashion. These uncertainties may be due to a lack of information about the future state of the events, or they can be simply due to the **semantic vagueness** in the way they are described or defined. The former type of uncertainty is mainly probabilistic on either the frequency or the truth of the events statements, and can be referred to as **Stochastic Uncertainty**. On the other hand, the **vagueness in connection with the semantic meaning** of the events, the phenomena or the statements themselves can be referred to as **Fuzziness**.

Fuzziness can come along with the process of human judgement, reasoning, decision making, alternatively it can be innate in the "natural languages" or semantics in which events are described. Sometimes, the meaning of the words is in itself well defined, however when it is used as a label for a set, the qualification of an item to become an element of the set may well be marginal, uncertain and vague. **Fuzziness** can also be classified as being **Intrinsic** or **Informational**. Adjectives or descriptors, such as big, small, tall, short, fast, slow, etc. are considered intrinsically fuzzy. On the other hand, words such as sufficient, reliable, significant, outstanding, etc. can in theory be crisply defined with a large number of descriptors which may well be too clumsy in practice for everyday use. Fuzziness of the latter type is classified as being informational.

Zadeh (1965) put forward the concepts of Fuzzy Set Theory to accommodate and address the various type of fuzziness using the classical notion of set and a propositional statement. Fuzzy Sets can take the form of a function that maps a member of the set to a number between zero and one in order to indicate its actual degree (grade) of membership.

For instance, the concept of a "TALL" man in a crisp and fuzzy representation can be illustrated in Figures 5.1 and 5.2 respectively.

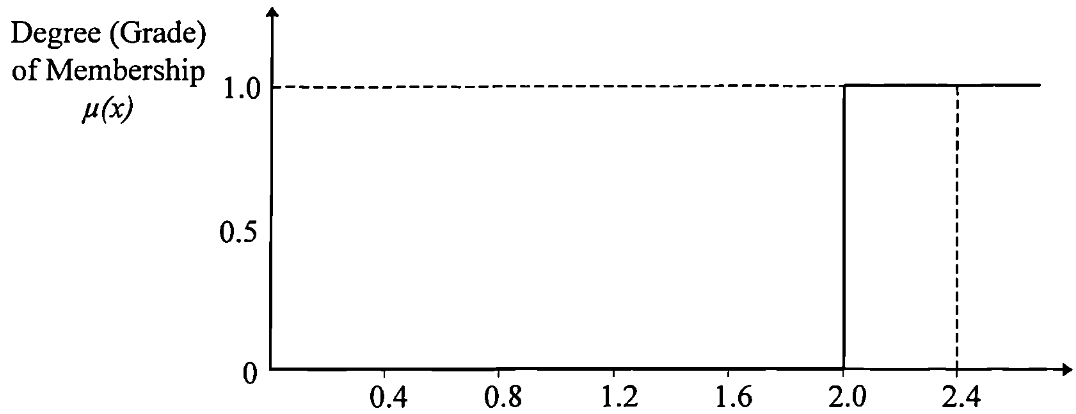


Figure 5.1: The Crisp Set for the Concept of TALL

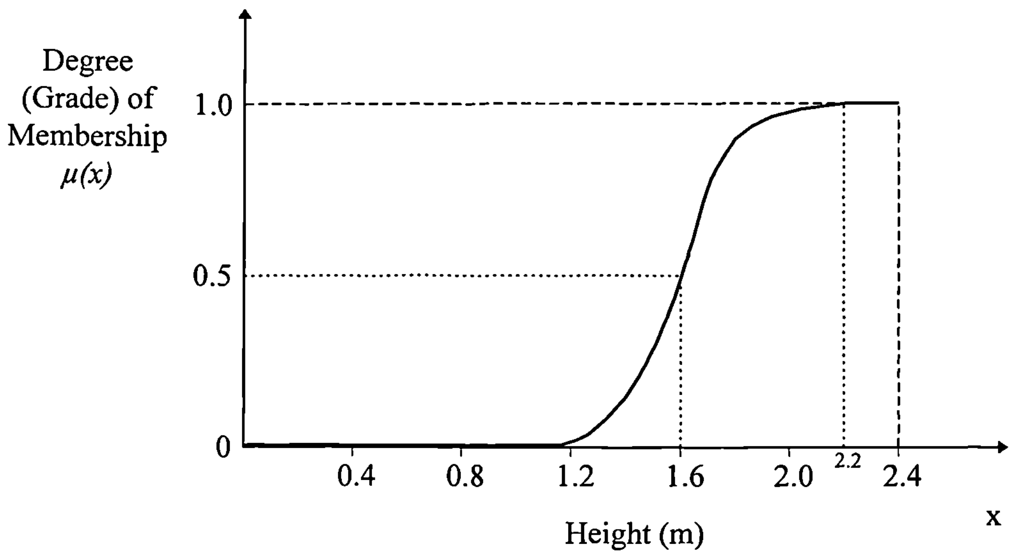


Figure 5.2: The Fuzzy Set of the Concept of TALL

As it can be seen in Figure 5.1, there is a quantum leap from a value of "zero" (not tall at all) at a height *x* just slightly below 2.0 metres to a value of "1.0" (absolutely tall) at a height *x* just slightly above 2.0 metres. This demarcation of the description of "TALL" is not really satisfactory, as two men having nearly the same height, say 1.99 metres and 2.0 metres can end up being classified into two extreme categories. On the contrary, in Figure 5.2 the Degree (Grade) of Membership for the fuzzy set "TALL" varies gradually from a value of almost zero at a height of 1.2m to a value of "1.0" (full membership) for any height above 2.2m. In the latter case, the fuzzy set certainly suggests a more reasonable, sensible and consistent definition of a TALL man. Other fuzzy sets, such as "VERY TALL" and "EXTREMELY TALL" for describing higher values of height, say well above 2.0 metres, can be defined either separately or by modifying the fuzzy set, "TALL" with the use of hedges.

5.4 Definitions and Glossary of Fuzzy Terms used in the Proposed Hybrid Model

Model Variable

This is a variable describing the input and output of a fuzzy model. Variables such as *top speed, weight, height, age*, etc. are typical examples of Model Variables which can be defined by the relevant fuzzy space composed of a number of discrete or overlapping linguistic variables, such as *extremely fast, usually very fast, not quite fast, slow, rather slow*, etc.

Linguistic Variable

This is a variable whose values are not numbers but words or semantics in a natural or artificial language, for examples,

almost always extremely late, *often unbearably noisy*, etc.

A fuzzy space or a fuzzy set can be established through evaluating the linguistic variable whose organisation can be represented as:

$$L_{var} <======= \{q_1 \ldots q_n\} \{h_1 \ldots h_n\} f_s$$

where the predicate q acts as the usuality or frequency qualifier (such as *"almost always"* and *"often"* in the above examples), h represents a hedge (such as *"very"*, *"extremely"*, *"unbearably"*), and f_s is the core of the fuzzy set. Therefore, in the organisation of a linguistic variable, there can be a number of optional qualifiers and hedges which serve to enrich the description of the central theme, such as *"extremely"*, *"unbearably"* in the above examples.

Hedge

This is sometimes referred to as a hedge qualifier or modifier. It is a term, basically linguistic in nature, that decorates or modifies the surface characteristics of a fuzzy set. Hedges can approximate a scalar or a fuzzy set by intensifying, diluting, diffusing through contrasting as well as creating the complement of its membership function. For instance, the fuzzy set "EXTREMELY TALL" can be derived by modifying the membership function of an existing fuzzy set "TALL" with the hedge "EXTREMELY".

Fuzzy Logic

This is a class of multivalent and usually continuous-valued logic based on Fuzzy Set Theory, concerning the nature, performance and interpretation of a set theoretic operations allowed on fuzzy sets. The relevant set implications are mostly based on the rules of min-max or bounded arithmetic sum.

Fuzzy Set

For a domain X containing a collection of objects x, the fuzzy set A in X can be expressed as a set of ordered pairs, such that

$$A = \{ (x, \mu_{A(x)}) \mid x \in X \}$$

where $\mu_{A(x)}$ denotes the membership function or degree (grade) of membership of x in A which maps X to the membership space M.

Fuzzy Number

This is a convex normalised set of positive real numbers with values between zero and one. It generally assumes the space of a bell-shaped or triangular curve with the most probable value for the space around the centre, obeying the rules of conventional arithmetic as well as other special properties, such as the laws of fuzzy set geometry.

Universe of Discourse

This is the total problem space from the smallest to the largest allowable value for a certain model variable. For instance, the speed of a motor car can range from zero to 250 km/hr, thus the corresponding Universe of Discourse can be expressed as [0, 250]. It can also be viewed as a super set of the domains of a related fuzzy set.

Domain

This is the range of monotonic real numbers over which a fuzzy set is mapped. In the construction of a fuzzy model, the relationship and synchronisation of the domains of individual or overlapping fuzzy sets must be categorically defined.

Term Set

This is a collection of fuzzy sets associated with a particular Model Variable.

Support Set

This is a subset of the Term Set representing the membership region which actually participates in the fuzzy implications and any relevant inference processes.

Membership Function

This is a function μ_A in the fuzzy set A for each unique value x selected from the domain, such that $\mu_A = T_{(x)}$, and it returns a unique degree of membership in the fuzzy regions. Membership Function is also known as Fuzzy Membership, Degree of Membership as well as Truth Function because it reflects the truth of the fuzzy proposition " *x is a member of the fuzzy set A* ". The function returns a vector for a second-order set and an $N \times M$ matrix of vectors for a third-order set, representing the value or the possibility density at the truth region.

Imprecision

This is a characteristic of a fuzzy system, showing the degree of intrinsic fuzziness associated with an event, a process or a concept. However, fuzziness and imprecision are intransitive phenomena. It means that a fuzzy system is always imprecise, but an imprecise system is not necessarily fuzzy, because the resolution of a control variables will become more and more precise as the level of detail or granularity of measurements increases.

Modus Ponens

This is a form of implication in both classical and fuzzy logic to infer the existence of a consequent state from an antecedent or premise state. In fuzzy logic, Modus Ponens is concerned with the degree of truth between the premise and the consequent. The rules of modus ponens follow the reasoning process of:-

$P \supset Q$, i.e. the Premise P implies a Consequent, Q.

Modus Tollens

This is an alternative form of the logical implication process used to infer the lack of a premise state given the negation of a consequent state. Similar to modus ponens, modus tollens is a reasoning process having the paradigm:-

$$Given\ P \supset Q, \quad \sim Q \Rightarrow \sim P$$

5.5 Approximate Reasoning using Fuzzy Systems

Fuzzy Logic forms the basis for the design and development of a fuzzy system. Fuzzy set theory provides a platform for a more general theory of fuzzy logic which in turn supports the logical constructs used to create and manipulate a fuzzy system. The functions of these fuzzy systems can be called Approximate Reasoning. Under most circumstances, the terms fuzzy logic and approximate reasoning can be used interchangeably to describe the process of representing imprecise and approximate concepts and relationships. Strictly speaking, fuzzy logic is a more formal representation of fuzzy set theory, supporting the activities of Approximate Reasoning as illustrated in Figure 5.3.

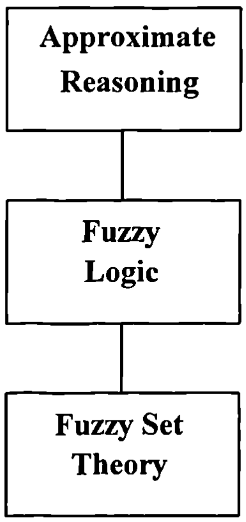


Figure 5.3: Level of Logic Supporting Approximate Reasoning

Approximate Reasoning can be simply defined as the process of inferring knowledge through conditional and unconditional fuzzy rules by combining the mathematics of fuzzy logic as well as other more conventional concepts and methods. The use of hedge qualifiers or modifiers is a typical example of incorporating non-fuzzy materials into the description of a fuzzy linguistic variable.

The basic performance and reliability of a fuzzy model is governed by its related fuzzy associations or propositions which can be looked upon as statements of relationships between model variables and one or more fuzzy regions. As a number of conditional and unconditional fuzzy propositions are executed, those which exhibit a certain degree of truth will contribute to the final state of the output region through the processes of implication and aggregation / composition to give a composite output fuzzy region. The ultimate output (expected) value can be obtained from the output fuzzy region through the process of defuzzification.

An approximate reasoning system combines the features of conditional and unconditional fuzzy propositions, the application of the relevant correlation, implication (truth transfer), aggregation / composition, and defuzzification techniques to yield a crisp expected value compatible with the meaning of the fuzzy state for each output model variable as illustrated in Figure 5.4.

In contrast to conventional rule-based reasoning or expert systems, where tasks are normally performed in series, fuzzy approximate reasoning processes are executed concurrently. Furthermore, instead of trying to reduce the number of rules to be examined as in the case of conventional systems, all propositions are simultaneously fired in a fuzzy system. During the evaluation process, those propositions that return negligible degree of truth will play no part in deriving the output expected value.

The amalgamation of approximate (fuzzy) reasoning and rule-based reasoning has offered a wide spectrum of practical applications, such as process control, systems modelling and the development of various types of inference systems. For instance, the **FCRIS** sub-system proposed in this research employs the Max-Min Compositional Method of Inference (Zadeh, 1973) to help set the target values for technical product attributes against the dynamic, quite often fuzzy and imprecise customer demands.

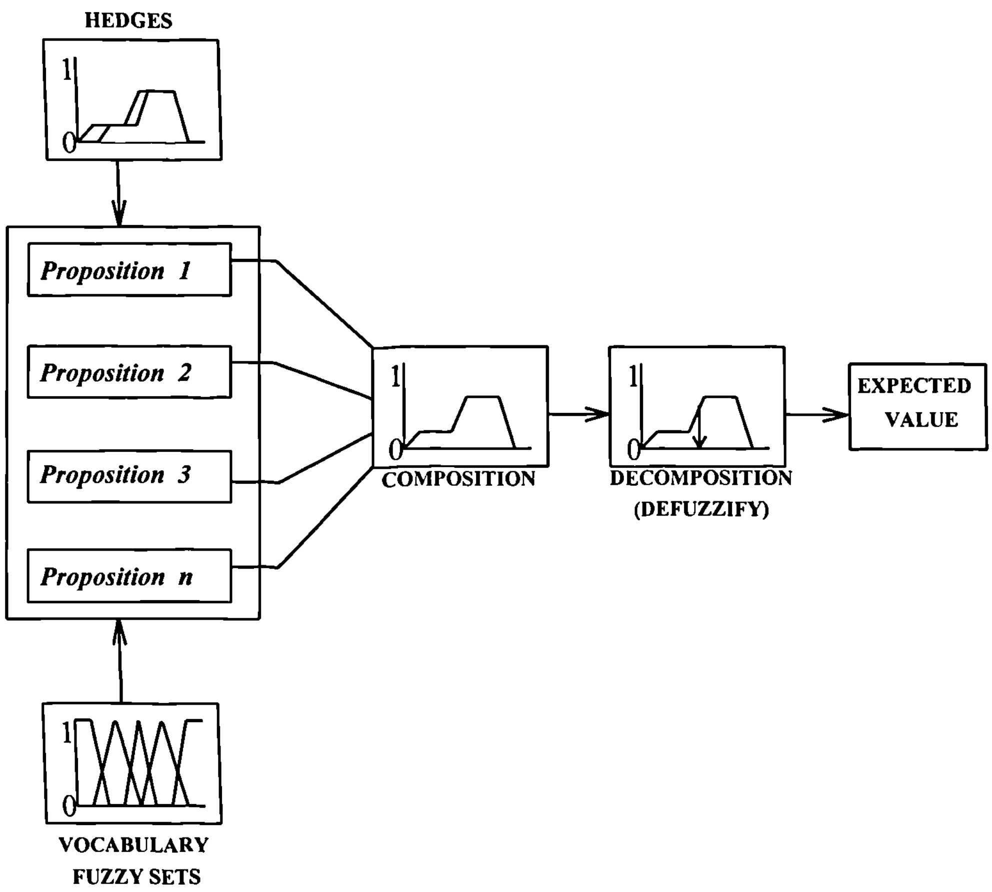


Figure 5.4: A Typical Fuzzy Inference Process
(Adapted from The Fuzzy Systems Handbook, by Earl Cox;
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5.6 The Fuzzy Inference Mechanism

A Fuzzy Inference Engine is a domain-specific knowledge base and problem-solving or reasoning algorithm which allows knowledge to be acquired and propositions to be modified during its operation. Since the propositions used by human experts are quite often imprecise or heuristic, the applications of approximate reasoning in inferring those fuzzy propositions will be discussed in the following sub-sections.

5.6.1 Conditional and Unconditional Propositions

Propositions usually connect antecedents with consequents, premises with conclusions, or conditions with actions. They are one of the basic constructs of a fuzzy inference system, specifying the relationships between model variables in the relevant fuzzy regions.

A Conditional Proposition is qualified by an *if statement*, having a general form similar to that of a rule of a conventional symbolic expert system, such as

If a is B then x is Y

where *a* and *x* are scalars from the relevant domains while *B* and *Y* are the relevant linguistic variables.

The proposition following the " *if* " term is the antecedent or predicate, while that following the " *then* " term is the consequent or the conclusion. In the content of a fuzzy system both the predicate and the consequent can be any arbitrary fuzzy propositions. The latter, *x is Y* is conditional on the truth of the predicate, that is *x* is a member of *Y* to the degree that *a* is member of *B*. This general form of a conditional fuzzy proposition can be extended with fuzzy connectors into a multiple antecedent proposition, for example

If *(a is B)* • *(c is D)* • ... • *(l is M)* *Then* *x is Y*

where "•" can be some fuzzy logic operators, such as *AND* or *OR*.

An Unconditional Fuzzy Proposition is a proposition which does not have a predicate or antecedent, and simply taking the form of

x is Y, where *x* is a scalar and *Y* is a linguistic variable.

It serves the purpose either to restrict the output space or to define a default solution source, should none of the conditional propositions execute. An unconditional proposition, say *x is Y*, can be interpreted as:

X is the minimum subset of *Y*, where *X* is a temporary fuzzy region of the model variable *x*. When the output fuzzy set *X* is empty, then *X* is restricted to *Y*, otherwise for the domain of *Y*, *X* becomes the *min (X,Y)*.

The truth values of unconditional fuzzy propositions will not be reduced before they are applied to the output space. The solution fuzzy space is updated by taking the intersection of the solution set and the target fuzzy set.

As a result of rule evaluation, those conditional and unconditional fuzzy propositions which carry some degree of truth will contribute to the final values of the output model variable set. The degree of truth from various propositions in related fuzzy regions are tied together through the Composition / Fuzzification process, whereas the functional operation used to determine the expected (output) value set from the composite output fuzzy region is called Decomposition or Defuzzification. Figure 5.4 shows the fundamental stages of a typical fuzzy inference process.

The sequence in which the propositions are executed is not important if they are all conditional or all unconditional. However, if a model contains a mixture of these two types, the sequence of execution will significantly affect the outcome. If one intends to define the boundary of the solution space in case none of the conditional propositions executes, normally the unconditional propositions should be applied first. Occasionally, the unconditional statements might be used to restrict the final solution space of a model to the maximum truth of their intersection in which case unconditional propositions are applied after all the conditional ones have been executed.

5.6.2 Monotonic / Proportional Reasoning

Monotonic or Proportional Reasoning is a basic method of fuzzy reasoning which can chain two fuzzy regions through a simple proportional implication function, such as:

If *x is Y* then *z is W*, or a transfer function, $z = f\,((x, Y), W)$.

The reasoning system can work out the expected (output) value without having to carry out any fuzzification, composition / combination nor any decomposition and defuzzification. In this case, under a restricted set of circumstances the value of the output is derived directly from a corresponding degree of membership in the antecedent fuzzy regions using a basic technique of fuzzy implication termed a Monotonic Selection.

For instance, given the membership functions for the fuzzy sets *FAST (speed)* and *HIGH (horsepower)* as shown in Figures 5.5 and 5.6 respectively, the process of projecting the required engine power of a motor car from its top speed using the monotonic selection technique of fuzzy implication can be illustrated in Figure 5.7.

Thus, the monotonic selection implication between any fuzzy domains (regions) *A* and *B* performs the following algorithm:

a) For a given element *x* in the domain *A*, its membership, $\mu_A(x)$ in the fuzzy region *A* is established.

b) In the fuzzy region *B*, the surface of manifold is found at a degree of membership corresponding to (equal to) $\mu_A(x)$. A vertical line is drawn from the corresponding point on the surface onto the domain axis. The intersecting point *z* on the domain axis will give the solution to the implication function, i.e.

$$z_B = f\,(\mu_A(x) \cdot D_B)$$

Example:

If the top speed of a motor car is 160 km/hr, its degree of membership (truth value) in the input fuzzy set *FAST* is *0.40*, i.e. the grade of truth for a Top Speed of 160 km/hr to be considered as FAST is only 40% as indicated by the corresponding fuzzy membership function shown in Figure 5.7. This truth value is projected across to the surface of the output fuzzy set *HIGH*. As a result, a corresponding estimated solution for the output model variable, i.e. 90 horsepower (hp) can be obtained from the corresponding point of intersection on the domain axis in the output fuzzy set. Similarly, for a top speed of 220 km/hr, the horsepower required can be estimated to be around 120 hp.

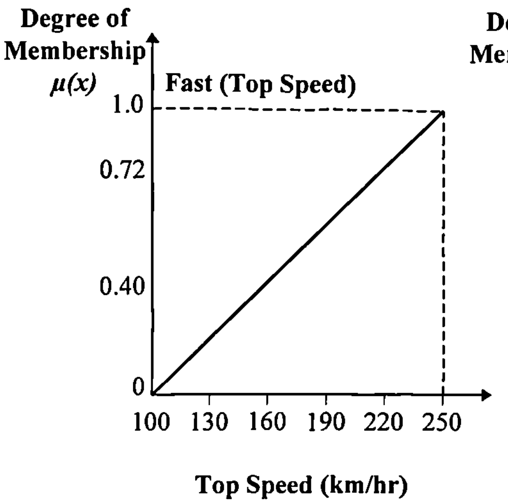

Figure 5.5: The Fuzzy Set "FAST" for the Top Speed of a Motor Car

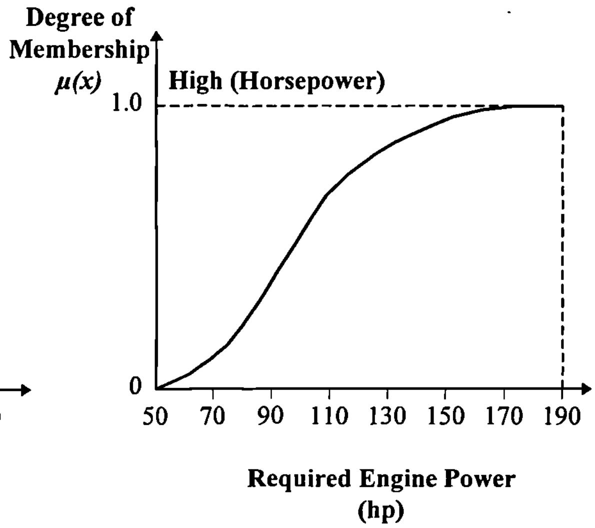

Figure 5.6: The Fuzzy Set "HIGH" for the Engine Power of a Motor Car

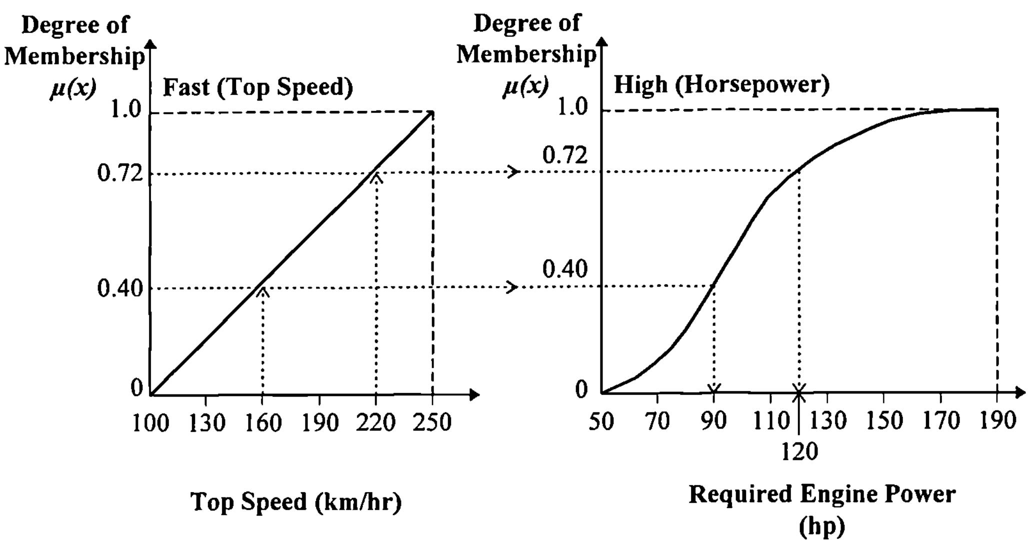

Figure 5.7: Projecting the Required Engine Power of a Motor Car from its Top Speed using Monotonic Reasoning

Monotonic reasoning works equally well with any arbitrary complex predicates, such as:

$$\textit{If} \quad (a \text{ is } B) \bullet (c \text{ is } D) \bullet \ldots \bullet (l \text{ is } M) \quad \textit{Then} \quad x \text{ is } Y$$

where the operator "•" can represent conjunction (logical *AND*) or disjunction (logical *OR*) in any of the operator classes.

As long as the aggregate truth of the predicate can be represented as a point in a fuzzy region bounded by the composite fuzzy set, the complex approximate expression can be reduced to a simple monotonic transfer function, such as:

$$x = f\ \{[(a, B), (c, D), (e, F)], Y\}$$

or in a more generalised form:

$$x = f\,(\Sigma\ (x_i, F_i) \cdot Y)$$

where the Σ operator represents a general aggregation operator acting on the variable and fuzzy set tuples to produce the fuzzy predicate truth value.

This monotonic or proportional approach to fuzzy reasoning (implication) is rather straight-forward, however it lacks a high level of orthogonality in the consequent (solution) fuzzy space. In other words, even the antecedent fuzzy set might be defined by complex expression, no formal defuzzifications or decompositions are involved with the determination of the output (expected) value, except by a direct slicing of the consequent fuzzy set at the antecedent's truth level.

Monotonic reasoning is an effective tool for linking the truth of two fuzzy regions to estimate the domain structure of one while the domain and truth value of a point in the other fuzzy region is known. However, this approach has certain limitations, such as:

- The output for the model has to be a single fuzzy variable controlled by a single fuzzy rule;
- The implication function between the two fuzzy regions has to be expressed in a correlated surface topology.

As the predicate of a proposition gets more complicated, the function of monotonic reasoning becomes inadequate, and as a result it is used in conjunction with the Compositional Reasoning approach in the proposed hybrid model in order to cope with a wider variety of scenarios.

5.6.3 Compositional Reasoning

Different approaches of fuzzy composition possess different mathematical properties and yield dissimilar results. Zadeh (1973) put forward the concept of Compositional Rule of Inference. It combines the properties of various rules of inference, such as the rules of projection, conjunction, disjunction, etc., to perform more diverse approximate reasoning, and is by far the most widely used method. This approach is ideal for dealing with fuzzy conditional inference in which the implication space is generated through aggregating and correlating the fuzzy spaces produced by the interaction of a number of rules or propositions. These rules or propositions are fired simultaneously to create an output space which contains the attributes from all the conditional propositions whose evaluated predicate truth value exceeds the prevailing alpha-cut threshold.

Relations in different fuzzy regions can be combined with each other by "composition". There are two relatively well known methods of compositional reasoning, namely the Max-Min Composition and Additive Composition. Both of them will attempt to reduce the truth of a consequent fuzzy region by the truth of the premise of the proposition before the fuzzy region for the output model variable is updated. The differences in which updates are made with the two compositional approaches as explained in the following sub-sections.

5.6.3.1 The Max-Min Compositional Inference

The Max-Min Composition is by far the most frequently used method of fuzzy inference (Zimmermann, 1991) whose principles can be defined as follows:

Let $R_1(x, y),\ (x, y) \in X \times Y$ and $R_2(y, z),\ (y, z) \in Y \times Z$ be two fuzzy relations. The Max-Min Composition of R_1 and R_2 can be given by the fuzzy set $R_1 \circ R_2$, such that

$$R_1 \circ R_2 = \{ [(x,y), \max_y \{ min \{ \mu_{R_1} (x, y), \mu_{R_2} (y, z) \} \}] \mid x \in X,\ y \in Y,\ z \in Z \},$$

and the membership function of the composed fuzzy relation can be denoted as $\mu_{R_1 \circ R_2}$.

With Max-Min Composition, the consequent fuzzy region is restricted to the minimum of the truth value of the premise by the *AND* operation, and the output fuzzy region is updated by taking the maximum of these minimised fuzzy sets by the *OR* operation (Cox, 1994). After all the propositions have been executed, the composite output fuzzy set will represent the resulting contribution from individual propositions.

The Max-Min compositional algorithm is used in the Fuzzy Customer Requirements Inference System **(FCRIS)** proposed in this research for combining the customer attributes (input model variables) to infer the necessary course of actions for each of the related engineering or product attributes (output model variables).

5.6.3.2 The Fuzzy Additive Compositional Inference

The fuzzy additive compositional operation is also a commonly used method of inference in fuzzy systems. It is similar to the Max-Min approach in that the consequent fuzzy region is reduced by the minimum truth value of the premise. However, its output fuzzy region is updated by taking the summation of the truth value from each of the minimised fuzzy sets (i.e. combining the truth membership functions). The output value is bounded between zero and one, hence it will not exceed the maximum truth value of a fuzzy set, i.e. 1.0.

For the two fuzzy relations $R_1\ (x, y),\ (x, y) \in X \times Y$ and $R_2\ (y, z),\ (y, z) \in Y \times Z$, their fuzzy addition composition can be represented as $R_1 \oplus R_2$, such that

$$R_1 \oplus R_2 = \{ (x, z), \sum_y \{ min\ [\ \mu_{R1}(x, y),\ \mu_{R2}(y, z)\ ] \} \} \mid x \in X,\ y \in Y,\ z \in Z$$

where $\sum_y$ represents the algebraic summation operator.

With the fuzzy additive composition, all the propositions contribute something towards the final output solution, unlike its max-min counterpart which will only take the maximum truth value among the predicates. The fuzzy additive composition is applicable in a large number of decision making problems, such as risk assessment, where accumulation of evidence in a fuzzy system is more essential.

5.6.4 Fuzzy Aggregation and Defuzzification

After proposition evaluation / execution, the consequent fuzzy sets relevant to a specific output model variable will be correlated and aggregated to give a composite output fuzzy set. The process of defuzzification or decomposition is then applied to establish a scalar value appropriately representing the information contained in the output fuzzy set as illustrated in Figure 5.8. In other words, a defuzzification process projects the output fuzzy set onto the output scalar set. Commonly used techniques of defuzzification include the methods of centroid, composite moments, composite maximum, composite mass, reduce entropy, and plateau positioning, etc. Irrespective of the method, the basic function of defuzzification is to select on the boundary of the output fuzzy region a point from which a "plumb line" can be dropped onto the underlying domain so that a scalar output value of the model variable can be obtained at the point where the line crosses the domain axis.

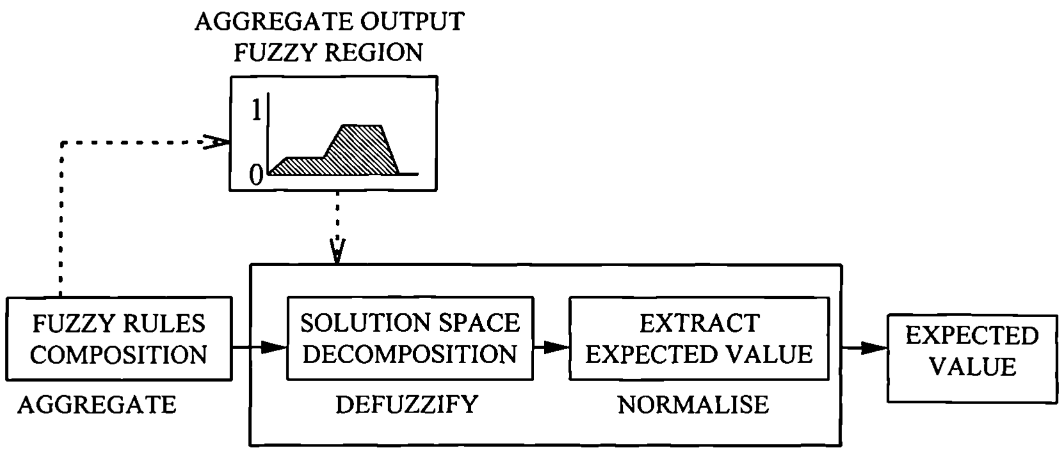

Figure 5.8: The Concept of Defuzzification / Decomposition
(Adapted from The Fuzzy Systems Handbook, by Earl Cox;
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For instance, after evaluating the following propositions,

- if a is A then W is X;
- if b is B then W is Y; and
- if c is C then W is Z,

the corresponding fuzzy regions for X, Y and Z can be aggregated to give a composite output fuzzy region W as shown in Figure 5.9. Through an appropriate method of defuzzification, the expected value (scalar output) of the fuzzy set can be obtained as the plumb-line intersects the output domain axis.

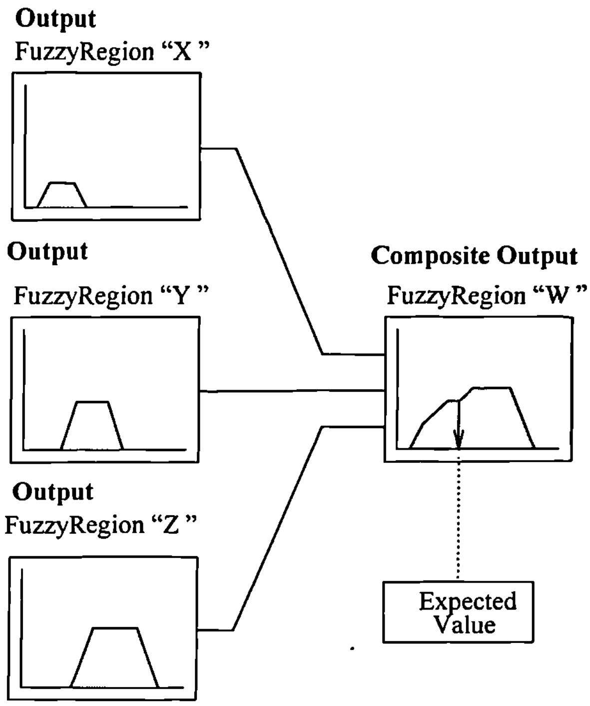

Figure 5.9: Aggregation of Output Fuzzy Regions
(Adapted from The Fuzzy Systems Handbook, by Earl Cox;
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The output fuzzy region can take the form of a continuous function as well as a singleton geometry space. In the latter case, a membership function is represented as a single support point (vertical line) in the output variable space and is identified by a label, such as fast, slow, average, etc. for the output model variable. In general, the process of implication using singletons is similar to that using continuous fuzzy sets. However, aggregation will not be required during the compositional inference of a singleton geometry model, since the singletons against different domain values cannot possibly be combined. As illustrated in Figure 5.10, a singleton represents a support point in the output space and is identified by a label, such as very slow, average, fast, etc. in the output model variable, the Top Speed. The output support points can be connected through linear interpolation for the purpose of easy presentation and they can be defuzzified to work out the expected (output) value.

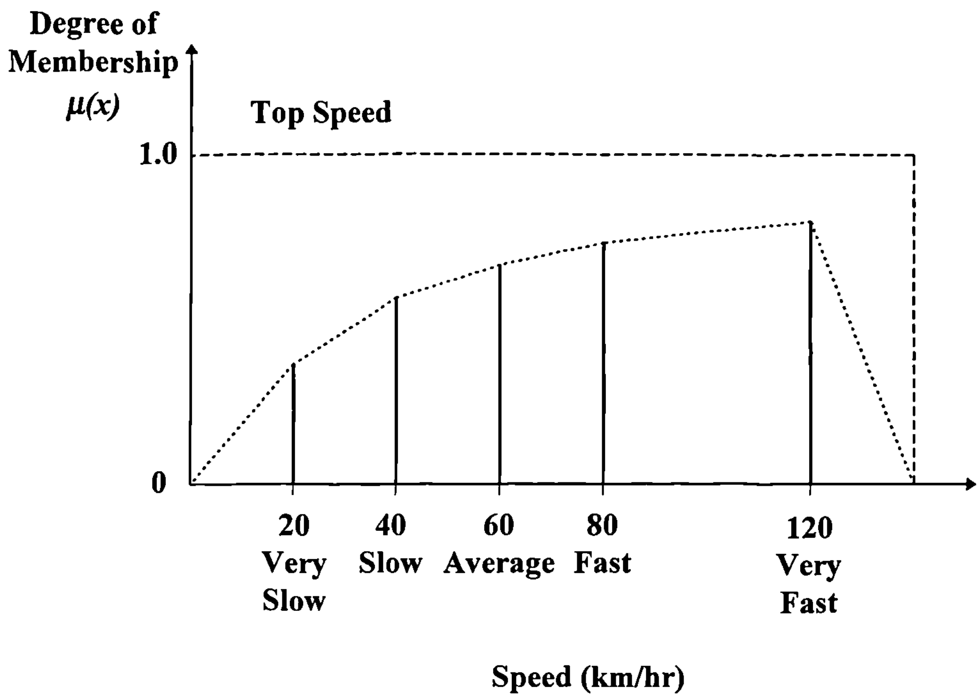


Figure 5.10: The Connected Singleton Support Points in the Output Space

In essence, the purpose of defuzzification is to find the best place along the surface of the output fuzzy set to drop the plumb line in order to decompose the output solution space and to extract the expected output value with minimum loss of information through this single point representation. The different methods of defuzzification for different circumstances and types of expectation associated with the composite output fuzzy region will be introduced in the following sub-sections.

5.6.4.1 The Centroid Method of Defuzzification

The Centroid Method of Defuzzification, also known as the Method of Centre of Gravity or the Method of Composite Moments, is to locate a point in the output fuzzy region by working out its weighted mean or its first moment of inertia, i.e.

$$\textit{Expected Value} = \frac{\sum_{i=0}^{n} d_i \cdot \mu_{(d_i)}}{\sum_{i=0}^{n} \mu_{(d_i)}}$$

where d_i is value at the i^{th} domain point and $\mu_{(di)}$ gives its degree of membership.

This technique is most commonly used because it is easy to use and can be applied to both fuzzy and singleton output set geometry.

When the output fuzzy region is represented by singleton support points, the centroid method of defuzzification can be simplified as follows:

$$\textit{Expected Value} = \frac{\sum_{i=0}^{n} d_i . \mu_{S_i}}{\sum_{i=0}^{n} \mu_{S_i}}$$

where d_i is the domain value at the singleton support point, S_i, and μ_{Si} is the corresponding truth value determined by the proportional modification according to the membership function of the predicate.

In essence, the centroid method of defuzzification selects an expected value which is supported by the knowledge accumulated from each executed proposition.

5.6.4.2 The Maximum Height Method of Defuzzification

The Maximum Height Method of Defuzzification is also known as the Method of Average Maximum, Centre of Maxima or Simple Composite Maximum. The general idea of this method is to establish the domain point with the maximum truth membership value. Should the maximum of the output fuzzy membership region lies along a plateau, its central point or the average of the maxima can be taken to obtain the output expected value as shown in Figure 5.11.

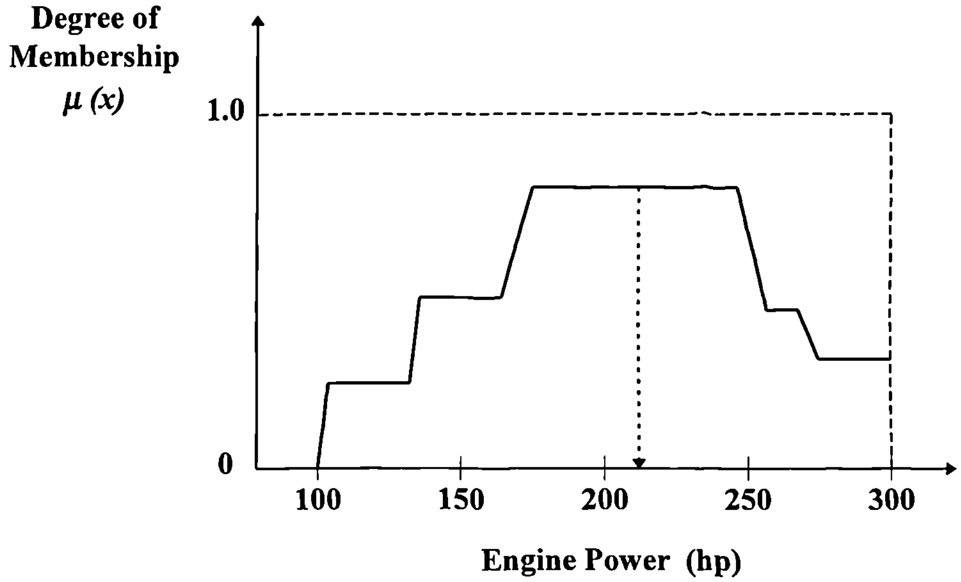


Figure 5.11: Determination of the Required Engine Power using the Maximum Height Method of Defuzzification

The scope of application for this defuzzification method is relatively narrower because the output expected value can be biased towards a single proposition which gives rise to the maximum. Besides, the output expected value might shift from one frame to another as the shape of the fuzzy region changes. However, this composite maximum technique is very suitable for those problems in which the maximum of the fuzzy property is essential. For instance, in a model for assessing the likelihood of systems breakdown in a Flexible Machining Cell which consists of a number of inter-linked equipment, the method of maximum height will yield a more sensitive and responsive result to the outstanding element (proposition) within a closely clustered set of proposition truths.

5.6.4.3 Other Methods of Defuzzification

The methods of Composite Moments (Centroid) and Composite Maximum are the most commonly used approaches of defuzzification. The former is more suitable for situations in which most of the information in the output fuzzy set is to be engulfed, while the latter is more responsive to a single dominating proposition. Under most circumstances, either one or both of these methods can be attempted first.

There are however other methods of defuzzification some of which are briefly introduced as follow:

- The **Method of Average of Maximum Values** with which the mean maximum value of the fuzzy region is taken.
- The **Method of the Average of the Support Set** with which the average of the support set (i.e. the non-zero region) for the output fuzzy region is taken.
- The **Method of Far and Near Edge of the Support Set** with which the value at the right fuzzy set edge is selected.
- The **Method of Centre of Maxima** with which the mid-point between the centres of the highest and the second highest plateau is taken. This technique is particularly useful for problems where multi-modal or multi-plateau output fuzzy region is involved. If no plateau can be found, the maximum point in the output fuzzy region will be chosen.

5.7 The Fuzzy Inference Process in the Proposed Hybrid Model

The hybrid model proposed in this research employs the concepts of approximate reasoning and rule-based reasoning to interpret the commonly ambiguous and imprecise linguistic customer attributes. In the model, the fuzzified customer attributes are submitted to rule evaluation, and the Max-Min Compositional Method of Inference is applied. After rule evaluation, sub-conclusions are drawn and aggregated to form a composite output fuzzy region which is then defuzzified using the Centroid Method. As a result, crisp target values for individual product attributes can be determined. Details of the inference process will be elaborated further in Chapters 6 and 7.

5.8 Summary

This chapter considers the various aspects of uncertainty, vagueness and imprecision that one has been facing in the description of daily problems and events, and that one has to cope with in real life phenomena. It touches on the concepts of Fuzzy Logic initially conceived by Zadeh (1964). The ideas of continuum of grades of membership commonly encountered in the process of human judgement, reasoning, and decision making have been introduced. The glossary of terms used in the hybrid model proposed in this research for mapping customer attributes are defined. The principles of fuzzy reasoning adopted in the hybrid model has also been outlined here.

Chapter 6
The Proposed Hybrid Model

6.1 Introduction

In previous chapters, the necessity and importance of being able to capture, understand and respond to the dynamic VoC have been considered. In addition, the strengths and weaknesses of some commonly used techniques for representing, analysing and interpreting customer requirements, such as the Market-Perceived Quality Profile, Customer Value Map, QFD, HoQ, Affinity Diagram, etc., have been discussed. In this chapter, a non-conventional and innovative hybrid model incorporating the principles and characteristics of Affinity Diagram, AHP and Fuzzy Set Theory will be introduced to revolutionise the approach in managing customer requirements. The proposed hybrid model will be capable of performing the following functions:

- Capturing, filtering, categorising and prioritising a given set of customer attributes;
- Mapping the customer attributes onto the relevant product attributes;
- Establishing the relative weight of importance for each product attribute; and
- Finally, determining the quantitative target value for each product attribute in response to specific customer attributes in order to guide the downstream design and engineering activities.

The operating principles and functional characteristics of the systems components in the proposed model will be discussed in details in the following sections.

6.2 Customer Attributes Establishment

The operation of the proposed model begins with the capture and organisation of the needs and wants of the customer. This information will form the basis for subsequent market analyses, requirements interpretation and product design.

6.2.1 Capturing and Categorising the Customer Attributes

In this research, a multi-stage survey involving customers from different backgrounds and market segments will be conducted in order to cover a wide spectrum of customer requirements. The scope will then be narrowed down to focus on the essential elements at later stages of the survey. The target customer groups, such as teenagers, married couples, university graduates, senior managers, decision makers, etc., have to be identified, so that questionnaires can be compiled with the relevant emphases and focus to facilitate the survey and interviews. The purpose of this multi-stage survey is primarily to solicit the customers so as to find out what they are mainly looking for from a given product, and the findings are not meant to be used for rigorous statistical analyses. Therefore, the sample size is not a crucial factor in this exercise, and it can be adjusted depending on the availability of the interviewees. Prioritisation of the findings will be required in order to ensure that the critical customer attributes can be tackled in an appropriate sequence in a structured and effective manner. During the survey, customers from each targeted customer group will be asked to express their views, opinions, comments, suggestions as well as complaints on the product being studied. Their likes and dislikes on the features and performance of the product will also be explored.

6.2.2 Processing the Findings from a Customer Survey

In the initial customer survey, the main target will be to gain a general understanding on the customer's opinions on the product. The findings from the survey will be filtered and streamlined in order to reveal the product characteristics that will appeal to the customers most, and to uncover any features that fall short of customer's expectations. At the same time, any important items which might have been overlooked during the design of the initial survey will be identified.

Based on the results and findings from the first survey, a revised and more focused set of customer attributes will be consolidated and compiled for later rounds of survey with the view to addressing the more specific issues. The Affinity Diagram technique, as explained in Section 3.5, can be applied here to help reorganise the attributes into more structured categories of customer attributes. These procedures can be computerised to facilitate data handling and subsequent updates. Besides, the customers grouping and market segmentation can be revised and reorganised as appropriate to suit different scenarios.

6.2.3 Subsequent Customer Surveys and Interviews

During subsequent customer surveys, the target customers can be arranged into focus groups in order to encourage synergetic interactions among the group members as well as facilitating the progress of the exercise. However, the group membership should be restricted so as to allow every participant to have a fair hearing and sufficient "airtime".

In a focus group survey, the interviewer will act as a facilitator to ensure that the survey is conducted effectively in a controlled fashion. The effect of intersubjectivity has to be minimised particularly when the group members happen to have conflicting views. Griffin & Hauser (1992) studied the relative effectiveness between one-to-one and focus group interviews by counting the number of unique customer attributes generated by each of the interview styles. The outcomes were mixed and far from conclusive. Besides, the choice between individual and focus group interview also depends on a number of internal and external factors, such as the availability of budget, time, interviewees, interviewers, etc.

Further surveys with specific emphases can be conducted if necessary to clarify certain key issues and seek the views and responses of the customers in certain target areas. In later rounds of survey, open-ended questions should be used as far as possible in order to allow the customers to express their opinions and speak for themselves more freely. This multi-stage approach of capturing and processing the VoC should continue until a consistent and representative set of customer attributes has been established.

6.3 Establishing the Product Attributes

Following the multi-stage survey, the customer attributes (i.e. the "what's") will then be translated into the technical language of the designers and engineers in the form of product attributes (i.e. the "hows"). In this context, the word "products" is used in a loose sense to include all services which may or may not result in any physical goods. In other words, product attributes encompass the product features, trade descriptions, engineering characteristics as well as technical specifications offered by an organisation. The product attributes can normally be established through discussions and brain-storming among the designers and engineers. Certain products attributes might be implicitly derived from the customer requirements, while others might be explicitly suggested by customers who have sufficient knowledge on the products. If similar products are already available in the market, most of the product attributes can be extracted from the features and specifications of existing offerings. On the other hand, for relative new or conceptual designs more extensive inputs from the product designers and engineers will be required so as to establish the product attributes. As explained Section 3.4, the mapping between the customer and product attributes is a two-way process which allows the upstream attributes to be elaborated or fine-tuned according to the complexity and feasibility of the downstream activities. Similar to the customer attributes, the product attributes can exist in either a qualitative or quantitative form depending upon the products and the engineering practice in the company concerned.

6.3.1 Mapping the Customer Attributes onto the Relevant Product Attributes

The mapping between the attributes begins with the definition of the performance measures or technical features for each of the key customer attributes identified from the customer surveys.

For instance, the "cylinder capacity" and the "gearbox ratios" of a motor car are the possible performance measures and product attributes that can contribute to a given customer attribute, say "powerful acceleration". Furthermore, the direction of goodness, such as "the higher the better", "the lower the better", or "target is best" should also be indicated for each product attribute in order to guide the policy of resource deployment in product development.

Traditionally, the process of projecting the product attributes is a complex process, owing to the inter-dependency among the attributes and the lack of a comprehensive approach. A more dynamic and interactive approach for analysing and mapping customer attributes, such as the interactive software routine put forward by Omar &

Popplewell (1997), can facilitate the specification of the product attributes and the construction of the relevant HoQ.

Once the product attributes have been identified, they will be categorised into hierarchies in the from of a Function Tree, as illustrated in Figure 6.1. It is the responsibility of the product development team to determine the level of sophistication at which each product attribute is to be dealt with. Analysing the items qualitatively at a higher level of the function tree will normally be less time-consuming, which might well be sufficient for QFD at the strategic level. However, these outcomes may not be able to provide sufficient details. On the other hand, for an in-depth investigation and design of a product at an operational level, analyses at a lower level of the function tree preferably in quantitative terms will be more appropriate.

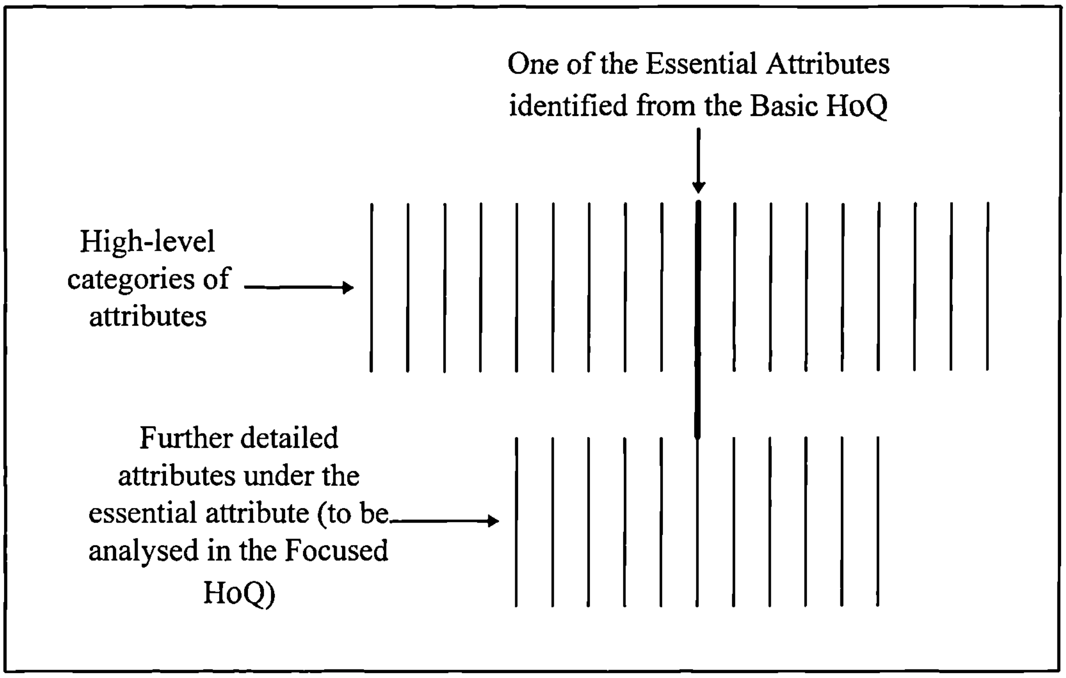


Figure 6.1: Explosion of an Essential Attribute using a Function Tree

6.3.2 Identifying and Resolving the Correlation among Product Attributes

As explained in Section 3.4, the linkage between the customer attributes and product attributes is usually a many-to-many mapping in which a product attribute might relate to a number of customer attributes, and vice versa. Similarly, certain product attributes can also be inter-dependent on and correlating to one another. Hence, substantial communications and collaborations will be required to co-ordinate the design and engineering activities.

In general, if the attributes are supporting or complementing one another, they do not normally pose too much of a problem to the design process. However, certain product attributes might interfere with one another, in which case their correlation will become negative. For instance, "powerful acceleration" and "fuel economy" are both desirable product attributes of a motor car, however they normally work against each other.

Although this research will not attempt to suggest a complete solution to resolve the conflicts in attributes correlation, due consideration has been given to alleviate any dominant negative elements as far as possible in the proposed hybrid model. One simple way of doing that is to substitute the conflicting product attributes by alternative features which can result in less overall attribute inter-dependencies. Furthermore, as discussed in Section 3.4.5, the strength of correlation between a given pair of attributes might not necessarily be bi-directional, care has to be taken in deciding which attributes are to be replaced.

6.4 Construction of the Basic House of Quality

The primary constructs of a HoQ for a given product include the customer attributes, product attributes, relationships matrix, planning matrix and correlation matrix. The architecture of this basic HoQ looks identical to a typical HoQ in any QFD exercise, however the approach proposed in this research contrasts by incorporating some well proven techniques in its construction. The essential steps in building the basic HoQ can be described as follows.

6.4.1 Categorisation and Hierarchical Analysis of the Customer Attributes

Depending on the complexity of the product and the depth of investigation required, the customer data captured through the multi-stage survey might be voluminous. Certain categorisation and prioritisation are usually necessary for arranging the data into a more co-ordinated and manageable format.

In this research, Affinity Diagrams, whose working principles and characteristics have been discussed in Section 3.5, are used for grouping the customer attributes into more structured categories.

6.4.2 Prioritisation of the Customer Attributes

In order to help focus the attention of the analysis and deploy the product development resources effectively, in the proposed hybrid model the priority among the categories of customer attributes can be identified using the Analytic Hierarchy Process (AHP) technique as discussed in Section 3.6. The prioritisation exercise can be repeated for individual attributes within each category. As a result, the categories and their attributes are organised into levels or hierarchies of criteria and alternatives so that they can be handled in turn according to their relative importance.

During the AHP exercise, customers will be asked to indicate their preferences on a number of attributes. According to previous AHP researches (Saaty, 1980, 1990 & 1994), the accuracy and consistency of an AHP exercise does not normally change significantly as the number of participants increases beyond a certain level as indicated by the Inconsistency Ratio (IR) obtained from the AHP exercise. Therefore, a group of around ten experienced and dedicated customers is recommended here, unless the inconsistency of the outcomes prompts for a larger group size.

An AHP exercise normally starts with pairwise comparisons. In this research, individuals are asked to indicate their view on the relative importance of each pair of attribute categories in turns in either qualitative or quantitative term through an user interface offered by a proprietary AHP software, Expert Choice. Details of the process will be illustrated in the Case Study presented in Chapter 8. The relative weight of importance of each category can be worked out to a known Consistency Ratio. Based on the results of experiments and tests, Saaty (1994) concluded that the outcomes from an AHP exercise can be considered reasonably reliable and acceptable as long as the Consistency Ratio converges to a value below 0.01.

The AHP exercise is performed again to prioritise the items within each category in order to work out the relative weights of importance of individual customer attributes within the specific category. The results can be entered alongside their respective category or attribute on the left hand side of the basic HoQ as shown in Figure 6.2.

6.4.3 Establishment of the Relationships between the Customer Attributes and Product Attributes

The next task in constructing the basic HoQ is to enter the relevant relationships between the customer attributes and the product attributes into the Relationship Matrix.

Identifying the relationships between the customer and product attributes requires team effort from different departments including sales, marketing, design, engineering, etc. It is not unusual to find that while a product attribute contributes positively towards satisfying some customer attributes, it may well be jeopardising or undermining the effectiveness of other attributes. Hence, the relationships can be positive as well as negative. Should the negative elements become too dominant, certain attributes would have to be substituted so as to reduce the negative elements and alleviate the conflicts in a way similar to the approach described in Section 6.3.2. For the basic HoQ, the attributes relationships can be represented in qualitative terms according to the 1-3-9 Scale or other suitable grading systems as explained in Section 3.4.4. A typical relationship matrix can be shown in Figure 6.2.

6.4.4 Determination of the Performance Targets for the Customer Attributes

In order to help effectively deploy the company resources against a set of customer attributes, the technical as well as commercial capability of the company needs to be assessed. To do that, inputs from relevant departments in the company, data on competitors' current performance, and customer perceptions on the competing products need to be considered. Through marketing survey, the Company's Own Rating (i.e. the company's performance rating in the eyes of the customers) on each particular customer attribute can be revealed. After a series of analyses and calculations as described in Section 3.5.2, the corresponding Planned Level (representing the company's target performance rating) can be determined. Hence, the Improvement Ratios can be worked out.

Having determined the targets of improvement, the company will be in a position to evaluate its own opportunities in capitalising on individual customer attributes and expressing them in terms of Sales Points, bearing in mind that not all the customer attributes can bring about equal sales returns to the company.

Finally, the Relative Weight of Importance for the customer attributes can thus be calculated. These values are normalised so that their total will amount to 100% so as to ease subsequent analyses. The Planning Matrix in the HoQ is thus fully established.

In addition, as explained in Section 3.4.2, customer perceptions on the performance of the products offered by the major competitors against the customer attributes revealed from previous surveys and interviews can also be displayed in a chart alongside the Planning Matrix as shown in Figure 6.2.

6.4.5 Determination of the Relative Weight of Importance for the Product Attributes

Based on the Relative Weights of Importance of individual customer attributes and the entries to the relationships matrix, the Relative Weights of Importance for the product attributes can be calculated and normalised into percentages in a way as described in Section 3.4.6. The results are entered at the bottom part of the HoQ.

6.5 Further Investigations on the Major Customer Attributes

The construction of the basic HoQ is now completed. A general picture of how customer attributes are captured, projected and related to the appropriate product attributes has been given. The establishment of the relationships, correlation and relative weights of importance for the customer and product attributes have also been discussed in some depth here.

From a functional viewpoint, the basic HoQ offers an overall view of how the customer attributes can possibly be met. Typical HoQ analyses and practices in most companies normally terminate at this point. However, in the proposed hybrid model, this basic HoQ only represents the starting point of a series of investigations which include customer requirements analysis, knowledge representations, fuzzy inference and design target setting for individual product attributes / technical features.

As it can be imagined, when a more complicated product is being considered, the volume of data held in the HoQ would become very congested to the extent that the key issues might well be over-shadowed. Owing to limited company resources, certain trade-offs have to be made to ensure that the resources are being deployed most effectively. In the proposed hybrid model, the more essential customer and product attributes identified in the basic HoQ will be extracted and submitted to further work which commences with the construction of the Focused HoQ as discussed below.

6.5.1 Construction of the Focused House of Quality

The structural framework of the Focused HoQ is similar to that of the basic HoQ, however more detailed quantitative analyses will be carried out to help establish its basic constructs. The Affinity Diagram will be applied again to regroup the more crucial customer attributes. A pairwise comparison exercise is performed once more on the customer attributes, and the findings are further analysed using the AHP technique supported through the software package, Expert Choice. The resulting Relative Weights of Importance for the customer attributes are normalised and expressed in percentages.

One of the distinct merits in this focused HoQ lies in the fact that the attribute relationships are established quantitatively, instead of relying on qualitative interpretation, such as the symbolic 1-3-9 scale used in the basic HoQ. The attribute relationships are worked out based on the contributions and thus the importance of individual product attributes towards the fulfilment of the customer attributes. AHP plays an important role in determining the quantitative entries in the Relationship Matrix. One of the possible ways of conducting pairwise comparisons between the product attributes of a hi-fi system with respect to the customer attribute, say "powerful output" can be illustrated in Figure 8.6 later in the Case Study (Chapter 8). The priorities of the product attributes worked out from the AHP exercise as shown later in Figure 8.7 are then multiplied by the Relative Weight of Importance of the corresponding customer attribute explained in the last paragraph. The quantitative results against each specific customer attribute are entered into the relevant row of the Relationships Matrix. The procedures are repeated for every customer attribute (i.e. row by row) until the entire matrix is completed.

Eventually, the Relative Weight of Importance for each product attribute in the focused HoQ can be worked out by summing up the numerical entries in the corresponding column in the Relationships Matrix as shown in Figure 8.7. These values support the setting of more objective and reliable priority for deploying design and development efforts among competing product attributes.

6.5.2 Establishment of the Target Values

The construction of the Focused HoQ is nearly finished except its bottom row, the Target Values. **A Target Value represents the definitive and quantitative technical specification for a given product attribute required to satisfy a given set of customer attributes.**

Example:

In the design a motor engine, the "output horsepower", "cylinder size" and "compression ratio" are among the major product attributes for which specifications or target values have to be determined prior to product further development.

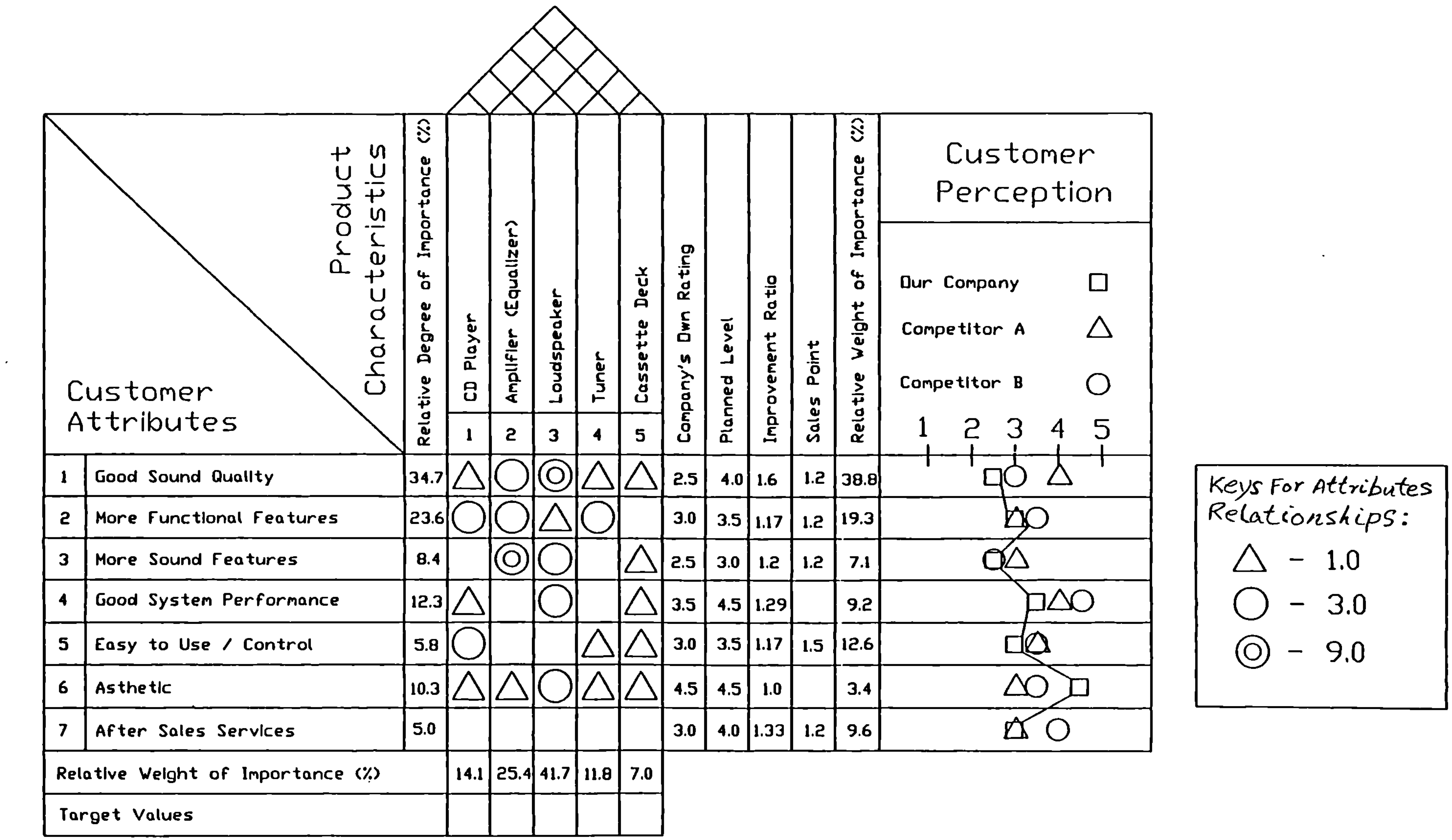


Figure 6.2: A House of Quality (HoQ) for the Design of Mid-Range hi-fi's

As discussed in Sections 3.4.7 and 3.4.8, Target Values are essential for determining the specifications and performance measures for relevant product features versus a given set of customer requirements. Traditionally, the task of setting the design targets relies primarily on the professional experience, intuition and "gut feel" of the designers and engineers. Hitherto, no robust and scientific formulae or methodologies have been available to systematically and effectively direct the customer requirements towards the determination of quantitative design specifications.

This thesis puts forward a novel and intelligent approach for interpreting the linguistic, and often vague and imprecise customer requirements through a series of well proven techniques and methodologies to enable the design targets to be determined swiftly, quantitatively and consistently.

In this research, the Target Values for product attributes are determined through a fuzzy inference process. To facilitate the approximate reasoning exercise, the marketing information, customer requirements, product features and technical know-how of the engineers and designers previously built into the relevant knowledge bases will be called upon.

6.6 The Fuzzy Customer Requirement Inference System

Imprecision, inexactness, ambiguity, uncertainty and vagueness quite often hinder human description of physical and conceptual phenomena (Cox, 1994). The VoC or customer attributes, which are normally expressed in semantic terms, often inherit and exhibit some forms of imprecision and vagueness. In this research, a fuzzy inference process supported by a mathematical model is used to interpret the qualitative and imprecise customer attributes into some quantitative targets values for the product attributes by amalgamating the knowledge of the customers and the product designers.

The proposed concepts are realised through the development of a hybrid artificial intelligence model, the Fuzzy Customer Requirement Inference System (**FCRIS**). An overview of the framework and functional components of **FCRIS** has been revealed in Chapter 4.

6.6.1 The Basic Constructs of FCRIS

FCRIS essentially consists of three major systems building blocks, namely

- the User Interface,
- the Knowledge Base, and
- the Inference Engine.

The Knowledge Base captures the opinions, experience and technical know-how of the customers and designers. Through a friendly systems interface, the knowledge can be continually revised and supplemented as the product becomes more mature, and as the market feedback and design experience are accumulated. The knowledge base is partitioned into three logical sectors, namely

- **K-CA**, Knowledge on the Customer Attributes,
- **K-PA**, Knowledge on the Product Attributes, and
- **K-CA-PA**, Knowledge of the Relationships between the Customer Attributes and Product Attributes.

Both **K-CA** and **K-PA** are expressed in Fuzzy Sets described by their relevant Membership Functions, while the rule base **K-CA-PA** represents the relationship between the customer attributes and product attributes in the form of Fuzzy Propositions.

FCRIS is a generic system which can be applied to different products or services as long as the relevant product information has been incorporated into the systems knowledge base and rule base. These knowledge bases require frequent updates in order to reflect the state-of-the-art development of the products. Once these basic data have been established, the system will be ready to deal with any specified customer attributes and work out the technical targets for the corresponding product design features.

6.6.2 An Overview of the Fuzzy Inference Process in FCRIS

The fuzzy inference process is triggered by the input of specific customer attributes through the User Interface. The customer data will then be fuzzified and qualified as appropriate by the relevant hedges, and expressed as input fuzzy regions prior to being submitted to the Rule Evaluation routine. Relations in different input fuzzy regions are then combined by merging (composing) the properties of various rules of inference during fuzzy reasoning. The principles of Compositional Rule of Inference, which is a combination of the Projection Rule and Conjunction Rule put forward by Zadeh (1973), has been adopted in this research.

There are different methods of fuzzy composition which have different mathematical properties and can generate dissimilar results. Max-Min Composition and Additive Composition are two of the more commonly used methods of implication in fuzzy systems. They both tend to restrict the consequent fuzzy region to the minimum of the truth of the premise of a proposition. However, as explained in Section 5.6.3, the two methods differ in the ways in which the output fuzzy region is updated. The

Max-Min compositional operation takes the maximum among the output fuzzy sets as implied by the maximum truth of the predicate, while the Additive method sums up the truths of individual fuzzy sets.

The Max-Min Method of Composition is employed in **FCRIS** to cope with the fuzzy conditional inference in which the implication space is generated through aggregating and correlating the fuzzy spaces produced by the intersection of a number of rules or propositions. During the inference process, the rules / propositions are fired simultaneously to create an output space that contains all the attributes from the conditional propositions whose evaluated grade of certainty exceeds the respective alpha-cut thresholds. As a result, a number of sub-conclusions can be drawn.

After rule evaluation, all the sub-conclusions are aggregated to give a complete conclusion for each output model variables (product attribute), e.g. the "output power of a motor engine". The conclusion will then be defuzzified in order to work out a crisp output which represents the quantitative Target Value for the particular product attribute. This value sets the target for the related design and engineering activities in order to fulfil the specific set of customer attributes.

Example:

In the design of a motor engine, if the specified linguistic customer requirements, such as "fast acceleration", "fewer gear changes", "reasonable fuel economy", etc. are to be satisfied simultaneously, a minimum target output power, say 100 hp, has to be delivered by the motor engine.

6.7 Mathematical Modelling for FCRIS

In order to put **FCRIS** into practice, a mathematical model based on fuzzy sets and matrix computations is developed to handle the necessary data manipulation. The matrix representations have the advantage of being simple in nature and easy for software programming. The mathematical model of fuzzifying the input space, evaluating the fuzzy rule-base, aggregating the resulting sub-conclusions to give a composite output fuzzy region and ultimately defuzzifying the region to yield the required target values will be discussed in details in Chapter 7.

6.8 Software Programming for FCRIS

The procedures and algorithms of **FCRIS** described above have been coded into an object-oriented software programme using C++ language. The system is menu driven, running on personal computers with straight-forward user interfaces to allow easy input and maintenance of the fuzzified customer attributes and specification of the suitable hedges, interactive establishment of the relevant membership functions as well as regular updates of the knowledge and rule bases. The inference process can be invoked interactively, and its ultimate output will take the form of a crisp target value for each relevant product attribute. A detailed description of the logic and data flow in **FCRIS** is given in Appendix I, and the related systems operating instructions can be found in a comprehensive User Guide given in Appendix II.

6.9 Case Study for FCRIS

In addition to the illustrative examples given in Chapters 6 and 7 during the explanation of the hybrid model, a detailed Case Study describing the design of a range of hi-fi equipment will be presented in Chapter 8. It gives a full-blown demonstration of the hybrid approach proposed in this research, covering the acquisition and analysis of customer requirements, the interpretation of the requirements into technical product features, and finally the determination of the target values for individual product features.

6.10 Summary

This chapter gives a detailed account of the hybrid model proposed in this research which extends the application of QFD beyond its traditional roles of purely mapping the customer attributes onto product attributes qualitatively. Instead, a quantitative routine for projecting the linguistic customer attributes onto crisp design targets has been introduced. This approach provides a much more in-depth treatment of the VoC, covering right from the capturing, categorising, and filtering of the customer attributes, and the identification, prioritisation of the relevant product attributes using a basic and a Focused HoQ. In the end, the quantitative target value for each product / design attribute is worked out using fuzzy inference. Well proven principles and techniques including Affinity Diagram, AHP, Fuzzy Sets Theory are incorporated to construct the inference system, **FCRIS.** A mathematical model using matrix computations has been developed to support the data manipulations in the fuzzy inference process. The algorithm has been coded into an object-oriented software system with friendly user interfaces. The hybrid model put forward in this research is essentially a comprehensive tool which allows the engineering and technical specifications for a product to be established systematically and consistently in response to changing customer requirements in the dynamic and fiercely competitive market.

Chapter 7

Modelling of the Fuzzy Customer Requirement Inference System

7.1 Introduction

In Chapter 6, the operating principles of the proposed hybrid system are explained. Among various methodologies and techniques incorporated in the proposed system, fuzzy inference is the major mechanism for mapping the customer requirements onto the relevant product specifications. The concepts have subsequently been coded into a software system, **FCRIS**. In this chapter, the functional description of the fuzzy inference process in **FCRIS** is described in quantitative terms, and the mathematical representation of the system will be discussed and exemplified.

7.2 The Data Representation in FCRIS

The problem domain in **FCRIS** takes care of the interpretation of customer attributes into the relevant product attributes and the determination of their corresponding target values using fuzzy inference. Each attribute is represented by a model variable which is in turn described by the relevant linguistic variables in individual and sometimes overlapping fuzzy sets. The meaning of these fuzzy sets can be enriched by appropriate hedges or qualifiers in order to accommodate the possible ambiguity, vagueness, imprecision and inexactness commonly innate in the semantics of the VoC. The fuzzy representation of the basic constructs of **FCRIS** can be described as follows.

7.2.1 The Fuzzy Space of Customer Attributes, *V*

The set of customer requirements (attributes) of a given product can be denoted by an *N*-dimensional fuzzy vector *X*, such that

$X = (X_1, X_2, \ldots, X_N)$ in the fuzzy space of *V*,

where $V = V_1 \times V_2 \times \cdots \times V_N$, and "$\times$" is the Cartesian product operator,

i.e. the i^{th} input model variable (customer attribute) X_i of a given product, for instance, the *"Top Speed"* of a motor car, can be defined in the crisp set V_i $(i=1,2,\ldots,N)$ which represents the corresponding universe of discourse, say from 100 km/hr to 250 km/hr.

For each customer attribute X_i, a linguistic variable d_i $(i=1,2,\ldots,N)$ exists in the set of all real numbers, ***R***. It represents the relative weight of importance (priority) of X_i in the set of customer attributes *X*. This priority may be specified directly by the customers themselves or established through analytical means, such as the AHP technique employed in this research. Hence, for the input fuzzy vector *X*, there exists a real vector *d* which represents the relative weights of importance for the various customer attributes, such that $d = (d_1, d_2, \ldots, d_N)$.

7.2.2 The Space of Product Attributes, *P*

Similarly, the set of model variables representing the product / engineering attributes can be denoted by an *M*-dimensional fuzzy vector *Y*, such that

$Y = (Y_1, Y_2, \ldots, Y_M)$ in the fuzzy space of *P*,

where $P = P_1 \times P_2 \times \cdots \times P_M$, and "$\times$" is the Cartesian product operator, i.e. the i^{th} output model variable (product attributes) Y_i , for instance the *"Engine Power"* of a motor car, can be defined in the crisp set P_i $(i=1,2,...,M)$ which covers the corresponding universe of discourse, say from 50 hp to 125 hp. The relative weights of importance of the relevant product attributes can be represented by a real vector *w*, such that $w = (w_1, w_2, ..., w_M)$.

7.2.3 The Rule-Base Inter-Relating the Customer and Product Attributes

For a given product, the relationships between the set of customer attributes, *X* and the set of product attributes, *Y* can be described by a number of fuzzy inference rules / propositions in an " *if-then* " format. These propositions describe the relationships between the linguistic variables of the customer attributes (input model variables) and those of the product attributes (output model variables).

Example:

"If the Top Speed of a motor car is rather fast and its Seating Capacity is fairly large, then the required Engine Power would be reasonably high".

The general form of a typical fuzzy inference rule can be expressed as follows:

R_i : If $(X_{i1}$ *is* x_{i1}, *and* X_{i2} *is* x_{i2}, *and* ..., X_{ik} *is* $x_{ik})$, then Y_i is y_i,

where x_{i1}, x_{i2}, ... and x_{ik} are the linguistic variables corresponding to the input model variables X_{i1}, X_{i2}, ... and X_{ik} respectively, while y_i is the linguistic variable applicable to the output model variable, Y_i.

For each of the rules R_i $(i = 1,2,..., k)$ in the fuzzy rule base, there exists a linguistic variable r_i defined in the interval [0,1]. It represents the Certainty Factor which denotes the confidence of the product engineers or designers on the rule, R_i.

7.3 The Functional Description of FCRIS

The fuzzy inference process in **FCRIS** is the mechanism for projecting the output target value for each specific product / engineering attribute by executing the fuzzy rule base against an input set of customer attributes. The Schematic Representation and the Architecture of **FCRIS** can be shown in Figures 7.1 and 7.2 respectively. The implementation and application of the system take a number of logical stages as explained in the following sub-sections.

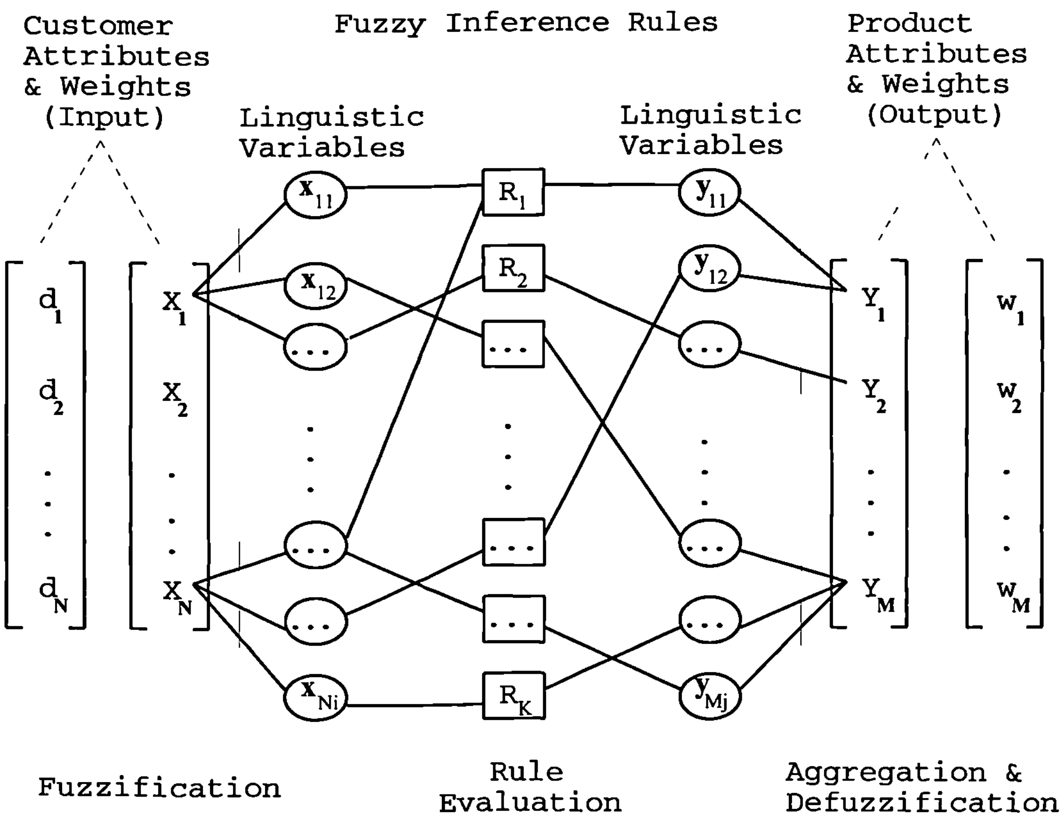
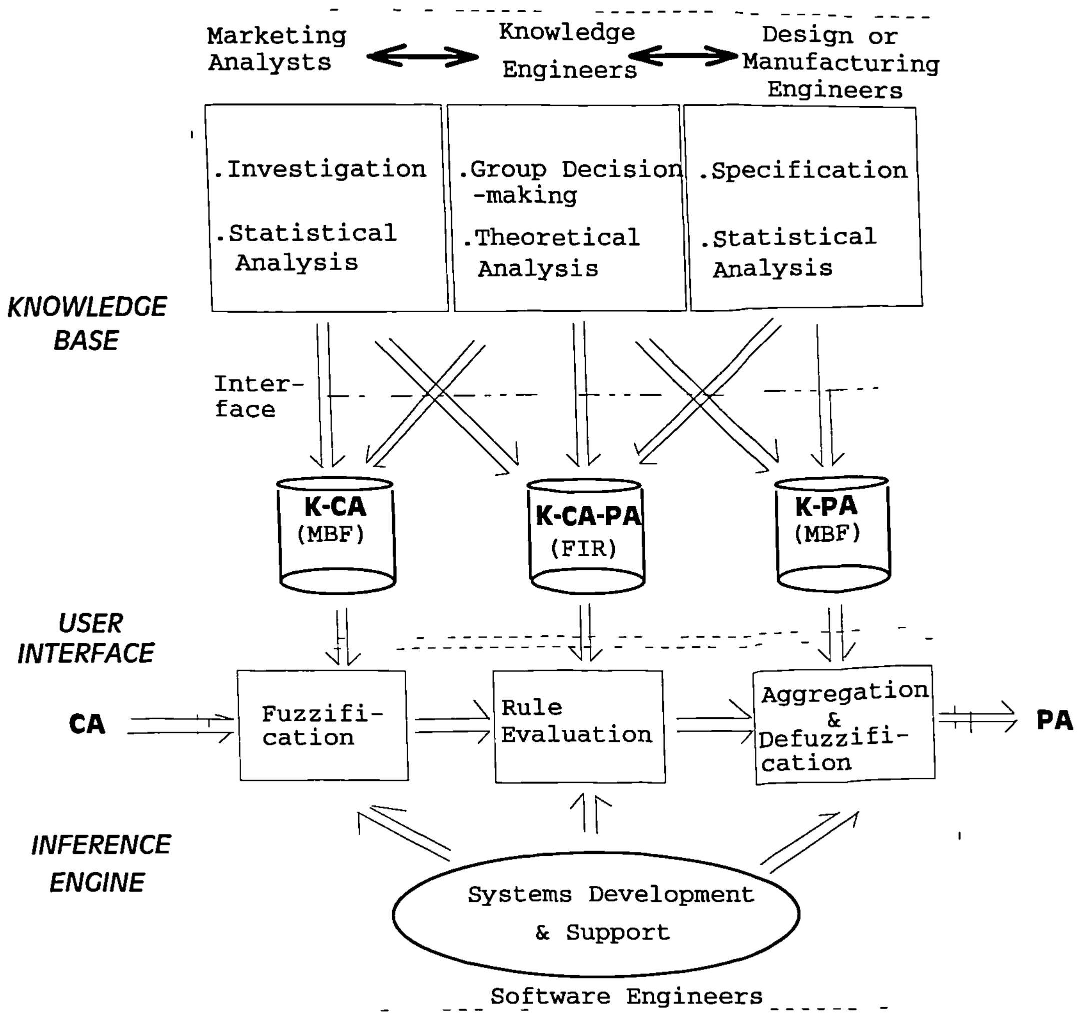


Figure 7.1: The Schematic Representation of FCRIS



CA : Customer Attributes / Customer Requirements (Inputs)
PA : Product Attributes / Engineering Characteristics (Outputs)
K-CA : Knowledge about Customer Attributes / Requirements
K-PA : Knowledge about Product Attributes / Characteristics
K-CA-PA: Knowledge about the Relationships between CA and PA
MBF : Membership Functions
FIR : Fuzzy Inference Rules / Propositions

Figure 7.2: Architecture of the Fuzzy Customer Requirement Inference System (FCRIS)

7.3.1 Fuzzification of the Customer Attributes

In this stage, the customer attributes and their respective relative weight of importance are fed into the system through a users interface. The data are then transformed into fuzzy numbers or fuzzy sets with the knowledge held in **K-CA**. During this transformation, specifications against individual customer attributes are converted into the respective grades of certainty (degrees of membership) against the relevant membership function of the corresponding input linguistic variables in the fuzzy sets. These grades of certainty are regarded as the basic "facts" of the fuzzy inference process.

7.3.2 Evaluation / Execution of the Fuzzy Rule-Base

The fuzzy sets or membership functions established during the fuzzification of customer requirements are evaluated against the premise (conditions part) of the fuzzy inference rules held in **K-CA-PA**. As a result, sub-conclusions are drawn as the grade of certainty (truth) of a predicate in the rule exceeds a pre-set alpha-cut threshold, and the rule is then fired. The procedures of fuzzy rule evaluation can be outlined as follows.

a) Evaluating the Premise of a Rule

The grades of certainty of the predicates in the premise of the rule R_i are given by:

The grade of certainty of "X_{i1} *is* x_{i1}" *is* g_{i1} ;

The grade of certainty of "X_{i2} *is* x_{i2}" *is* g_{i2} ;

... ;

The grade of certainty of "X_{ik} *is* x_{ik}" *is* g_{ik} respectively,

according to Fuzzy Set Theory (Zimmermann, 1987), the overall grade of certainty of the premise will take the minimum among the individual grades of certainty of the predicates. Hence, the overall grade of certainty, g_i in the premise of R_i can be denoted as:

$$g_i = Min \{ g_{i1} , g_{i2}, \dots , g_{ik} \}$$

b) Determining the Grade of Certainty of the Consequent (Conclusion Part) of the Rule

For the rule R_i, the grade of certainty of its consequent will be the same as the overall grade of certainty, g_i of its premise. Hence, the grade of certainty of the consequent "Y_i is y_i" is also equal to g_i.

7.3.3 Aggregation and Defuzzification of the Output Fuzzy Regions

After rule evaluation, the sub-conclusions are aggregated into an output fuzzy region. This region will be defuzzified according to the knowledge held in **K-PA** to yield an expected output which represents the deterministic crisp target value for the relevant product attribute.

Example:

The k sub-conclusions related to the product attribute, Y_i drawn from the rule evaluation exercise can be expressed together with their respective relative weights of importance in the form of:

$$Y_j \text{ is } y_{j1} : g_{j1}, w_{j1} ;$$
$$Y_j \text{ is } y_{j2} : g_{j2}, w_{j2} ;$$
$$\dots ;$$
$$Y_j \text{ is } y_{j3} : g_{j3}, w_{jk} .$$

These sub-conclusions can be amalgamated to give a complete output conclusion "Y_j is $y'_j : w_j$" as shown in Figure 7.3, where y'_j is the aggregated and defuzzified output value of Y_j, and w_j is the relative weight of importance of the product attribute Y_j.

The Centroid Method of Defuzzification is adopted for the examples and case study in this research. In fact, different methods of defuzzification as outlined in Section 5.6.4 can be selected to suit various problem domains as well as the preference of the decision makers.

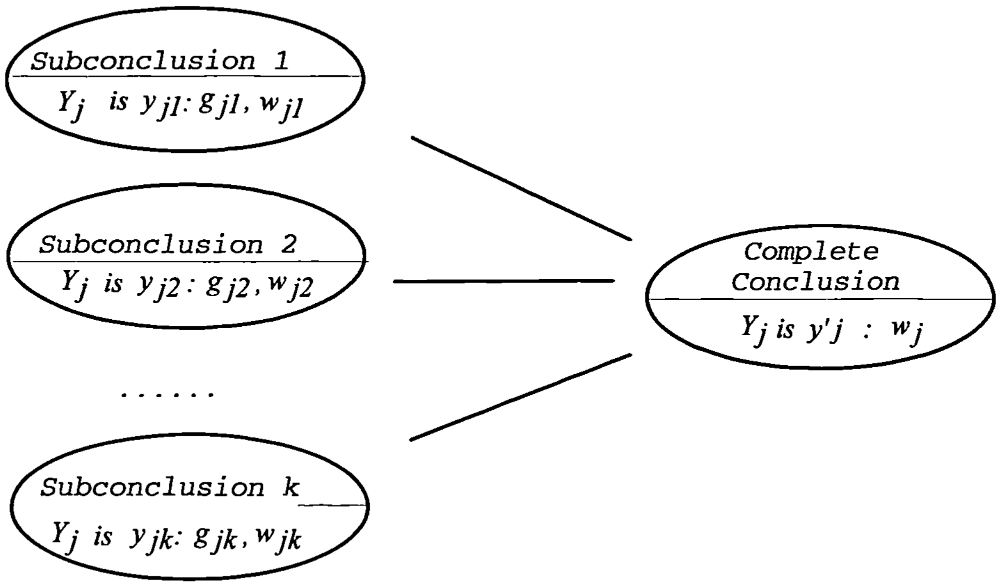


Figure 7.3: Aggregation of the Subconclusions to yield a Complete Conclusion for a given Output Model Variable

7.4 Mathematical Modelling of the Fuzzy Inference Process

The conceptual and functional design of **FCRIS** has been described in depth in the above sections. In order to put the design into practice, the various functions have to be expressed in mathematical terms to facilitate data manipulation and subsequent software development. Since the membership functions of fuzzy sets are expressed in vectors in the proposed model, mappings of the fuzzy relationships will naturally take the form of multi-dimensional matrices. Therefore, Linear Algebra becomes an obvious choice for modelling **FCRIS** because it is simple to describe, easy to understand and the resulting algorithms are more readily transformed into programming codes to facilitate software development.

The mathematical representation of the fuzzy data manipulations in the proposed system will be introduced in the following sub-sections.

7.4.1 Discretisation of the Fuzzy Spaces for Customer and Product Attributes

In the proposed fuzzy inference process, the spaces of customer attributes and product attributes are denoted by V and P respectively. The sets of universes of discourse V_i $(i=1,2,...,N)$ and P_j $(j=1,2,...,M)$ in the fuzzy spaces V and P can be subdivided into a finite number of domain elements by points discretisation.

Example:

If there are n_i domain elements in the universe of discourse V_i, and m_j domain elements in the universe of discourse P_j after discretisation, they can be represented as follows:

$$V_i = \{v_{i1}, v_{i2}, \cdots, v_{in_i}\} \quad (i=1,2,...,N), \tag{1}$$

and

$$P_j = \{p_{j1}, p_{j2}, \cdots, p_{jm_j}\} \quad (j=1,2,...,M) \tag{2}$$

respectively, where $v_{i1}, v_{i2}, \cdots, v_{in_i}$ and $p_{j1}, p_{j2}, \cdots, p_{jm_j}$ are discrete points in the domains of the respective fuzzy spaces. Fuzzy sets representing the linguistic variables for the customer or product attributes (model variables) will return a "grade of certainty" against each of the domain points in the respective universe of discourse.

7.4.2 Matrix Representation of the Fuzzy Inference Process

The fuzzy inference process consists of the stages of fuzzification, rule evaluation, aggregation and defuzzification, and the activities in each stage can be described mathematically as follows.

7.4.2.1 Defining the Input and Output Model Variables (Attributes)

Based on the findings of the previous customer surveys, the customer attributes are fuzzified according to the term sets (sets of linguistic variables) of the relevant model variables and modified by the fuzzy hedges as appropriate.

A general linguistic variable (fuzzy set) x_i for the customer attribute X_i defined on the universe of discourse V_i in the fuzzy space of V can be denoted by a membership function, A_i, such that

$$A_i = (\mu_{i1}, \mu_{i2}, \cdots, \mu_{in_i}) \quad (i=1,2,...,N) \tag{3}$$

where μ_{il} $(l = 1,2, ..., n_i)$ is a real number from the interval [0,1] representing the grade of certainty for the fuzzy set x_i at the domain point v_{il} in V_i.

Similarly, any specific customer requirement corresponding to model variable X_i $(i=1,2,...,N)$ can be described by a specific fuzzy set A'_j, such that

$$A'_i = (\mu'_{i1}, \mu'_{i2}, \cdots, \mu'_{in_i}) \tag{4}$$

On the other hand, for the corresponding product attribute Y_j, there exists a linguistic variable y_{jl} defined over a specific domain in the universe of discourse of P_j in the fuzzy space of P. The membership function of y_{jl} $(l = 1,2,...,m_j)$ $(j = 1,2,...,M)$ can be expressed as:

$$B_{jl} = \left(\eta_{j1}, \eta_{j2}, \cdots, \eta_{jm_j}\right) \tag{5}$$

7.4.2.2 Representing and Evaluating the Fuzzy Rule-Base

A general fuzzy rule, R_i relating a number of customer attributes X_i with linguistic variables x_i $(i = 1,2, ..., N)$ to a product attribute Y_j with linguistic variable y_{jl} can be expressed as:

R_i: *If* X_1 *is* x_1, *and* X_2 *is* x_2, *and...,* X_N *is* x_N,

then Y_j *is* y_{jl} $(j = 1,2, \ldots, M)$ *and* $(l = 1,2, \ldots, m_j)$ (6)

and, the confidence of the designers / engineers on this rule can be denoted by a Certainty Factor, r_i.

A fuzzy sets x_i describing the model variable X_i can be represented by a membership function A_i, such that $A_i = (\mu_{i1}, \mu_{i2}, \cdots, \mu_{in_i})$ $(i=1,2,...,N)$. If a given customer attribute X_i does not appear in the premise of a rule, it can be described by a unit fuzzy set x_i with a unit membership function $A_i = (1,1,...,1)$ in order to maintain uniformity in subsequent matrix computations.

Hence, the premise (condition part) of the rule R_i as described in (6) can be represented by a Conditions Matrix C_i, such that $C_i = A_1 \times A_2 \times \cdots \times A_N$ (the Cartesian product of A_1, A_2, ..., A_N) in the set of real numbers $\mathbf{R}$, i.e.

$C_i \in \mathbf{R}^{n_1 * n_2 * \cdots * n_N}$. In other words, C_i is an N-dimensional matrix with a total of $n_1 * n_2 * \ldots * n_N$ entries, each of which can be defined as:

$$
\begin{aligned}
&c_{j_1 j_2 \cdots j_N} = \mu_{1 j_1} \wedge \mu_{2 j_2} \wedge \cdots \wedge \mu_{N j_N}, \\
&\forall \quad j_1 = 1,2,\cdots,n_1; \quad j_2 = 1,2,\cdots,n_2; \quad \cdots; \quad j_N = 1,2,\cdots,n_N
\end{aligned} \tag{7}
$$

where " $\wedge$ " is the logical AND operation (minimisation operation).

Furthermore, a Conditions Vector $\overline{C}_i$ can be derived from the matrix C_i with entries:

$$
\begin{aligned}
&\bar{c}_i = c_{j_1 j_2 \cdots j_N} \\
&where \quad i = [\{[(j_1 - 1) * n_2 + (j_2 - 1)] * n_3 + (j_3 - 1)\} * n_4 + \cdots + (j_{N-1} - 1)] * n_N + j_N, \\
&\forall \quad j_1 = 1,2,\cdots,n_1; \quad j_2 = 1,2,\cdots,n_2; \quad \cdots; \quad j_N = 1,2,\cdots,n_N.
\end{aligned} \tag{8}
$$

In Equation (8), the index of entry i in the vector $\overline{C}_i$ can be simply determined based on its index in the original matrix, C_i. The procedures for re-ordering the entries from C_i to $\overline{C}_i$ can be further described with the help of the following pseudo codes which can be readily translated into a programming subroutine in **FCRIS**.

```
Begin
        i=0;
        for j1 = 1 to n1
                for j2 = 1 to n2
                        for j3 = 1 to n3
                                ......
                                for jN = 1 to nN
                                        begin
                                                i = i + 1;
                                                c̄i = cj1j2…jN ;
                                        end;
end
```

Example:

If the membership functions of a number of fuzzified customer attributes can be given as $A_1 = (a_{11}, a_{12})$, $A_2 = (a_{21}, a_{22})$, $A_3 = (a_{31}, a_{32}, a_{33})$ respectively, i.e.

$n_1 = n_2 = 2$ and $n_3 = 3$, then the Conditions Matrix C_i ($C_i = A_1 \times A_2 \times A_3$) will be three-dimensional (i.e. $N=3$) with 2*2*3 (i.e.12) entries. The vector $\overline{C}_i$ can be expressed as:

$$\overline{C}_i = (a_{11} \wedge a_{21} \wedge a_{31},\ a_{11} \wedge a_{21} \wedge a_{32},\ a_{11} \wedge a_{21} \wedge a_{33},\ a_{11} \wedge a_{22} \wedge a_{31},\ a_{11} \wedge a_{22} \wedge a_{32},\ a_{11} \wedge a_{22} \wedge a_{33},$$
$$a_{12} \wedge a_{21} \wedge a_{31},\ a_{12} \wedge a_{21} \wedge a_{32},\ a_{12} \wedge a_{21} \wedge a_{33},\ a_{12} \wedge a_{22} \wedge a_{31},\ a_{12} \wedge a_{22} \wedge a_{32},\ a_{12} \wedge a_{22} \wedge a_{33})$$

Hence, the fuzzy proposition R_i in (8) for product attribute Y_j with fuzzy set y_{jl} described by a membership function B_{jl} can be expressed by the Cartesian Product between $\overline{C}_i$ and B_{jl} into a Rule Matrix Q_{ji}, such that

$$Q_{ji} = \overline{C}_i \times B_{jl} \qquad (9)$$

The element q_{jl} in the Rule Matrix Q_{ji} can be expressed as:

$$q_{jl} = \overline{c}_j \wedge \eta_l \quad (j = 1,2,\cdots,n_1 * n_2 * \cdots * n_N;\ l = 1,2,\cdots,m_j) \qquad (10)$$

If there are k rules in total in connection with Y_j in the fuzzy rule-base, the matrices can be combined into a Consolidated Rule Matrix Q, such that

$$Q = \sum_{i=1}^{k} (r_i * Q_{ji}), \qquad (11)$$

where Q and all Q_{ji} $(i=1,2,...,k)$ are two-dimensional matrices with $n_1 * n_2 * ... * n_N$ rows and m_j columns, and the summation operator Σ will perform a series of logical OR ("$\vee$" or maximisation) operations in this formula.

Hence, as a specific set of customer attributes is received, they can be fuzzified and expressed in membership vectors A'_i as described in Equation (4), the resulting specific Conditions Matrix C'_i and the corresponding Conditions Vector, $\overline{C}'_i$ can then be established according to Equations (7) and (8) respectively.

The set of fuzzified customer attributes represented by $\overline{C}'_i$ will be submitted to rule evaluation. The resulting sub-conclusions relevant to the product attribute Y_j can be drawn and described by the membership function vector, B'_j, such that

$$B'_j = \overline{C}'_i \circ Q \qquad (12)$$

where "$\circ$" is the Max-Min Compositional Operation which works in a way similar to an ordinary matrix multiplication, except that the addition operation "+" is replaced by the maximisation operation "$\vee$", and the multiplication operation "$\cdot$" is replaced by the minimisation operation "$\wedge$".

7.4.2.3 Aggregating and Defuzzifying the Fuzzy Sub-Conclusions

The sub-conclusions drawn from rule evaluation will then be aggregated into one or more complete conclusions in various output fuzzy regions for individual output variables.

Aggregating the output fuzzy regions over the entire output space P_j $(j=1,2,\ldots,M)$, the composite output fuzzy region described by the membership function B_j for the output model variable Y_j can be expressed as:-

$$B_j = \overline{C}'_i \circ Q = (\eta'_{11}, \eta'_{12}, \cdots, \eta'_{1m_1}, \eta'_{21}, \eta'_{22}, \cdots, \eta'_{2m_2}, \cdots, \eta'_{M1}, \eta'_{M2}, \cdots, \eta'_{Mm_M}) \qquad (13)$$

where η'_{jl} $(l = 1,2,\ldots,m_M)$ $(j = 1,2,\ldots,M)$ is a real number from the interval [0,1] representing the grade of certainty at various domain points p_{jl} in the universe of P_j.

Each composite output fuzzy region is subsequently defuzzified to yield a crisp output target value for the corresponding product attribute. The choice of methods of defuzzification depends on the nature of the analysis as well as the preference and emphasis adopted by the decision makers. For demonstration purpose, the Centroid Method of Defuzzification (i.e. Weighted Average Method of Defuzzification) is used here. With the Centroid Method of Defuzzification, the expected output value y'_j for the product attribute Y_j can be worked out as follows:

Let $P_j = [a, b]$ be the universe of discourse of the j^{th} product attribute represented by the output model variable Y_j, hence a and b are the lower and upper limits for the domain elements of Y_j respectively. Thus, the target value y'_j for the composite conclusion, "Y_j is y'_j : w_j" can be given by the centroid of the aggregate output fuzzy region,

$$\text{i.e.} \quad y'_j = \int_a^b x\mu(x)dx \Big/ \int_a^b \mu(x)dx$$

where $\mu_{(x)}$ is the grade of certainty at the given domain point x $(x \in [a,b])$ in the aggregated output fuzzy region for the model variable Y_j as illustrated in Figure 7.4.

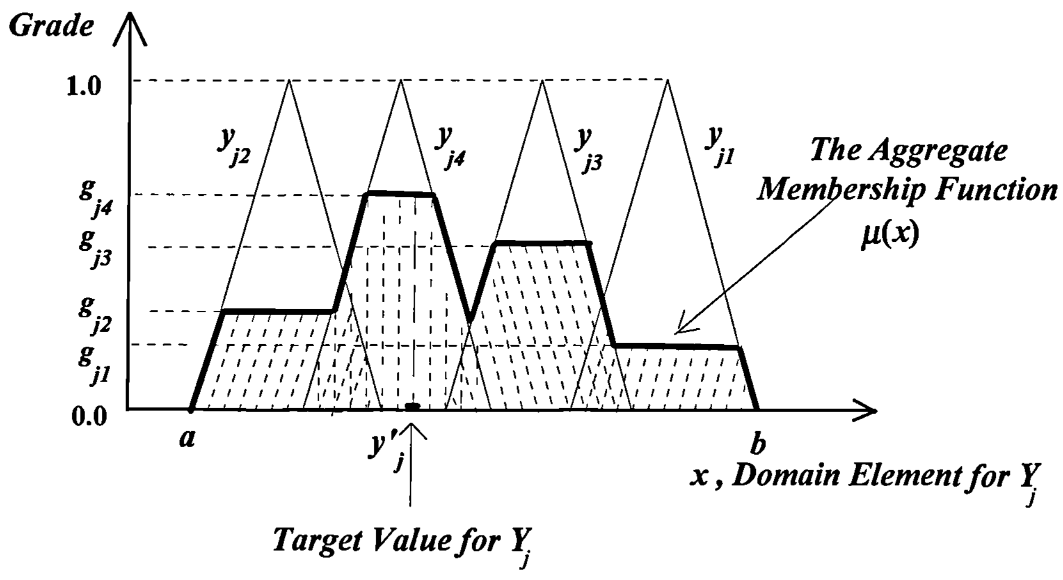


Figure 7.4: Aggregating and Defuzzifying the Subconclusions by the Centroid Method

7.5 Illustrating the Mathematical Model for the Fuzzy Inference Process

To illustrate the mathematical computations described above, the following example demonstrates how a set of specific customer requirements can be analysed using the fuzzy inference process to determine the design target value for a given product attribute.

Example:

The problem domain in this example is to determine the Target Value of the product attribute, the "*Engine Power*" required to satisfy specified customer attributes, the "*Top Speed*" and the "*Seating Capacity*" of a given model of motor car. Hence, in this case $N=2$ and $M=1$.

(a) Data Representation

The customer attribute "*Top Speed*" is denoted by the input model variable X_1. If the minimum and maximum speed of the model of motor car concerned are 0 and 250 kilometres per hour (km/hr) respectively, the universe of discourse (V_1) for X_1 lies in the real interval [0, 250], i.e. $V_1 = [0, 250]$. For simplicity, the universe of discourse is evenly discretised (subdivided) into 6 sections (i.e. n_1=6), therefore V_1 contains 6 discrete elements (real numbers) v_{1l}, such that $v_{1l} = 50 * (l - 1)$ $(l=1,2,3,4,5,6)$. By Equation (1), $V_1 = \{0, 50, 100, 150, 200, 250\}$.

If there are four linguistic variables x_{11} *"slow"*, x_{12} *"moderate"*, x_{13} *"fast"* and x_{14} *"extremely fast"* defined in the term set of the input model variable X_1, the *"Top Speed"*. By Equation (4), these linguistic variables can be described by the fuzzy sets A_{11}, A_{12}, A_{13} and A_{14} respectively with their corresponding membership functions represented by vectors:

$A_{11} = (1.0,0.5,0.0,0.0,0.0,0.0)$, $A_{12} = (0.0,0.0,1.0,0.0,0.0,0.0)$

$A_{13} = (0.0,0.0,0.0,0.5,1.0,1.0)$, $A_{14} = (0.0,0.0,0.0,0.0,0.5,1.0)$ respectively, as illustrated in Figure 7.5.

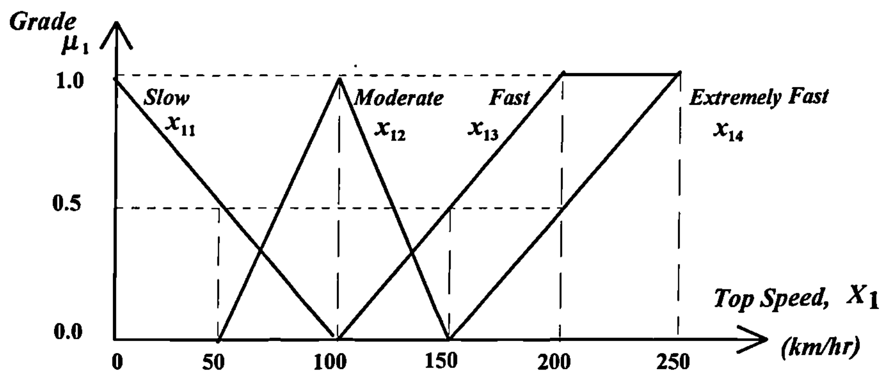


Figure 7.5: Fuzzy Membership Functions Related to the "Top Speed"

Similarly, another customer attribute "*Seating Capacity*" can be denoted by the model variable X_2. If the minimum and maximum seating capacity of a car are two and nine respectively. The universe of discourse (V_2) of the model variable X_2 lies in the real interval [2, 9], i.e. $V_2 = [2, 9]$. The interval is evenly discretised into n_2 sections (say $n_2 = 8$ in this case) in the universe of discourse of V_2 which contains 8 discrete domain elements, v_{2l} such that $v_{2l} = 1 + l$ ($l=1,2,3,4,5,6,7,8$), i.e. $V_2 = \{2, 3, 4, 5, 6, 7, 8, 9\}$.

If there are four linguistic variables x_{21} *"small"*, x_{22} *"medium"*, x_{23} *"large" and* x_{24} *"very large"* defined in the term set of the input model variable X_2, the *"Seating Capacity"*, their corresponding fuzzy sets can be described by the membership vectors:

$A_{21} = (1.0,0.5,0.0,0.0,0.0,0.0,0.0,0.0)$, $A_{22} = (0.0,0.5,1.0,0.5,0.0,0.0,0.0,0.0)$,

$A_{23} = (0.0,0.0,0.0,0.5,1.0,0.5,0.0,0.0)$, $A_{24} = (0.0,0.0,0.0,0.0,0.0,0.0,0.5,1.0)$

respectively as illustrated in Figure 7.6.

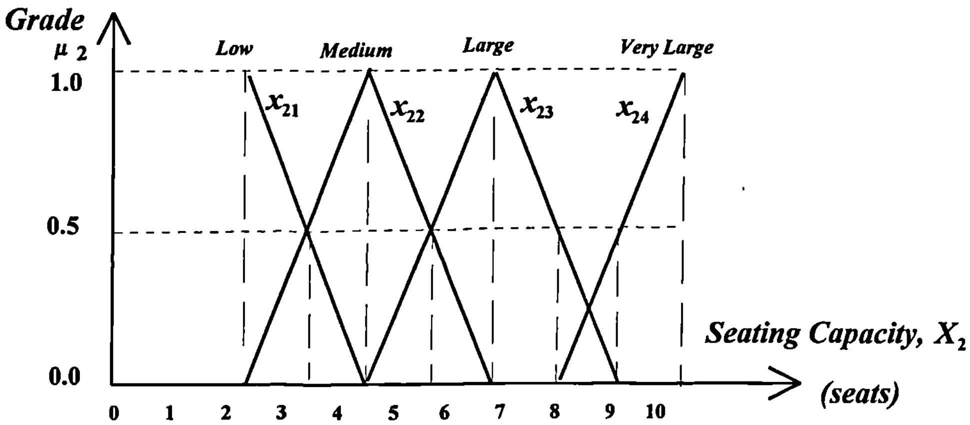


Figure 7.6: Fuzzy Membership Functions Related to the "Seating Capacity"

On the other hand, the product attribute "*Engine Power*" is denoted by the output model variable Y_1 with 0 and 125 horse-power (hp) as its minimum and maximum limits respectively. Hence, the universe of discourse of Y_1 lies in a real interval [0, 125], i.e. $P_1 = [0, 125]$.

If this interval is evenly discretised into 6 sections *(i.e. m=6)*, thus P_1 contains 6 discrete domain elements p_l, such that $p_l = 25 \cdot (l - 1)$ $(l=1,2,3,4,5,6)$. By Equation (2), $P_1 = \{0, 25, 50, 75, 100, 125\}$. Assuming there are four linguistic variables y_1 *"low"*, y_2 *"medium"*, y_3 *"high" and* y_4 *"very high"* defined in the term set of the output model variable Y_1, the "*Engine Power*", the membership functions of their respective fuzzy sets can be represented by the following vectors:

$$B_1 = (1.0,0.5,0.0,0.0,0.0,0.0), \quad B_2 = (0.0,0.0,1.0,0.0,0.0,0.0),$$
$$B_3 = (0.0,0.0,0.0,0.5,1.0,1.0), \quad B_4 = (0.0,0.0,0.0,0.0,0.5,1.0)$$

respectively as illustrated in Figure 7.7.

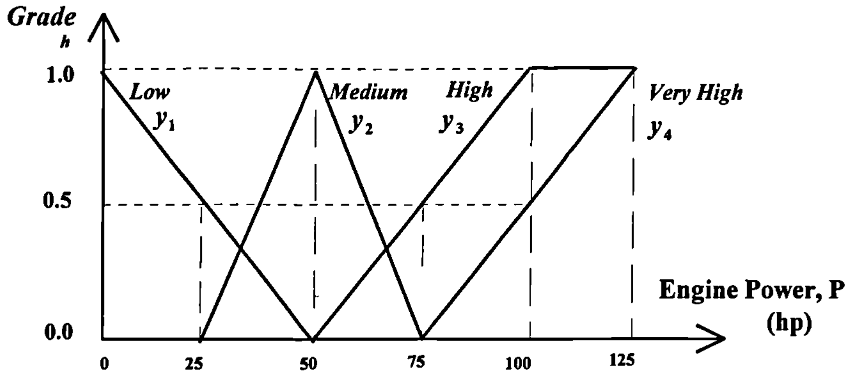


Figure 7.7: Fuzzy Membership Functions Related to the "Engine Power"

(b) Rule Evaluation

The fuzzy rule-base relevant to the problem domain can be evaluated as follows:

Rule 1:

"If the Top Speed is slow and the Seating Capacity is small, then the Engine Power is low", i.e. "If $X_1 = x_{11}$ and $X_2 = x_{21}$, then $Y_1 = y_1$".

By Equation (7), the predicates of this rule can thus be represented by a Conditions Matrix C_1, such that

$$C_1 = A_{11} \times A_{21} = (1.0,0.5,0.0,0.0,0.0,0.0) \times (1.0,0.5,0.0,0.0,0.0,0.0,0.0,0.0)$$

$$= \begin{bmatrix} 1.0 & 0.5 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\ 0.5 & 0.5 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\ 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\ 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\ 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\ 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \end{bmatrix}$$

Furthermore, the above matrix can be transformed into a Conditions Vector, $\overline{C_1}$ as explained in Equation (8), i.e.

$$\overline{C}_1 = (1.0,0.5,0.0,0.0,0.0,0.0,0.0,0.0,0.5,0.5,0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0,$$
$$0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0)$$

By Equations (9) and (10), **Rule 1** can be expressed in a Rule Matrix, Q_1 such that

$$Q_1 = \overline{C}_1 \times B_1$$
$$= (1.0,0.5,0.0,0.0,0.0,0.0,0.0,0.0,0.5,0.5,0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0,$$
$$0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0)$$
$$\times\ (1.0,0.5,0.0,0.0,0.0,0.0)$$

$$= \begin{bmatrix} 1.0 & 0.5 & 0.0 & 0.0 & 0.0 & 0.0 \\ 0.5 & 0.5 & 0.0 & 0.0 & 0.0 & 0.0 \\ 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\ 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\ 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\ 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\ 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\ 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\ 0.5 & 0.5 & 0.0 & 0.0 & 0.0 & 0.0 \\ 0.5 & 0.5 & 0.0 & 0.0 & 0.0 & 0.0 \\ 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\ :::: & :::: & :::: & :::: & :::: & :::: \\ 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \end{bmatrix}_{48*6}$$

This is a 48x6 matrix with its unspecified entries ":::" taking a value of zero ("0.0").

Rule 2:

"If the Top Speed is moderate and the Seating Capacity is medium, then the Engine Power is medium", i.e. *"If* $X_1 = x_{12}$ *and* $X_2 = x_{22}$, *then* $Y_1 = y_2$*"*.

Thus, the Conditions Matrix for **Rule 2** can be given as follows:

$$C_2 = A_{12} \times A_{22} = (0.0,0.0,1.0,0.0,0.0,0.0) \times (0.0,0.5,1.0,0.5,0.0,0.0,0.0,0.0)$$

$$= \begin{bmatrix} 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\ 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\ 0.0 & 0.5 & 1.0 & 0.5 & 0.0 & 0.0 & 0.0 & 0.0 \\ 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\ 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\ 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \end{bmatrix}$$

The corresponding Conditions Vector becomes

$$\overline{C_2} = (0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.5,1.0,0.5,0.0,0.0,0.0,0.0,$$
$$0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0)$$

Hence, the resulting Rule Matrix, Q_2 can be expressed as:

$$
\begin{aligned}
Q_2 &= \overline{C}_2 \times B_2 \\
&= (0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.5,1.0,0.5,0.0,0.0,0.0,0.0, \\
&\quad 0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0) \\
&\times (0.0,0.0,1.0,0.0,0.0,0.0)
\end{aligned}
$$

$$
= \begin{bmatrix}
0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\
0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\
0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\
0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\
0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\
0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\
0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\
0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\
0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\
0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\
0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\
0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\
0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\
0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\
0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\
0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\
0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\
0.0 & 0.0 & 0.5 & 0.0 & 0.0 & 0.0 \\
0.0 & 0.0 & 1.0 & 0.0 & 0.0 & 0.0 \\
0.0 & 0.0 & 0.5 & 0.0 & 0.0 & 0.0 \\
0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\
:::: & :::: & :::: & :::: & :::: & :::: \\
0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0
\end{bmatrix}_{48*6}
$$

Rule 3:

"If the Seating Capacity is very large, then the Engine Power is high", i.e. *"If* $X_2 = x_{24}$, *then* $Y_1 = y_3$*"*.

Since the *"Top Speed"* does not appear in the premise of this rule, its corresponding membership function can be represented by a unit vector *(1,1,1,1,1,1)*, so that the Conditions Matrix can be given as:

$$C_3 = (1,1,1,1,1,1) \times A_{24} = (1.0,1.0,1.0,1.0,1.0,1.0) \times (0.0,0.0,0.0,0.0,0.0,0.0,0.5,1.0)$$

$$= \begin{bmatrix} 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.5 & 1.0 \\ 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.5 & 1.0 \\ 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.5 & 1.0 \\ 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.5 & 1.0 \\ 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.5 & 1.0 \\ 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.5 & 1.0 \end{bmatrix}$$

The corresponding Conditions Vector becomes

$$\overline{C_3} = (0.0,0.0,0.0,0.0,0.0,0.0,0.5,1.0,0.0,0.0,0.0,0.0,0.0,0.0,0.5,1.0,0.0,0.0,0.0,0.0,0.0,0.0,0.5,1.0,$$
$$0.0,0.0,0.0,0.0,0.0,0.0,0.5,1.0,0.0,0.0,0.0,0.0,0.0,0.0,0.5,1.0,0.0,0.0,0.0,0.0,0.0,0.0,0.5,1.0)$$

Hence, the resulting matrix for **Rule 3** can be expressed as:

$$Q_3 = \overline{C}_3 \times B_3$$

$$= (0.0,0.0,0.0,0.0,0.0,0.0,0.5,1.0,0.0,0.0,0.0,0.0,0.0,0.0,0.5,1.0,0.0,0.0,0.0,0.0,0.0,0.0,0.5,1.0,$$
$$0.0,0.0,0.0,0.0,0.0,0.0,0.5,1.0,0.0,0.0,0.0,0.0,0.0,0.0,0.5,1.0,0.0,0.0,0.0,0.0,0.0,0.0,0.5,1.0)$$
$$\times\ (0.0,0.0,0.0,0.5,1.0,1.0)$$

$$= \begin{bmatrix}
0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\
0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\
0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\
0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\
0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\
0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\
0.0 & 0.0 & 0.0 & 0.5 & 0.5 & 0.5 \\
0.0 & 0.0 & 0.0 & 0.5 & 1.0 & 1.0 \\
0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\
0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\
0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\
0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\
0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\
0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\
0.0 & 0.0 & 0.0 & 0.5 & 0.5 & 0.5 \\
0.0 & 0.0 & 0.0 & 0.5 & 1.0 & 1.0 \\
0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\
0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\
0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\
0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\
0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\
0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\
0.0 & 0.0 & 0.0 & 0.5 & 0.5 & 0.5 \\
0.0 & 0.0 & 0.0 & 0.5 & 1.0 & 1.0 \\
0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\
0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\
0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\
0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\
0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\
0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\
0.0 & 0.0 & 0.0 & 0.5 & 0.5 & 0.5 \\
0.0 & 0.0 & 0.0 & 0.5 & 1.0 & 1.0 \\
0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\
0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\
0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\
0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\
0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\
0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\
0.0 & 0.0 & 0.0 & 0.5 & 0.5 & 0.5 \\
0.0 & 0.0 & 0.0 & 0.5 & 1.0 & 1.0 \\
0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\
0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\
0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\
0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\
0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\
0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\
0.0 & 0.0 & 0.0 & 0.5 & 0.5 & 0.5 \\
0.0 & 0.0 & 0.0 & 0.5 & 1.0 & 1.0
\end{bmatrix}$$

By Equation (11), the above matrices can be combined into a single Consolidated Rule Matrix through a series of fuzzy OR "$\vee$" operations, i.e. $Q = r_1 {\cdot} Q_1 \vee r_2 {\cdot} Q_2 \vee r_3 {\cdot} Q_3$, where r_i is the Certainty Factor for the fuzzy proposition R_i, $(i=1,2,3)$.

Assuming all the $r_i = 1$ in this case, hence the Consolidated Rule Matrix becomes

$$Q = Q_1 + Q_2 + Q_3$$

$$= \begin{bmatrix}
1.0 & 0.5 & 0.0 & 0.0 & 0.0 & 0.0 \\
0.5 & 0.5 & 0.0 & 0.0 & 0.0 & 0.0 \\
0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\
0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\
0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\
0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\
0.0 & 0.0 & 0.0 & 0.5 & 0.5 & 0.5 \\
0.0 & 0.0 & 0.0 & 0.5 & 1.0 & 1.0 \\
0.5 & 0.5 & 0.0 & 0.0 & 0.0 & 0.0 \\
0.5 & 0.5 & 0.0 & 0.0 & 0.0 & 0.0 \\
0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\
0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\
0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\
0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\
0.0 & 0.0 & 0.0 & 0.5 & 0.5 & 0.5 \\
0.0 & 0.0 & 0.0 & 0.5 & 1.0 & 1.0 \\
0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\
0.0 & 0.0 & 0.5 & 0.0 & 0.0 & 0.0 \\
0.0 & 0.0 & 1.0 & 0.0 & 0.0 & 0.0 \\
0.0 & 0.0 & 0.5 & 0.0 & 0.0 & 0.0 \\
0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\
0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\
0.0 & 0.0 & 0.0 & 0.5 & 0.5 & 0.5 \\
0.0 & 0.0 & 0.0 & 0.5 & 1.0 & 1.0 \\
0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\
0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\
0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\
0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\
0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\
0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\
0.0 & 0.0 & 0.0 & 0.5 & 0.5 & 0.5 \\
0.0 & 0.0 & 0.0 & 0.5 & 1.0 & 1.0 \\
0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\
0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\
0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\
0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\
0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\
0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\
0.0 & 0.0 & 0.0 & 0.5 & 0.5 & 0.5 \\
0.0 & 0.0 & 0.0 & 0.5 & 1.0 & 1.0 \\
0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\
0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\
0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\
0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\
0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\
0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\
0.0 & 0.0 & 0.0 & 0.5 & 0.5 & 0.5 \\
0.0 & 0.0 & 0.0 & 0.5 & 1.0 & 1.0
\end{bmatrix}$$

(c) *Representation of a given set of Customer Attributes*

Now, assuming the product engineers have to re-design the engine for a model of motor car in response to a specific set of customer attributes on the " *Top Speed*" X_1 and the "*Seating Capacity*" X_2, they want to know the minimum output power that the engine has to deliver in order to meet the customer attributes.

The relevant linguistic variables for X_1 and X_2 are fuzzified and represented by the membership vectors,
$A'_1 = (0.0,0.1,0.8,0.2,0.0,0.0)$ and $A'_2 = (0.1,0.6,0.4,0.2,0.0,0.0,0.0,0.0)$ respectively.

Hence, the Conditions Matrix representing these specific customer specifications can be expressed as:

$$C' = A_1' \times A_2' = (0.0,0.1,0.8,0.2,0.0,0.0) \times (0.1,0.6,0.4,0.2,0.0,0.0,0.0,0.0)$$

$$= \begin{bmatrix} 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\ 0.1 & 0.1 & 0.1 & 0.1 & 0.0 & 0.0 & 0.0 & 0.0 \\ 0.1 & 0.6 & 0.4 & 0.2 & 0.0 & 0.0 & 0.0 & 0.0 \\ 0.1 & 0.2 & 0.2 & 0.2 & 0.0 & 0.0 & 0.0 & 0.0 \\ 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\ 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \end{bmatrix}$$

and, the Conditions Vector becomes

$$\overline{C}' = (0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.1,0.1,0.1,0.1,0.0,0.0,0.0,0.0,0.1,0.6,0.4,0.2,0.0,0.0,0.0,0.0,$$
$$0.1,0.2,0.2,0.2,0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.00.0,0.0,0.0,0.0,0.0,0.0)$$

(d) *Evaluation of the Fuzzy Rule Base*

Then, the set of customer attributes represented by the Conditions Vector, $\overline{C}'$ is submitted to rule evaluation. The corresponding output membership vector, B' worked out through Max-Min Compositional Inference on the Condition Vector and the Consolidated Rule Matrix can be given as:

$$B' = \overline{C}' \circ Q = (0.1, 0.1, 0.5, 0.0, 0.0, 0.0)$$

It represents the membership function of the output fuzzy region after aggregating all the sub-conclusions for the product attribute Y_1, the "*Engine Power*" in the universe of discourse P_1.

(e) Defuzzification to yield the Design Target

The resulting Target Value y' for the model variable Y_1 can be determined by defuzzifying the singleton output fuzzy region using the Centroid Method, i.e.

$$y' = (0.1*0 + 0.1*25 + 0.5*50 + 0.0*75 + 0.0*100 + 0.0*125)$$
$$/ (0.1 + 0.1 + 0.5 + 0.0 + 0.0 + 0.0)$$
$$= 27.5 / 0.7$$
$$= 39.3 \text{ hp (horsepower)}$$ as described in Figure 7.8.

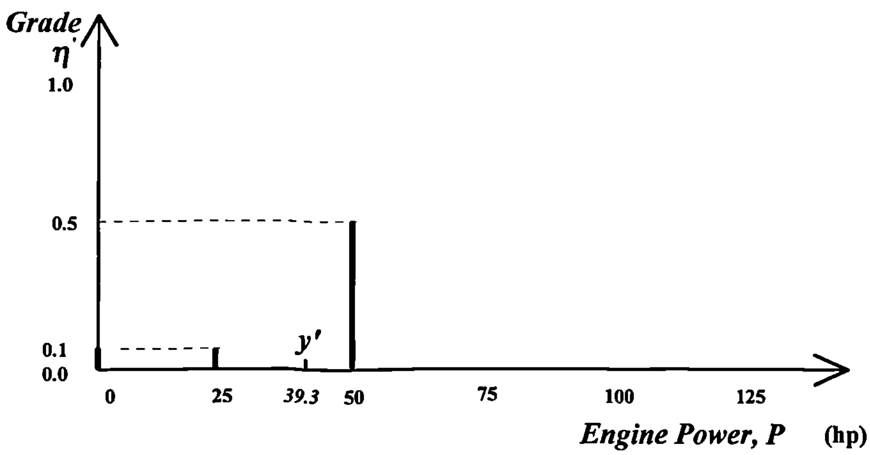


Figure 7.8: Defuzzifying the Singleton Output Region to yield the Minimum Engine Power Required

This example illustrates how the fuzzy inference process in the proposed hybrid model can be used to determine the minimum power that the engine has to deliver in order to fulfil the specified customer requirements on the *Top Speed* and the *Seating Capacity* of a certain model of motor car using matrix computations. More complex problems can be processed in a similar manner. A full-blown Case Study demonstrating the operations of the entire hybrid model proposed in this research will be presented in Chapter 8.

7.6 Summary

This chapter covers the functional description and mathematical modelling of the proposed Fuzzy Customer Requirement Inference System, **FCRIS**. Examples are given where necessary to help clarify the concepts. To start with, an explanation on how the customer and product attributes can be represented by model variables in the input and output fuzzy spaces is given. The formulation of the fuzzy rule-base relating the customer attributes and product attributes is then expounded. The mathematical modelling of the fuzzy inference process using matrix computations has been methodically described. Finally, the applicational aspects of **FCRIS** are duly demonstrated through a practical example of redesigning a motor engine.

Chapter 8
Case Study

8.1 Introduction

The construction and characteristics of the proposed hybrid model for analysing and interpreting the voice of customer are described in detail in Chapter 6. The importance and practical significance of determining a target value / design goal for the relevant product attributes are discussed there. In Chapter 7, the modelling aspects of the Fuzzy Customer Requirement Inference System **(FCRIS)** are discussed with the help of a number of simple examples. In this chapter, the implementation of the entire hybrid model will be further illustrated through demonstrating the various operational stages of the proposed hybrid model with a real-life case study. It describes the scenario of designing the major features of a mid-range hi-fi equipment in response to the requirements of an important customer. However, this case study is not designed to test the robustness of the system which actually depends on a number of internal and external factors as described later in Section 8.6.2.

A hi-fi equipment is chosen for this case study mainly because it is a common household appliance whose functions and features are more or less self-explanatory and found familiar by most people. Besides, the information and data relevant to such a popular consumer product are more readily available and they can be easily accepted by the readers. Hi-fi products can vary over a rather wide spectrum from a simple personal "Walkman" or "Discman" to enormous systems, such as those used in a theatre or a concert hall for producing professional effects. In view of that, the scope of this case study is restricted to mid-range hi-fi's in a moderate price bracket, say between US$600 to US$1,000, which are believed to have a larger customer population. The customer attributes do vary significantly among different customer categories, such as age groups, interest groups, etc. The customer category in this case study is targeted at the young people aged between 20 to 30. It is because the prices of mid-range hi-fi's are within their financial reach and their expected product attributes on the equipment tend to be quite general and more easily understood by the readers.

8.2 Outline of the Case Study

In this case study, the customer requirements / attributes are captured through customer surveys and interviews which are conducted in stages, starting from considering the general aspects and moving on to focusing on the specific issues. The samples questionnaires used in this case study and their design rationale are described in Appendix III. The product attributes / design features are identified through reviewing the best-selling trade magazines as well as discussing with product designers from local hi-fi manufacturing companies. The findings are categorised using an Affinity Diagram whose procedures can be facilitated using a simple computer programme instead of the traditional card shuffling exercise which tends to be laborious. The relevant attributes categories can be reflected in an HoQ based on the QFD principles. Through manipulating the data in the Planning and Relationship Matrices in the HoQ, the essential customer and product attributes can be identified and selected for subsequent investigations.

Further surveys and analyses are then conducted on those selected attributes, and the outcomes are represented quantitatively in a Focused HoQ with the respective Relative Weights of Importance obtained from an AHP.

In order to determine a realistic and quantitative design target for each of the major product features, the information and data on the customer and product attributes as well as their inter-relationships derived from previous studies are built into the relevant knowledge-bases. The fuzzy inference process offered by **FCRIS** is then applied to respond to a specific set of customer requirements. Through fuzzification, rule evaluation and defuzzification, crisp quantitative design targets required to satisfy the given customer attributes can be worked out for the product attributes.

8.3 Establishing the Customer and Product Attributes for Mid-Range hi-fi's

This case study begins with capturing the likes and dislikes of the customers on mid-range hi-fi's. A preliminary study is conducted to obtain a feel of the fashionable product features and the latest design trend from popular hi-fi magazines and through discussions with hi-fi enthusiasts and product engineers from local hi-fi manufacturers.

With the basic knowledge derived above, a checklist containing the essential and popular requirements and features is prepared. A multi-stage survey is then conducted through customer interviews to reveal their views on various aspects of selecting and using hi-fi products. Questionnaires are compiled to address the general as well as more focused issues on the integral parts of a hi-fi system, including amplifier, equaliser, tuner, cassette deck, CD player and loudspeaker, etc. A sample population of around 300 interviewees aged twenty to thirty was selected in this case study because they are believed to represent the major users group for mid-range hi-fi equipment. The design rationale and sample questionnaires used at different stages of the survey on CD players can be found in Appendices III(a), (b), (c) & (d) respectively.

The customer attributes captured from the surveys are arranged in categories with the use of an Affinity Diagram. Besides, customers' preferences on individual attributes as well as the priority of the attributes within each category are established using pairwise comparisons offered by the AHP software, (Expert Choice, 1986).

8.4 Constructing the Basic HoQ

The outcomes from the surveys, categorisation and prioritisation are entered alongside the customer and product attributes into the framework of a basic HoQ according to the QFD principles. The Planning and Correlation Matrices are completed in the way described in Sections 3.4.3 and 3.4.5 with inputs from experienced hi-fi engineers and designers. Entries to the Relationship Matrix are determined qualitatively based on the conventional 1-3-9 or any other scales at the discretion of the development team as explained in Section 3.4.4. Finally, the Relative Weight of Importance for each product attribute can be calculated as described in Section 3.4.6. The resulting basic HoQ can be shown in Figure 8.1.

8.5 Further Analyses on the Essential Attributes

Although the basic HoQ offers an overall picture on the mapping between customer and product attributes, it can become over-congested with information when a complex product. In order to gain a better insight into individual categories of attributes, the basic HoQ is sub-divided into a number of smaller but more focused HoQ's. The key elements in the basic HoQ (Figure 8.1) are summarised into a consolidated HoQ as shown in Figure 8.2 to give a clearer view on the individual categories. The cumulative Relative Weight of Importance for each category of product attributes can be found at the bottom section of this consolidated HoQ. It has become apparent from the studies that requirements relating to the loudspeaker unit seem to have attracted most attention and have obtained the highest relative weight of importance among the categories of product attributes (i.e. 41.7%), hence it is chosen for further demonstrating the characteristics of the proposed hybrid model. Figure 8.3 shows an abridged version of the basic HoQ (Figure 8.1), giving a close-up view of the elements relevant to the loudspeaker unit. These details will be extracted for the construction of a Focused HoQ.

8.5.1 Constructing a Focused HoQ

As it can be seen in Figure 8.3, there are nine customer attributes affecting the product attributes in the category of loudspeaker unit. These attributes are extracted to construct a Focused HoQ (Figure 8.4) in which the relative importance of each of the customer attributes is recalculated by applying the AHP again with the inputs from a group of ten dedicated and experienced hi-fi users. The group size for the AHP exercise can be adjusted as required according to the consistency of the results. Based on the experiments performed by Saaty (1980), an AHP exercise can be deemed reasonably accurate provided its resulting Inconsistency Ratio (IR) lies below 0.1. The structure of the AHP model and an example of pairwise comparisons can be shown in Figures 8.5 and 8.6 respectively. The outcomes of the AHP exercise on the customer attributes are normalised and expressed in percentages (e.g. 30.2% for "Strong Bass") as shown in Figure 8.7. In the example shown in this case study, the IR is worked out to be 0.04 which can be considered rather satisfactory.

The AHP is also applied for determining the contributions of individual product attributes towards the fulfilment of each customer attribute with inputs from product engineers from local hi-fi manufacturers, and the results are shown in Figure 8.8. The Relative Weight of Importance of each product attribute can be worked out by summing up its respective contributions to various customer attributes. Findings from the above analyses are entered into the Focused HoQ (Figure 8.4) which gives a more detailed and quantitative account of the relationships among the attributes together with their relative importance.

8.6 Determining the Design Target for Each Product Attribute

The Focused HoQ highlights the contributions of each product attribute or design feature towards satisfying the customer requirements. However, the technical / design target for each product attribute required to deliver the specific output performance remains to be determined. In this research, an approximate reasoning approach using fuzzy inference is adopted for deriving these design targets, called the Target Values.

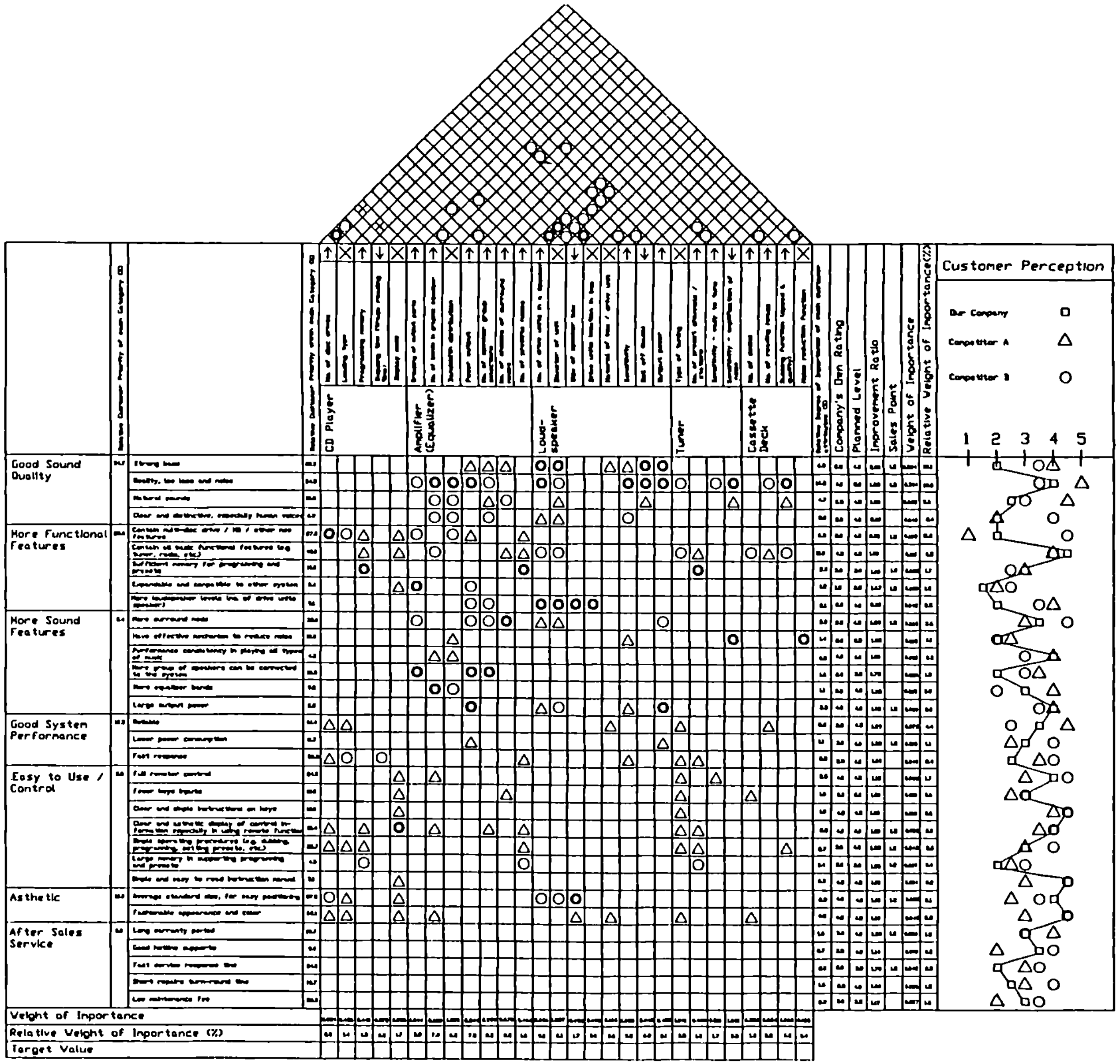


Figure 8.1: A Basic HoQ for the Design of Mid-Range Hi-Fi's

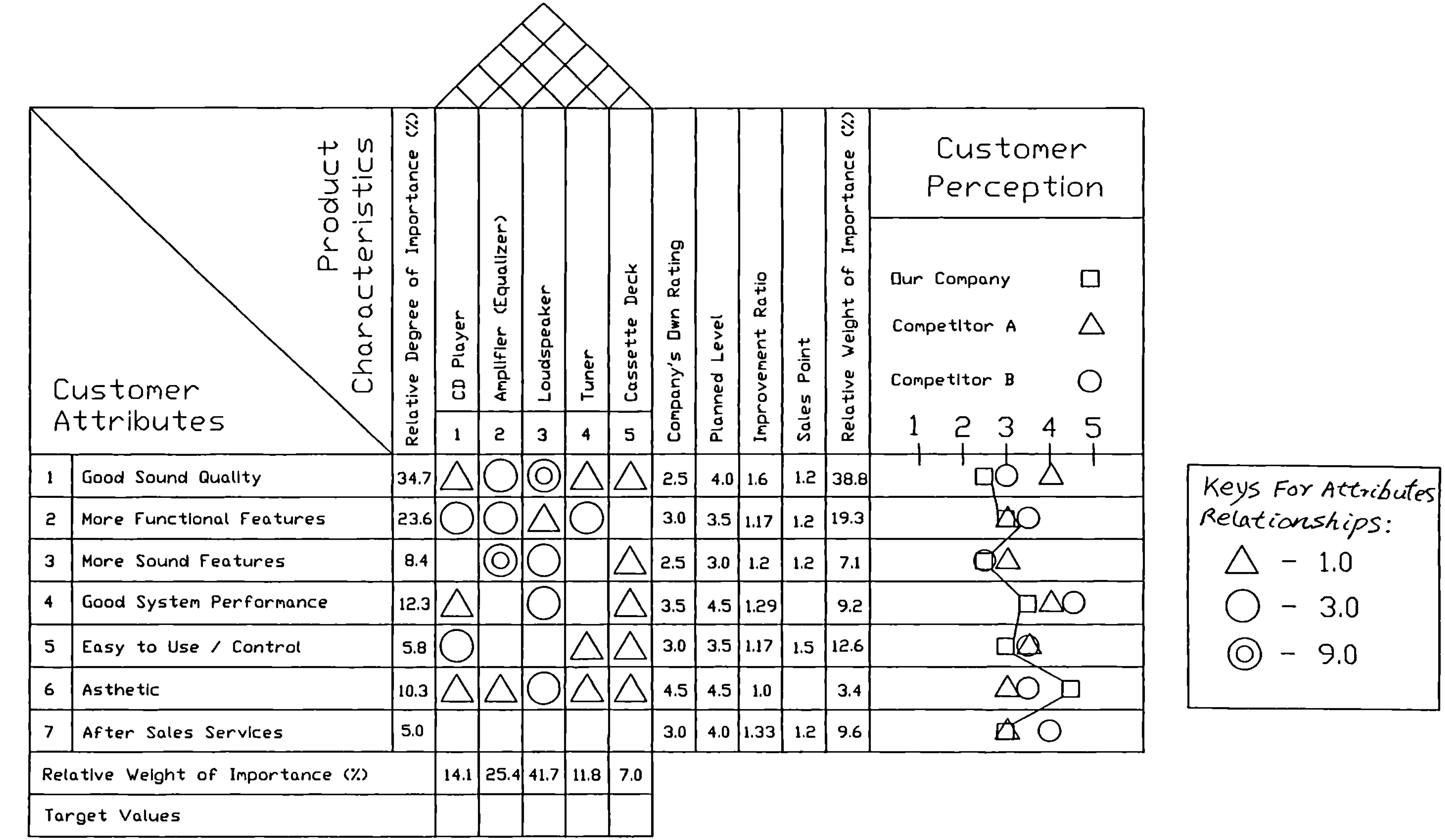


Figure 8.2: A Consolidated HoQ for the Design of Mid-Range Hi-Fi's

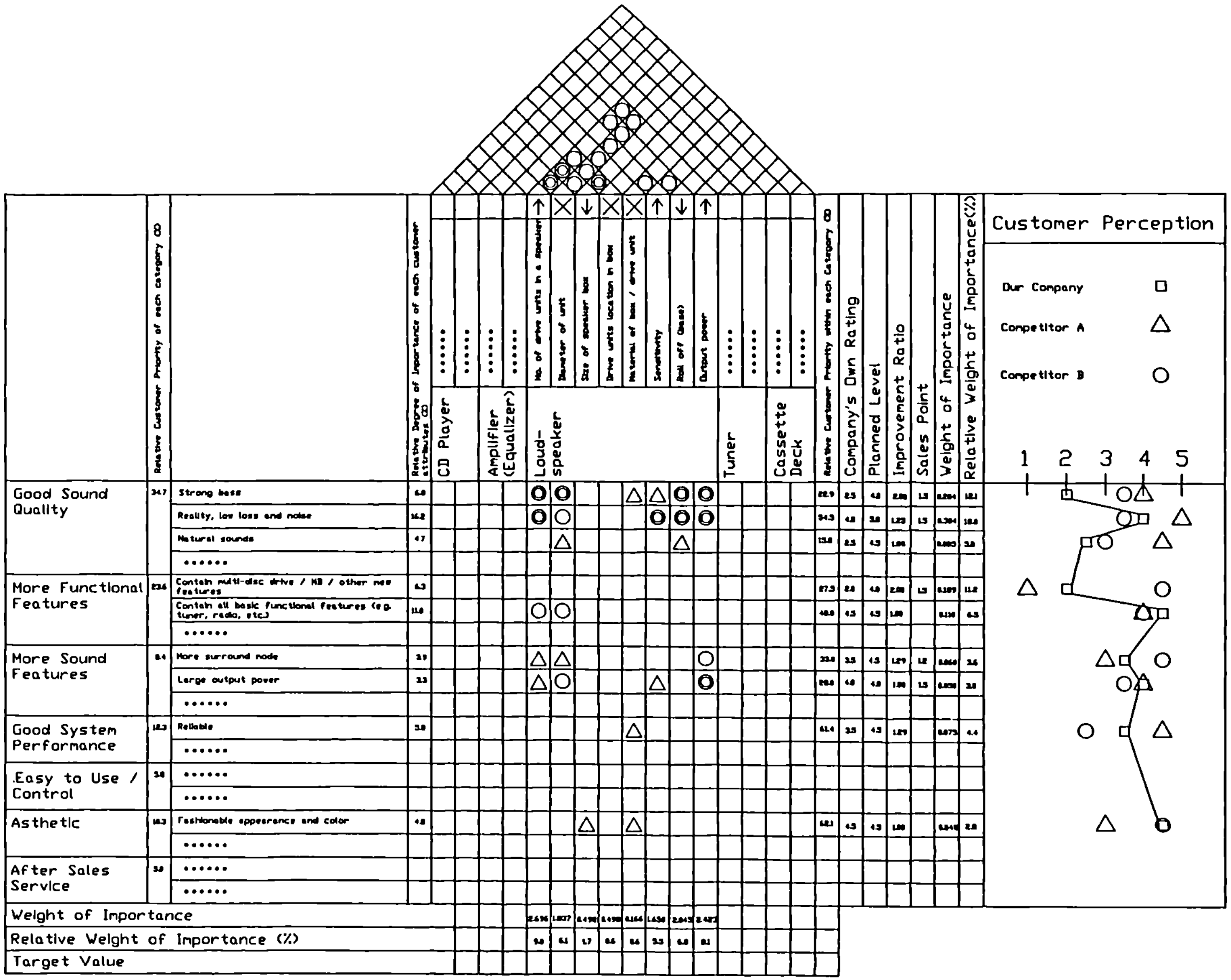
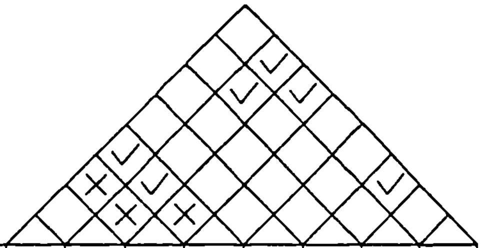


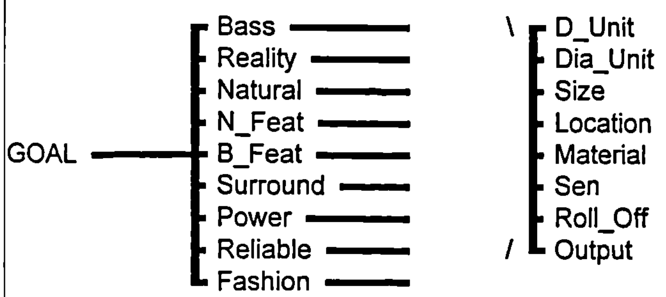
Figure 8.3: An Abridged Version of the Basic HoQ showing only the Product Attributes Category, Loudspeaker



Customer Attributes \ Product Attributes		Relative Degree of Importance (%)	No of drive units in a speaker	Diameter of unit	Size of speaker box	Drive units location in speaker box	Material of box / drive unit	Sensitivity	Bass roll off	Output power
			1	2	3	4	5	6	7	8
			↑	×	↓	×	×	↑	↓	↑
1	Strong bass	30.2	2.7	10.3	4.4	0.8	1.0	2.1	1.6	7.2
2	Reality, low loss and noise	20.5	4.3	6.7	3.2	0.6	0.9	2.2	1.1	1.6
3	Natural sounds	6.5	0.5	2.3	0.7	0.2	0.3	0.2	1.4	0.9
4	Contain multi-disc / MD / other new features	7.1	2.3	0.4	0.9	0.9	1.3	0.4	0.4	0.5
5	Contain all basic functional features (e.g. tuner, etc.)	10.3	3.5	1.6	1.1	0.3	0.6	0.4	0.5	2.3
6	More surround feature selection	2.2	0.6	0.3	0.1	0.1	0.2	0.1	0.2	0.6
7	Large output power	15.7	1.6	3.0	2.3	0.4	0.6	1.2	0.8	5.7
8	Reliable	3.2	0.3	0.3	0.4	0.3	1.4	0.2	0.2	0.3
9	Fashionable appearance & color	4.3	0.6	0.5	0.9	0.2	1.7	0.2	0.2	0.2
Relative Weight of Importance (%)			16.3	25.4	14.0	3.8	8.0	7.0	6.3	19.3

Figure 8.4: A Focused HoQ for the Design of Bass Loudspeaker Units

Further Analysis of New HiFi System



Abbreviation	Definition
GOAL	
B_Feat	Contain all basic functional features (e.g. tuners, radio, etc.)
Bass	Strong Bass
D_Unit	No of drive units in a speaker
Dia_Unit	Diameter of Unit
Fashion	Fashionable Appearance & Color
Location	Drive units location in speaker box
Material	Material of box / drive unit
N_Feat	Contain multi-disc drive / MD / other new features
Natural	Natural sounds
Output	Output Power
Power	Large Output Power
Reality	Reality, low loss and noise
Reliable	Reliable
Roll_Off	Bass Roll Off
Sen	Sensitivity
Size	Size of speaker box
Surround	More surround feature selection

Figure 8.5: The Structure and Definition of an AHP Model for Prioritising the Customer Attributes for Bass Loudspeaker Units

Node: 0

Compare the relative IMPORTANCE with respect to: GOAL <

1=EQUAL 3=MODERATE 5=STRONG 7=VERY STRONG 9=EXTREME

1	Bass	9	8	7	6	5	4	3	(2)	1	2	3	4	5	6	7	8	9	Reality
2	Bass	9	8	7	6	(5)	4	3	2	1	2	3	4	5	6	7	8	9	Natural
3	Bass	9	8	7	6	(5)	4	3	2	1	2	3	4	5	6	7	8	9	N_Feat
4	Bass	9	8	7	6	5	(4)	3	2	1	2	3	4	5	6	7	8	9	B_Feat
5	Bass	9	8	(7)	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Surround
6	Bass	9	8	7	6	5	4	(3)	2	1	2	3	4	5	6	7	8	9	Power
7	Bass	9	8	7	(6)	5	4	3	2	1	2	3	4	5	6	7	8	9	Reliable
8	Bass	9	8	7	6	(5)	4	3	2	1	2	3	4	5	6	7	8	9	Fashion
9	Reality	9	8	7	6	5	4	(3)	2	1	2	3	4	5	6	7	8	9	Natural
10	Reality	9	8	7	6	5	4	(3)	2	1	2	3	4	5	6	7	8	9	N_Feat
11	Reality	9	8	7	6	5	4	(3)	2	1	2	3	4	5	6	7	8	9	B_Feat
12	Reality	9	8	7	(6)	5	4	3	2	1	2	3	4	5	6	7	8	9	Surround
13	Reality	9	8	7	6	5	4	3	(2)	1	2	3	4	5	6	7	8	9	Power
14	Reality	9	8	7	(6)	5	4	3	2	1	2	3	4	5	6	7	8	9	Reliable
15	Reality	9	8	7	6	(5)	4	3	2	1	2	3	4	5	6	7	8	9	Fashion
16	Natural	9	8	7	6	5	4	3	2	(1)	2	3	4	5	6	7	8	9	N_Feat
17	Natural	9	8	7	6	5	4	3	2	1	(2)	3	4	5	6	7	8	9	B_Feat
18	Natural	9	8	7	6	5	(4)	3	2	1	2	3	4	5	6	7	8	9	Surround
19	Natural	9	8	7	6	5	4	3	2	1	2	(3)	4	5	6	7	8	9	Power
20	Natural	9	8	7	6	5	4	3	(2)	1	2	3	4	5	6	7	8	9	Reliable
21	Natural	9	8	7	6	5	4	3	(2)	1	2	3	4	5	6	7	8	9	Fashion
22	N_Feat	9	8	7	6	5	4	3	2	1	(2)	3	4	5	6	7	8	9	B_Feat
23	N_Feat	9	8	7	6	5	(4)	3	2	1	2	3	4	5	6	7	8	9	Surround
24	N_Feat	9	8	7	6	5	4	3	2	1	2	3	(4)	5	6	7	8	9	Power
25	N_Feat	9	8	7	6	5	4	(3)	2	1	2	3	4	5	6	7	8	9	Reliable
26	N_Feat	9	8	7	6	5	4	(3)	2	1	2	3	4	5	6	7	8	9	Fashion
27	B_Feat	9	8	7	6	(5)	4	3	2	1	2	3	4	5	6	7	8	9	Surround
28	B_Feat	9	8	7	6	5	4	3	2	1	(2)	3	4	5	6	7	8	9	Power
29	B_Feat	9	8	7	6	5	(4)	3	2	1	2	3	4	5	6	7	8	9	Reliable
30	B_Feat	9	8	7	6	5	4	(3)	2	1	2	3	4	5	6	7	8	9	Fashion
31	Surround	9	8	7	6	5	4	3	2	1	2	3	4	5	(6)	7	8	9	Power
32	Surround	9	8	7	6	5	4	3	2	1	(2)	3	4	5	6	7	8	9	Reliable
33	Surround	9	8	7	6	5	4	3	2	1	2	(3)	4	5	6	7	8	9	Fashion
34	Power	9	8	7	6	5	(4)	3	2	1	2	3	4	5	6	7	8	9	Reliable
35	Power	9	8	7	6	5	(4)	3	2	1	2	3	4	5	6	7	8	9	Fashion
36	Reliable	9	8	7	6	5	4	3	2	1	(2)	3	4	5	6	7	8	9	Fashion

Figure 8.6: Sample Inputs for the Pairwise Comparisons of Customer Attributes in the Design of Bass Loudspeaker Units

Further Analysis of New HiFi System

Abbreviation	Definition
Goal	Further Analysis of New HiFi System
Bass	
Reality	
Natural	
N_Feat	
B_Feat	
Surround	
Power	
Reliable	
Fashion	

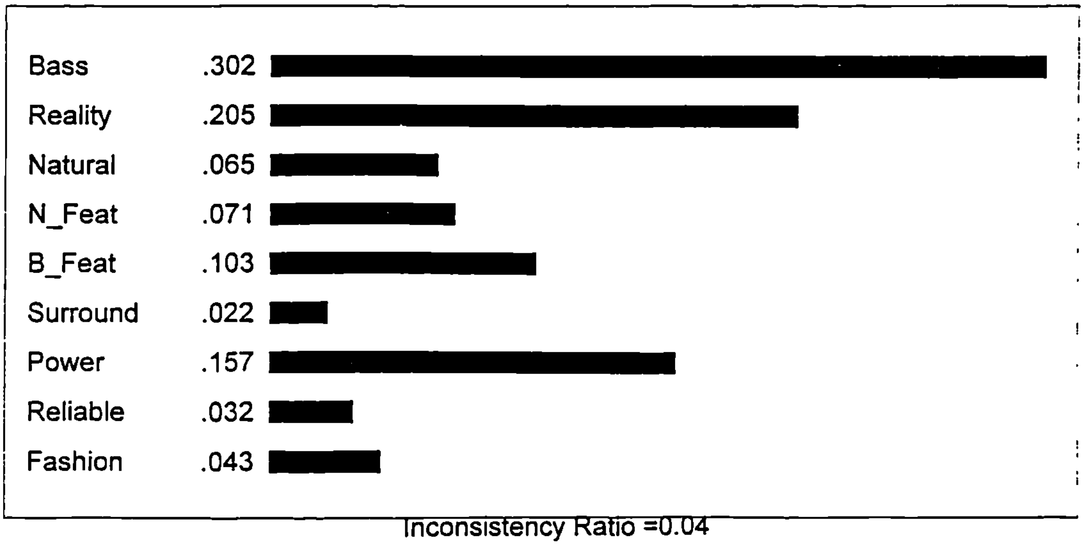


Figure 8.7: The Normalised Priorities for Customer Attributes derived from the AHP Exercise

Applying the Fuzzy Customer Requirement Inference System (FCRIS)

FCRIS is an interactive software system developed to support the analysis and interpretation of a given set of customer attributes by inferring the information held in the customer and product knowledge-bases as well as the fuzzy rule-base inter-linking the attributes. The system runs on PC's with interactive user interfaces. Responding to a specific set of customer attributes, **FCRIS** goes through the stages of fuzzification, rule evaluation and defuzzification, and in the end the crisp target values for the relevant product attributes are worked out as illustrated in the following example.

Example:

The simple fuzzy model used to demonstrate the features of **FCRIS** in this example comprises:

- Three Customer Attributes (Input Model Variables), namely "Bass", "Output Power" and "Reality" which are defined in Figure 8.9 and summarised in Figure 8.10 respectively;
- Two Product Attributes (Output Model Variables), namely "Diameter" and "Power Rating" of the Bass Loudspeaker Unit which are defined in Figure 8.11 and summarised in Figure 8.12 respectively;
- Thirty-six Fuzzy Rules (Propositions) represented in the form exemplified in Figure 8.13.

All the above data are entered into the system through the user interfaces in **FCRIS**. The fuzzy model is now ready to perform the fuzzy inference process against any specific set of customer requirements.

Further Analysis of New HiFi System

Synthesis of Leaf Nodes with respect to GOAL
Distributive Mode
OVERALL INCONSISTENCY INDEX = 0.04

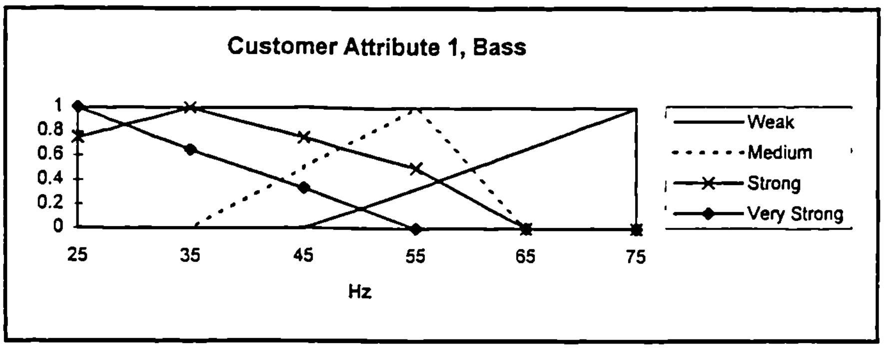
LEVEL 1	LEVEL 2		
Bass =.302		N_Feat =.071	
	Dia_Unit=.103		D_Unit =.023
	Output =.072		Material=.013
	Size =.044		Location=.009
	D_Unit =.027		Size =.009
	Sen =.021		Output =.005
	Roll_Off=.016		Dia_Unit=.004
	Material=.010		Sen =.004
	Location=.008		Roll_Off=.004
Reality =.205		Natural =.065	
	Dia_Unit=.067		Dia_Unit=.023
	D_Unit =.043		Roll_Off=.014
	Size =.032		Output =.009
	Sen =.022		Size =.007
	Output =.016		D_Unit =.005
	Roll_Off=.011		Material=.003
	Material=.009		Location=.002
	Location=.006		Sen =.002
Power =.157		Fashion =.043	
	Output =.057		Material=.017
	Dia_Unit=.030		Size =.009
	Size =.023		D_Unit =.006
	D_Unit =.016		Dia_Unit=.005
	Sen =.012		Location=.002
	Roll_Off=.008		Sen =.002
	Material=.006		Roll_Off=.002
	Location=.004		Output =.002
B_Feat =.103		Reliable=.032	
	D_Unit =.035		Material=.014
	Output =.023		Size =.004
	Dia_Unit=.016		D_Unit =.003
	Size =.011		Dia_Unit=.003
	Material=.006		Location=.003
	Roll_Off=.005		Output =.003
	Sen =.004		Sen =.002
	Location=.003		Roll_Off=.002

Figure 8.8: Summary of the Contributions of the Product Attributes to each of the Customer Attributes obtained from an AHP Exercise

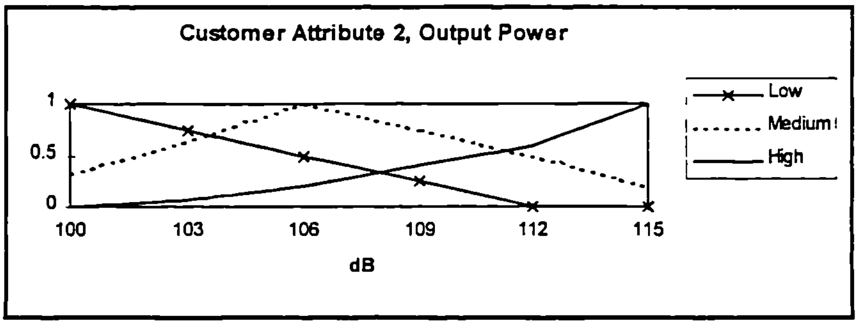
```
DATA DISPLAY OF THE FUZZY MODEL

          CUSTOMER ATTRIBUTE 1

Description                       : Bass
Minimum Value                     : 25
Maximum Value                     : 75
Number of Fuzzy Sets              : 4
Number of Domain Points           : 6
Unit of Measure                   : Hz
Domain points                     : 25,35,45,55,65,75,

Fuzzy set [0]                     : Unit -- 1,1,1,1,1,1,
Fuzzy set [1]                     : Weak -- 0,0,0,0.33,0.66,1,
Fuzzy set [2]                     : Medium -- 0,0,0.5,1,0,0,
Fuzzy set [3]                     : Strong -- 0.75,1,0.75,0.5,0,0,
Fuzzy set [4]                     : Very Strong -- 1,0.65,0.33,0,0,0,


          CUSTOMER ATTRIBUTE 2

Description                       : Output Power
Minimum Value                     : 100
Maximum Value                     : 115
Number of Fuzzy Sets              : 3
Number of Domain Points           : 6
Unit of Measure                   : dB
Domain points                     : 100,103,106,109,112,115,

Fuzzy set [0]                     : Unit -- 1,1,1,1,1,1,
Fuzzy set [1]                     : Low -- 1,0.75,0.5,0.25,0,0,
Fuzzy set [2]                     : Medium -- 0.32,0.65,1,0.75,0.5,0.2,
Fuzzy set [3]                     : High -- 0,0.06,0.2,0.4,0.6,1,


          CUSTOMER ATTRIBUTE 3

Description                       : Reality
Minimum Value                     : 83
Maximum Value                     : 98
Number of Fuzzy Sets              : 3
Number of Domain Points           : 6
Unit of Measure                   : dB
Domain points                     : 83,86,89,92,95,98,

Fuzzy set [0]                     : Unit -- 1,1,1,1,1,1,
Fuzzy set [1]                     : Low -- 0.75,1,0.5,0,0,0,
Fuzzy set [2]                     : Acceptable -- 0,0.3,0.6,1,0.7,0.5,
Fuzzy set [3]                     : High -- 0,0,0.35,0.8,1,0.6,
```

Figure 8.9: Definitions of the Input Model Variables (Customer Attributes) for the Sample Fuzzy Model

Customer Attribute 1, Bass						
Unit of Measure (Hz)	25	35	45	55	65	75
Weak	0	0	0	0.33	0.66	1
Medium	0	0	0.5	1	0	0
Strong	0.75	1	0.75	0.5	0	0
Very Strong	1	0.65	0.33	0	0	0



Customer Attribute 2, Output Power						
Unit of Measure (dB)	100	103	106	109	112	115
Low	1	0.75	0.5	0.25	0	0
Medium	0.32	0.65	1	0.75	0.5	0.2
High	0	0.06	0.2	0.4	0.6	1



Customer Attribute 3, Reality						
Unit of Measure (dB)	83	86	89	92	95	98
Low	0.75	1	0.5	0	0	0
Acceptable	0	0.3	0.6	1	0.7	0.5
High	0	0	0.35	0.8	1	0.6

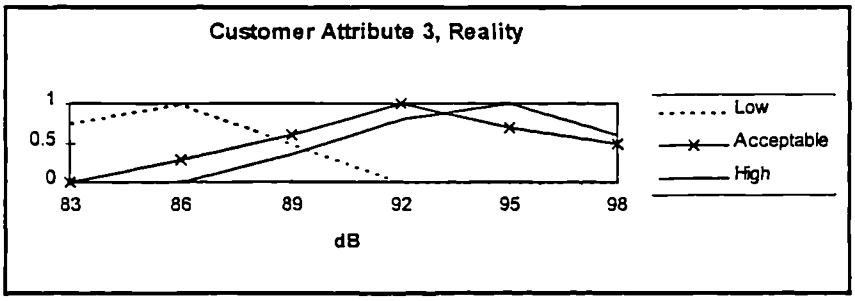


Figure 8.10: Summary of the Fuzzified Customer Attributes for the Sample Fuzzy Model

PRODUCT/ENGINEERING ATTRIBUTES 1

Description	: Diameter of Bass Unit
Minimum Value	: 100
Maximum Value	: 300
Number of Fuzzy Sets	: 4
Number of Domain Points	: 6
Unit of Measure	: mm
Domain range	: 100,140,180,220,260,300,
Fuzzy set [0]	: Unit -- 1,1,1,1,1,1,
Fuzzy set [1]	: Small -- 0.44,1,0.5,0.25,0,0,
Fuzzy set [2]	: Medium -- 0,0.75,1,0.3,0.15,0,
Fuzzy set [3]	: Large -- 0,0.3,0.78,1,0.8,0.45,
Fuzzy set [4]	: Very Large -- 0,0.15,0.6,0.83,1,1,

PRODUCT/ENGINEERING ATTRIBUTES 2

Description	: Power Rating
Minimum Value	: 30
Maximum Value	: 280
Number of Fuzzy Sets	: 5
Number of Domain Points	: 6
Unit of Measure	: W
Domain range	: 30,80,130,180,230,280,
Fuzzy set [0]	: Unit -- 1,1,1,1,1,1,
Fuzzy set [1]	: Very Low -- 1,0.75,0.25,0.1,0,0,
Fuzzy set [2]	: Low -- 0.55,1,0.6,0.35,0,0,
Fuzzy set [3]	: Medium -- 0.15,0.33,1,0.57,0.27,0,
Fuzzy set [4]	: High -- 0,0.14,0.8,1,0.75,0.5,
Fuzzy set [5]	: Very High -- 0,0,0.33,0.55,0.9,1,

Figure 8.11: Definitions of the Output Model Variables (Product Attributes) for the Sample Fuzzy Model

Assuming an important customer would like to place an order for a large quantity of Bass Loudspeaker Units which have to satisfy the following criteria:

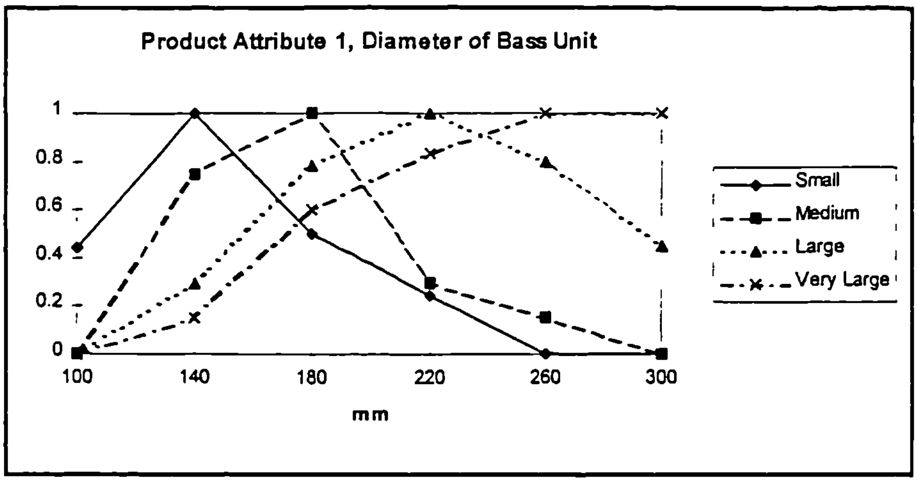
a) The Bass is "fairly strong";
b) The Output Power is "extremely high"; and
c) The Reality is "above average acceptable".

In order to gain this order, the product engineer is now going to determine the minimum i) "Diameter" and ii) "Power Rating" of the Bass Loudspeaker Units required to fulfil the above criteria. **FCRIS** is applied to perform the task as explained below:

- Invoke **FCRIS** and activate the relevant fuzzy model for the design of Bass Loudspeaker Unit;
- Run the Fuzzy Inference Programme;
- Select the Product Attribute, i.e. Diameter of the Bass Unit;
- Fuzzify the above customer requirements a), b) & c) by modifying the membership functions of existing fuzzy sets or by creating new fuzzy sets to describe the relevant Input Model Variables "Bass", "Output Power" and "Reality" as illustrated in Figures 8.14, 8.15 and 8.16 respectively;
- After fuzzification, the software will evaluate the fuzzy rule-base against the input requirements and some sub-conclusions will be drawn;
- These sub-conclusions representing the output fuzzy sets are aggregated to yield an individual output fuzzy region for each product attribute;
- The output fuzzy regions are then defuzzified. The results suggest the crisp Target Values of 224.3mm and 155W for the output model variables, "Diameter of Bass Unit" and "Power Rating" respectively.

Product/Engineering Attributes (Loud Speaker)

Product Attribute 1, Diameter of Bass Unit						
Unit of Measure (mm)	100	140	180	220	260	300
Small	0.44	1	0.5	0.25	0	0
Medium	0	0.75	1	0.3	0.15	0
Large	0	0.3	0.78	1	0.8	0.45
Very Large	0	0.15	0.6	0.83	1	1



Product Attribute 2, Power Rating						
Unit of Measure (Watt)	30	80	130	180	230	280
Very Low	1	0.75	0.25	0.1	0	0
Low	0.55	1	0.6	0.35	0	0
Medium	0.15	0.33	1	0.57	0.27	0
High	0	0.14	0.8	1	0.75	0.5
Very High	0	0	0.33	0.55	0.9	1

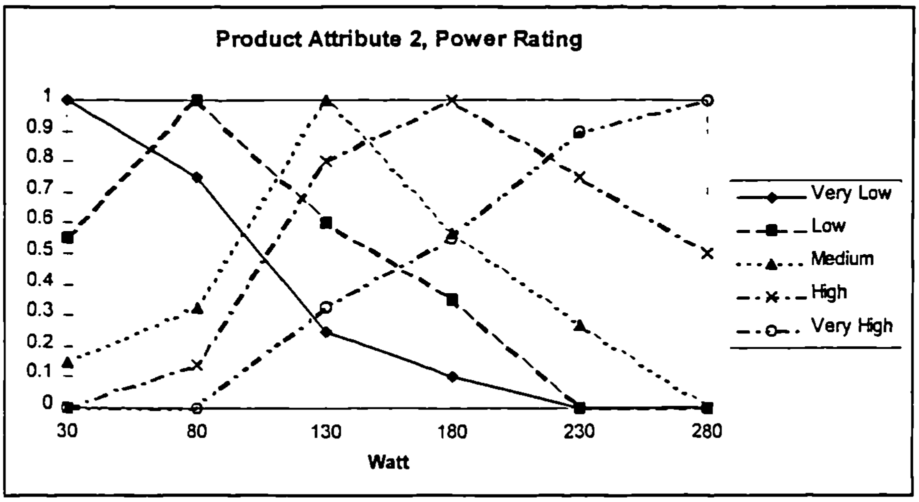


Figure 8.12: Summary of the Fuzzified Product Attributes for the Sample Fuzzy Model

```
DATA DISPLAY OF THE FUZZY MODEL

PRODUCT/ENGINEERING ATTRIBUTE - Diameter of Bass Unit

         FUZZY RULE BASE 32

If

        Bass is strong
        Output Power is high
        Reality is high

Then

        Diameter of Bass Unit is very large
```

Figure 8.13: A Typical Fuzzy Proposition relating the Customer Attributes to the Product Attributes in the Sample Fuzzy Model

```
For the Product/Engineering Attribute [1] Diameter of Bass Unit

The membership function of Bass
The domain range is from 25 to 75 Hz
0. The Fuzzy set 'unit' : 1,1,1,1,1,1,
1. The Fuzzy set 'weak' : 0,0,0,0.33,0.66,1,
2. The Fuzzy set 'medium' : 0,0,0.5,1,0,0,
3. The Fuzzy set 'strong' : 0.25,0.5,1,0.5,0,0,
4. The Fuzzy set 'very strong' : 1,0.55,0.4,0,0,0,
Do you want to apply the existing fuzzy sets (Y=Yes(default) or N=No)?
Which fuzzy set do you want (0-4) ? 3
The chosen fuzzy set is 'strong' -- 0.25,0.5,1,0.5,0,0,
Do you want to apply hedges to the chosen fuzzy set (Y=Yes or N=No(default))?
( 1.extremely 2.very 3.more 4.just more  )
( 5.average 6.fair 7.just less 8.less  )
Please select the appropriate hedge (1-8).3

The input fuzzy set of Bass becomes 'more strong'
=0.0625,0.25,1,0.25,0,0,
Would you like change these value (Y=Yes, No=(default))?
```

Figure 8.14: Modifying the Membership Function of the relevant Fuzzy Set for the Input Model Variable, Bass to represent the specific Customer Attribute, "Fairly Strong" Bass

Through the above fuzzy inference and calculations, the Bass Loudspeaker Units in question are found to need a minimum Diameter of 224.3mm and a minimum Power Rating of 155W in order to satisfy the set of requirements specified by the customer. Since definitive formulae for coping with fuzzy VoC are practically unavailable, without **FCRIS** the design engineers would have to resort to estimation by the rules of thumb to estimate the necessary design targets.

8.6.1 Remarks on FCRIS

The functionality of the **FCRIS** has been demonstrated in the last section. It can be noticed that the system is simple to understand and easy to use, and its effectiveness will very much depend on the following factors:

- The accuracy and timeliness of the customer and product data;
- The correct representation of the data with the relevant model variables and fuzzy sets in the knowledge bases;
- The validity and completeness of the fuzzy rule-base in describing the relationships between the attributes;
- The proper interpretation of any incoming customer requirements by selecting the appropriate fuzzy sets, and applying the relevant hedges.
- The complexity of the product being considered and extent of domain discretisation.

All these points can affect the performance of **FCRIS**. The systems response time can be substantially slowed down from less than one minute for a simple problem as illustrated in this case study to so long as half an hour as the problem becomes more complex when the model is run on a PC. A more powerful hardware platform, such as a super PC or a workstation, is recommended, if the proposed model is to be commercialised for use in the industry in order to warrant a more acceptable systems performance.

In conclusion, **FCRIS** can be used as a tool to help product engineers and designers project the dynamic and sometimes imprecise customer requirements into the corresponding target values for specific product design features. However, the effectiveness of the system does rely on the extent to which the VoC is understood, the completeness, and the accuracy of the knowledge bases as well as the proper interpretation of the results from the inference process.

8.7 Epilogue

This case study purports to give an overall demonstration of the hybrid approach proposed in this research. It covers the entire sequence of events right from the initial acquisition of basic customer and product attributes, through various data analyses, manipulation, representations, and finally to the fuzzy inference of specific customer requirements to yield the relevant design targets. Extensive inputs from experienced hi-fi users and product designers have been solicited throughout this exercise with the help of the questionnaires as attached in Appendix III.

At the end of the case study, engineering and marketing personnel from some hi-fi manufacturing firms were also invited to comment on the practical value of the proposed hybrid model. Their general response was positive, and they recognised that the approach could offer a useful tool to the product designers to systematically analyse and filter the VoC. They were particularly interested in the quantitative method of determining the design targets for various product attributes more objectively and consistently than the ad hoc rules of the thumb approaches they used to apply.

However, some of them expressed the concerns that substantial manual efforts are still required to set up the initial HoQ's and knowledge bases. Others *questioned* that if flexibility has been built into the system to cope with the requirements of more diverse product types and market sectors. For instance, new technology and standards are more desirable when dealing with an industrial user, while fashion, brand name and personal tastes may carry more weight when designing for the consumer market.

The latter comments have actually been borne in mind during the design of the hybrid model. With the generic systems approach, the choice of focus groups for the surveys and knowledge acquisitions, and the representation of the attributes relationships could be configured to suit different product or market scenarios. The former issue concerning the possible heavy workload required to set up the initial HoQ's and knowledge bases will be addressed in Chapter 9, and certain further work on dynamic HoQ construction and integrated knowledge representation will be recommended to that effect in Chapter 10 of this thesis.

8.8 Summary

In this chapter, the concepts and principles of the proposed hybrid model have been put into a practical context. A case study describing the design of a mid-range hi-fi equipment has been vividly presented. It covers the following systems aspects:

- the capture and interpretation of the customer requirements,
- the identification of the essential product features,
- the representation of the findings in a basic HoQ,

- the construction of a Focused HoQ,
- the prioritisation of the attributes,
- and finally the determination of the appropriate design targets in response to specific customer requirements.

The knowledge and propositions chosen for the case study are so well known and easy to understand that readers readily feel at home with the scenario and manage to find their way round without any difficulty. The detailed explanation of the procedures in implementing and applying the hybrid model with illustrative examples has helped clarify readers' queries on the approach and demonstrate how the stated objectives of this research programme can be achieved using the proposed hybrid model.

Chapter 9
Conclusions

9.1 Introduction

The process of developing a product that will be well received by the market begins with tapping the sources of ideas. These sources might be customer demands, technological development, new practices in engineering or production, inventions or patents resulting from research & development work, as well as the innovations initiated by the competitors. The findings are analysed, new ideas are generated and as a result improved product concepts will emerge. Marketing, design and engineering expertise will be called upon to evaluate the market potential of these new ideas and concepts, to adjust or refine their product positioning, and finally to convert the projected attributes into reality in the relevant products.

In practice, a significant proportion of successful product innovations are the results of prompt recognition of customer requirements and market demands. However, the VoC usually contains a degree of ambiguity and imprecision. This fuzziness innate in the VoC often complicates the transformation of market profiles into technical specifications, definitive design targets and performance measures.

9.2 Functional Characteristics of the Proposed Hybrid Model

This research puts forward an intelligent hybrid model which tackles customer requirements management through:

- Capturing the Customer Attributes;
- Identifying the relevant Product Attributes,

- Interpreting the attributes using the principles of QFD in the structural framework of an HoQ;
- Categorising and prioritising the attributes;
- Investigating the inter-relationships as well as the correlation among the attributes;
- Extracting the more important categories of attributes into a number of Focused HoQ's for further analyses;
- Applying the AHP to determine the quantified contributions of each product attribute towards the fulfilment of various customer requirements;
- Finally, using fuzzy inference to determine the quantitative target values / technical goals for individual product design features in response to any given set of customer requirements.

This hybrid model represents an original and novel approach to the analysis and interpretation of the linguistic and quite often imprecise customer requirements from various sources of ideas. The principles and characteristics of a number of well proven techniques and methodologies including QFD, HoQ, Affinity Diagram, AHP and Fuzzy Logic are merged for the first time to decode and respond to the VoC covering the general as well as specific issues. Any incoming customer requirements can be processed by the model to project and identify the relevant product features, and subsequently their design targets can be obtained. The combination of all these proven techniques to drive the fuzzy inference engine in order to determine the technical design targets represents the originality of this Ph.D. research. These target values set the goals for downstream manufacturing activities including materials planning, process planning and production planning, etc.

The proposed fuzzy inference mechanism has been coded into a software programme, **FCRIS** using an object-oriented language, C++ in order to allow the system to be applied easily and swiftly in an interactive manner. The knowledge bases supporting **FCRIS** can be updated and enhanced at the discretion of the users with any newly acquired information at the conclusion of each inference process for future systems applications. With its unique features in decoding the VoC and analysing other market related data, the proposed model can strengthen a company's ability in understanding and responding to the dynamic customer demands and as well as counteracting against the fierce competitions. As a result, a more effective product and market strategy can be formulated accordingly.

The proposed hybrid approach is demonstrated in a case study in Chapter 8. It has been shown a comprehensive and effective methodology for coping with the dynamic and largely linguistic customer / market demands. The relevant definitive and crisp technical product specifications can be determined in a structured and systematic fashion. The software system, **FCRIS** can facilitate the fuzzy inference process and allow new design targets to be set quickly and effectively during a product design or a re-engineering exercise.

9.3 Major Merits of the Hybrid Model

The strengths of the proposed model can be summarised as follows:

- It is generic. The model can be applied to any type of products in the industrial, commercial and service sectors, as long as the relevant attributes have been identified and the knowledge and rule bases have been established.
- It is easily expandable. The model encompasses a number of well proven techniques and methodologies to perform a sequence of inter-linked processes which can be arranged to suit different problem domains. The choices of techniques used are by no means exhaustive, other suitable tools and

methodologies can be incorporated when and where necessary. Some of the possible areas of improvement to the hybrid model will be suggested in Chapter 10 for future research pursuits.

- The systems intelligence and accuracy can be enhanced continuously. The knowledge bases and rule base for the fuzzy inference process can be constantly enriched and updated with experience gained through tackling real-life scenarios.
- The supporting software, **FCRIS** is straight-forward to master and simple to apply. Its operating parameters can be easily configured to suit any dynamic product and requirements patterns.

9.4 Limitations of the Hybrid Model

In its present form, the application of the proposed hybrid model is hampered by the following limitations:

- The representation of the attributes and manipulation of the data in an HoQ are primarily performed manually, and they tend to be cumbersome and time-consuming.
- The significance and impacts of the inter-dependency / orthogonality among the product attributes as highlighted in the correlation matrix in an HoQ required further investigation. This problem is particularly crucial when the attributes happen to be interfering with one another as suggested by their negative correlation.
- The current mathematical representation in the fuzzy model requires a large volume of internal arrays during matrix computations, particularly when an increasing number of domain points have to be dealt with in the universe of discourse. Hence, the systems response time will suffer when tackling a more complex product design.

- The user interfaces of the fuzzy inference software, **FCRIS** are character-based. Although they can support normal data maintenance and parameters specifications reasonably well, their screen handling capabilities tend to be old-fashioned and less flexible in comparison with the more popular windows-based presentations.
- Although tackling a relatively simple problem similar to the one quoted in the case study on a Pentium PC normally just takes a few minutes, the systems performance can significantly deteriorate as the problem becomes more complex. A more powerful hardware platform other than PC's may have to be used to secure a more acceptable response time, say of less than 15 minutes for more complex products.

All the same, the above limitations are not believed to hinder the functional application nor undermine the practical value of the proposed model, instead they can be viewed as some distinct opportunities for improving and extending the scope of the current research.

9.5 Summary

The approach proposed in this research can decode the VoC more effectively through extending the basic applications of QFD and HoQ quantitatively towards a new horizon of determining the technical design targets with the help of artificial intelligence. The principles and applications of the intelligent hybrid model for customer requirements analysis and product design targets determination have been explained and discussed throughout this thesis. The novel ideas of structuring the Focused HoQ with the use of AHP and Affinity Diagram for particular categories of product attributes, and implementing the fuzzy inference process using linear algebra have been vividly expounded. The potential areas for further improving the approach and enhancing the performance of the supporting software will be recommended in Chapter 10.

Thus, the central research theme of rationalising and improving the conventional approach in customer requirement analysis and design target determination has been fulfilled, and the aim and objectives set out for this Ph.D. research have all been achieved.

Furthermore, in addition to achieving the research objectives, the applicability of those well proven methodologies employed in the proposed hybrid model for analysing and exploring the information made available by the essentially qualitative techniques of QFD has been demonstrated. The outcomes from this hybrid intelligent approach can support more meaningful and reliable downstream manufacturing planning and control, and ultimately improve the customer-valued performance of a product.

Chapter 10

Future Work

10.1 Introduction

In order to improve the practicality, extend the scope of applications and overcome the limitations of the proposed hybrid approach for customer requirements management, certain items of work are recommended in the following sections.

10.2 Improving the Data Representation and Manipulation in an HoQ

The current manual method of attributes representation and data manipulation in an HoQ can be further automated. Proprietary software packages, such as QFD Design supplied by Qualisoft / Fulfilment Services, USA, can offer an easy and interactive way of specifying the entries in an HoQ. However, they cannot support the quantitative and focused analyses proposed in this research. As a better alternative, the research work currently undertaken at Loughborough University, UK in the development of an intelligent QFD support system under the MOSES (Model Oriented Simultaneous Engineering Systems) Concurrent Engineering Architecture (Omar, Harding & Popplewell, 1997) can be adopted to facilitate the construction and maintenance of the HoQ's in the hybrid model. In addition, in order to facilitate its application, the Affinity Diagram for attributes categorisation in the model can also be automated using a simple computer programme to substitute the conventional manual procedures.

10.3 In-depth Investigation of the Attributes Inter-Dependency and Correlation

As explained in Section 3.4.8, the inter-dependency among the product attributes as indicated in the Correlation Matrix of a typical HoQ is the least exploited area in QFD. However, these relationships have significant implications on resource deployment among the product attributes. They also affect the effectiveness of satisfying customer requirements particularly when the attributes are negatively correlated and quite possibly interfering with one another. For instance, "reducing the weight of a car body for better fuel economy" and "improving its collision resistance through using stronger material" are both important product attributes of a motor car, but their design principles may well be contradicting each other in practice.

Further studies are recommended in this area to alleviate the negative elements and improve the orthogonality among the attributes so that the design resources can be more effectively deployed towards meeting the customer requirements.

10.4 More Integrated and Generic Knowledge Representation

As it stands, the knowledge bases supporting the fuzzy inference process in **FCRIS** are created and maintained through character-based users interfaces which work reasonably well with simple products. However, as the knowledge bases will expand with its subsequent applications, its easy access and prompt maintenance are very important in order to tackle more diverse product design problems. Therefore, it would be advantageous if a common knowledge base, which can be accessed, shared and updated by other activities in the overall manufacturing system, is established. Such a common pool of knowledge will be particularly useful when a new product is being designed and the prompt interactions from various parties are critical in an overall concurrent engineering architecture.

Further work is thus recommended to incorporate the hybrid model into an overall framework of product design using a common knowledge base so that the information can be more readily available to all parties concerned. The Knowledge Representation Model (KRM) in a Computer-Aided Engineering (CAE) system architecture, as explained in the MOSES (Harding & Popplewell, 1994 a,b & 1995) (Molina et al., 1994 & 1995), will provide an ideal environment into which the proposed hybrid model can be integrated.

10.5 Improving the Users Interfaces in FCRIS

FCRIS was coded in C++, an object-oriented programming language, offering more traditional character-based users interfaces. It will be better if more user-friendly interfaces can be designed to improve the screen handling capabilities and ease the interaction with the system. One possible way of achieving this is to re-code the system using a windows-based programming language, such as Visual C++, if the system is to run on a PC platform. Alternatively, the system can be implemented as an element of the single Federated Object Oriented Database (FOOD) with graphical users interfaces (GUI) utilising the OSF/Motif package which runs on SUN Sparc workstations. The latter option has the advantage of being more easily synchronised with the knowledge representation work recommended above so that they can both operate on the same hardware platform.

10.6 Improving the Systems Performance of FCRIS

The fuzzy inference process in **FCRIS** was modelled using linear algebra, and the relevant calculations involved a series of matrix multiplication and compositions which require a large volume of internal arrays. As the fuzzy model becomes more complex with increased number of attributes and inference rules, the system response time will inevitably deteriorate. One way of speeding up the operations of the system is to express those conditional matrices and rule matrices which are holding a large proportion of null entries into more compact and concise Sparse Matrices (Schendel, 1989). These sparse matrices will have much reduced dimensions, and thus less internal arrays will be tied up during the fuzzy inference computations. As a result, the system will be able to run faster, and more complex fuzzy models can be processed more efficiently within a much shorter time span.

10.7 Summary

The proposed intelligent hybrid model addresses the acquisition and processing of customer requirements. It purports to clarify and compress the fuzzy front end in the product design cycle by performing some quantitative analyses and determining the relevant technical targets to guide downstream activities in product planning and manufacturing. However, many related areas including the data manipulations in HoQ's, the inter-dependency of attributes, the knowledge representation, the software interfaces and the mathematical modelling, can be further studied and improved. Supported by these additional efforts, the hybrid model proposed in this research will be further strengthened to become an integral building block in the overall architecture of the market-focused culture in modern manufacturing.

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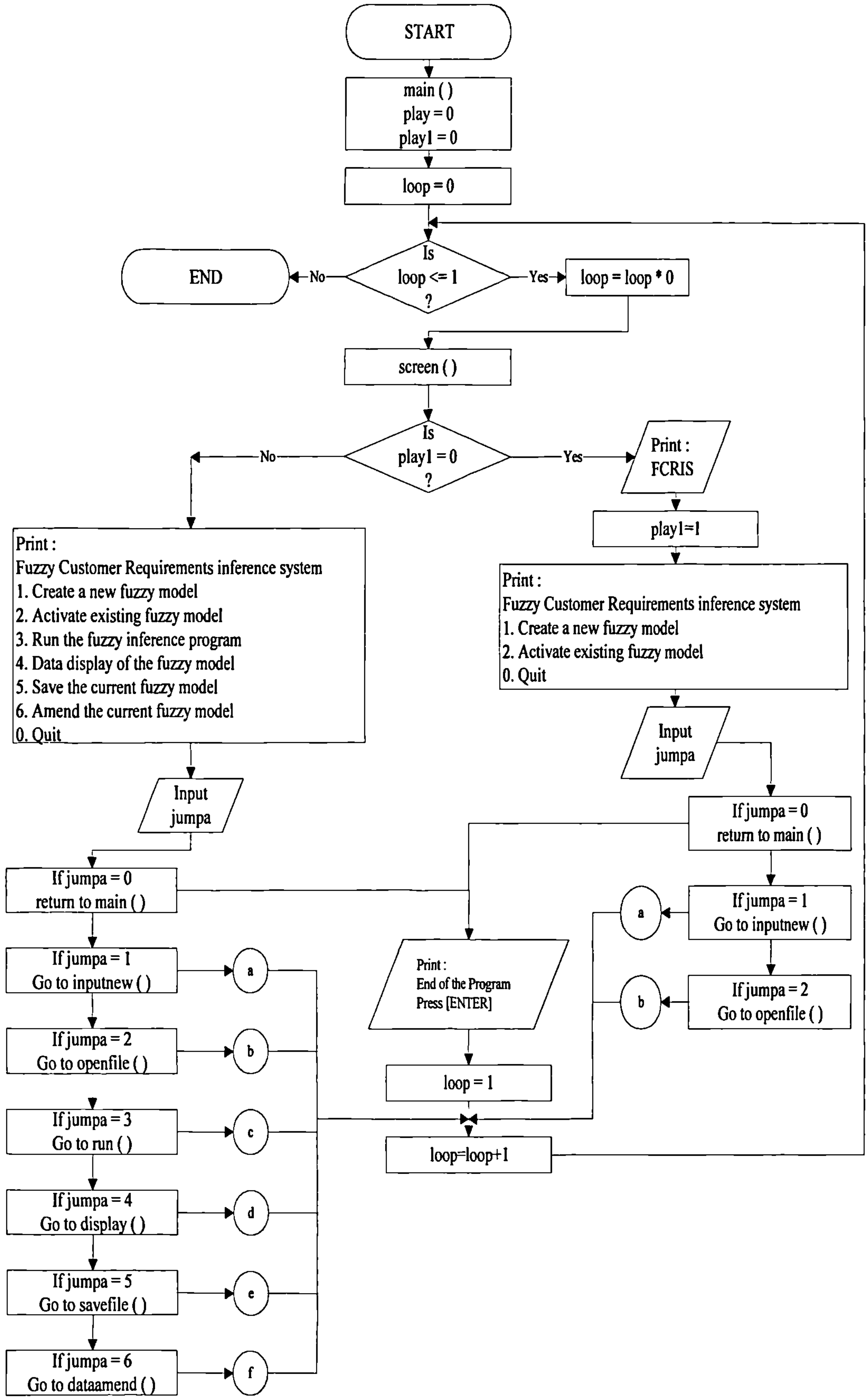
APPENDIX I

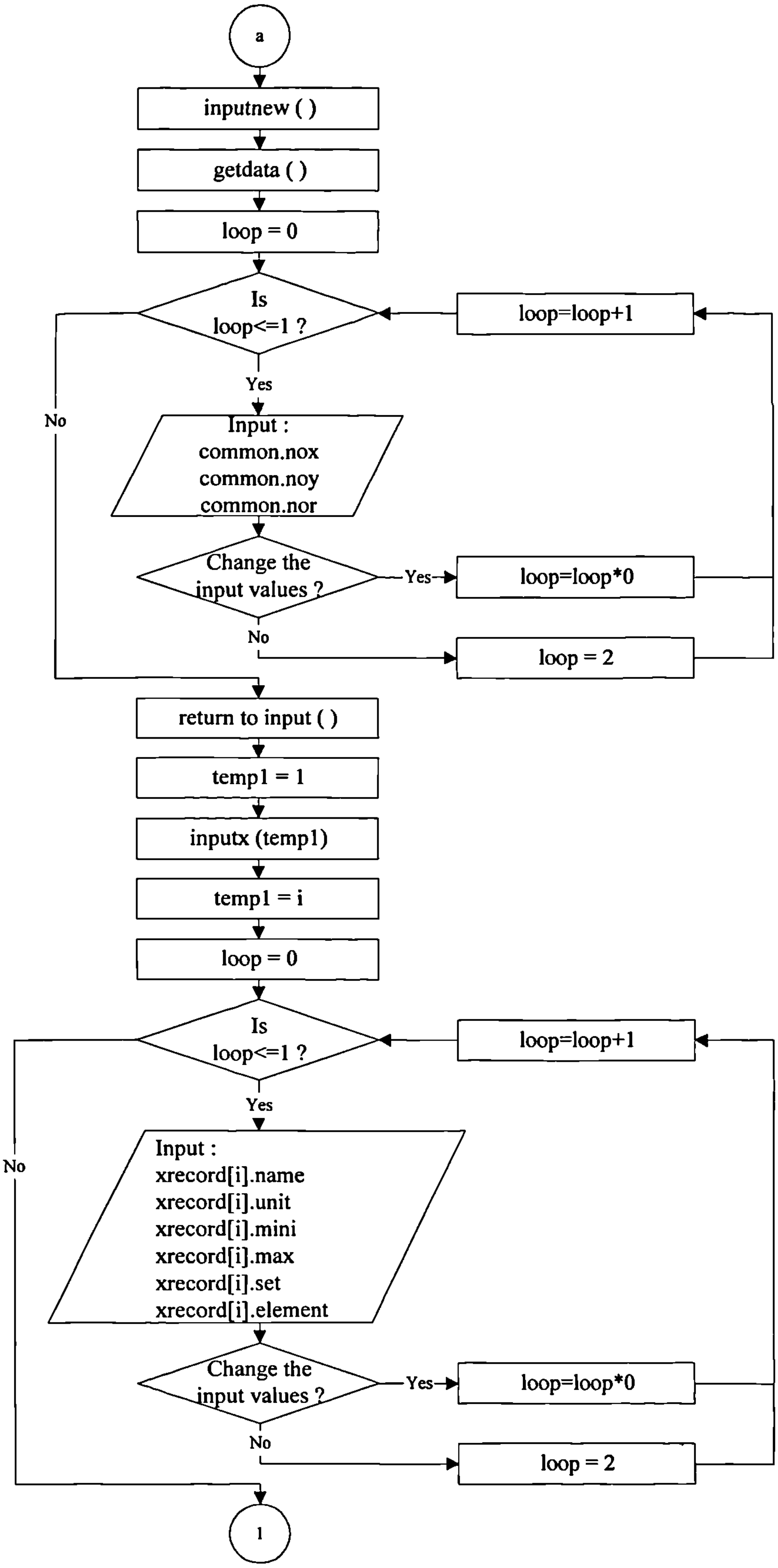
FLOW DIAGRAMS OF THE

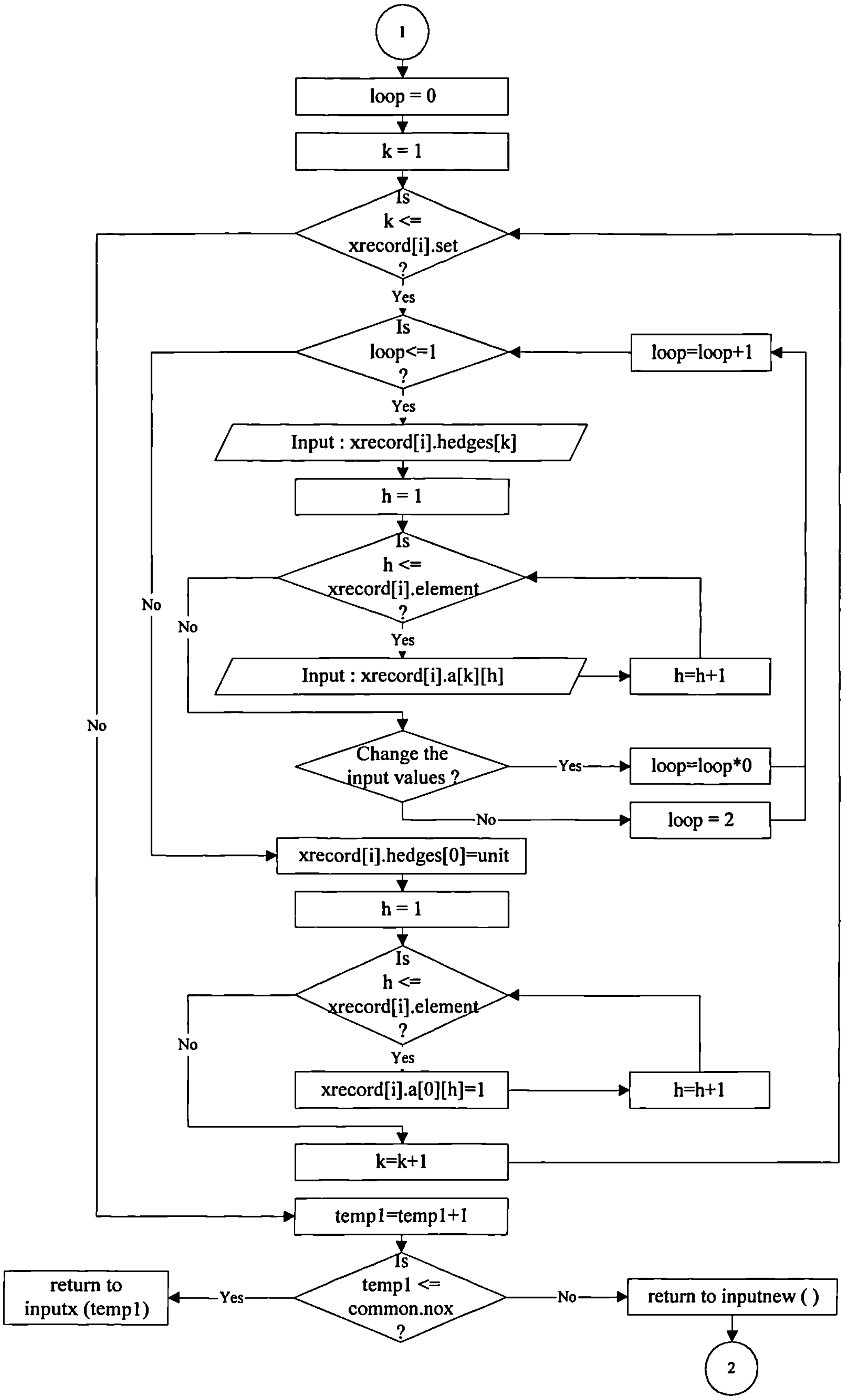
FUZZY CUSTOMER REQUIREMENT

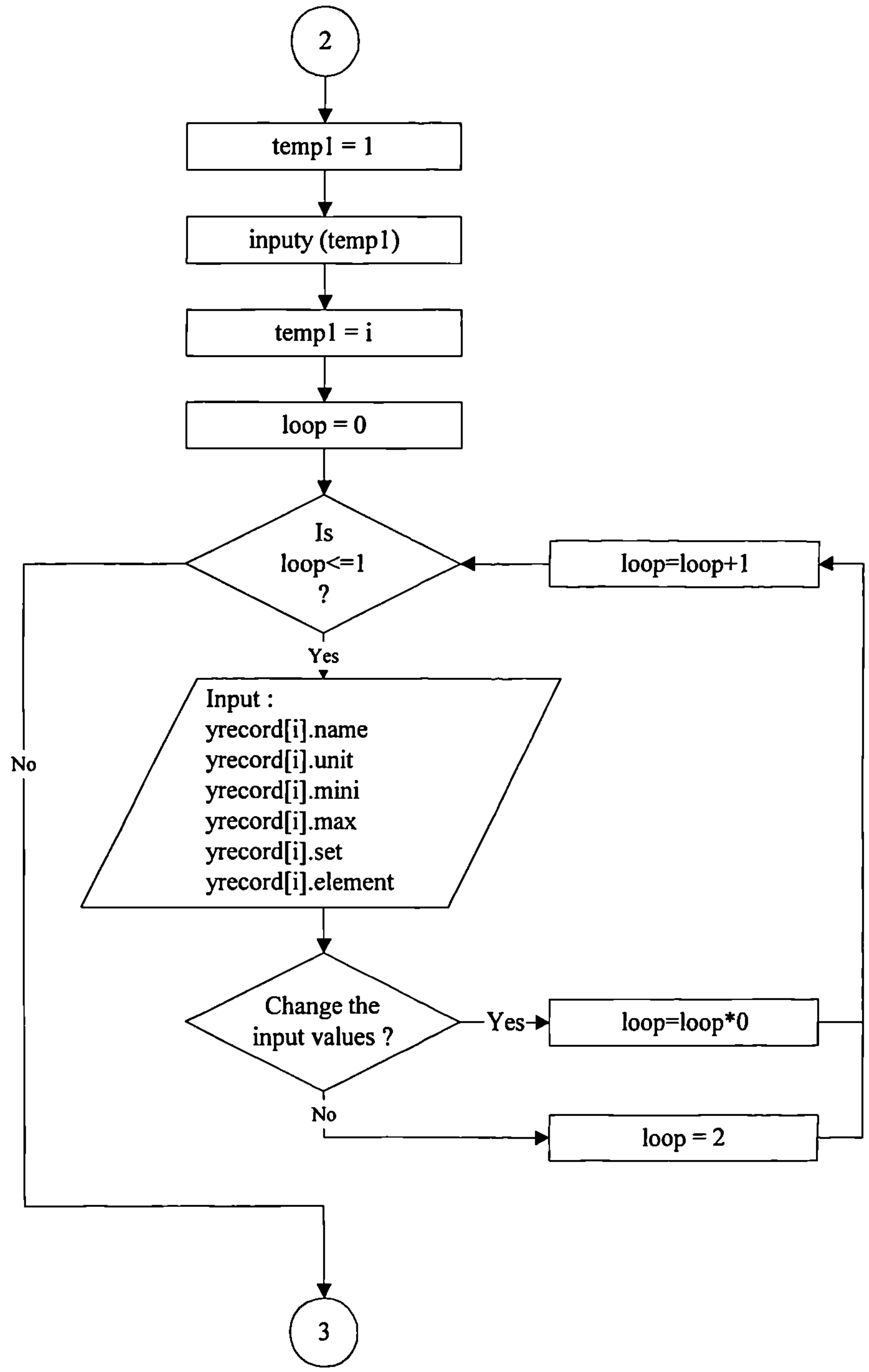
INFERENCE SYSTEM

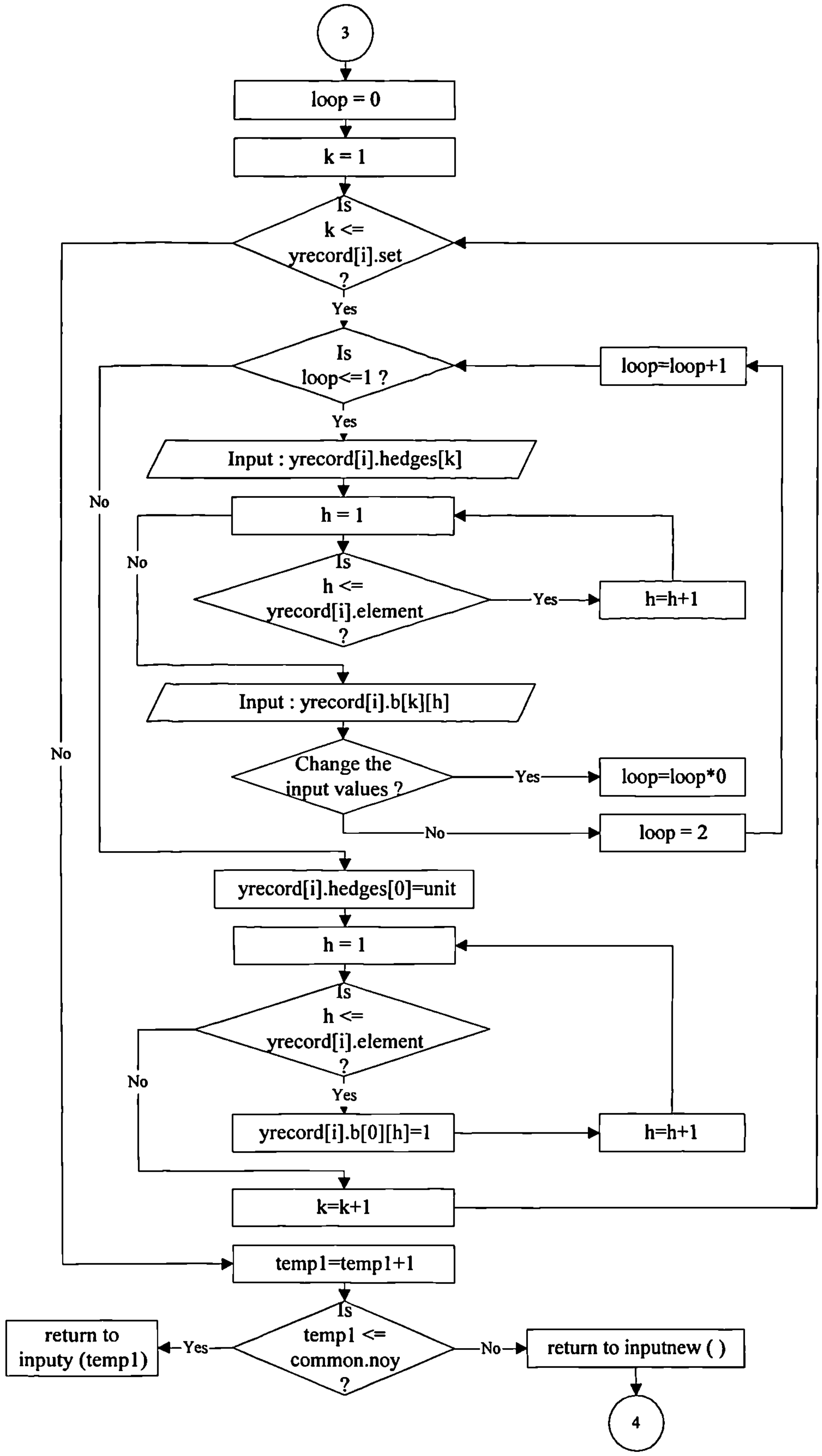
(FCRIS)

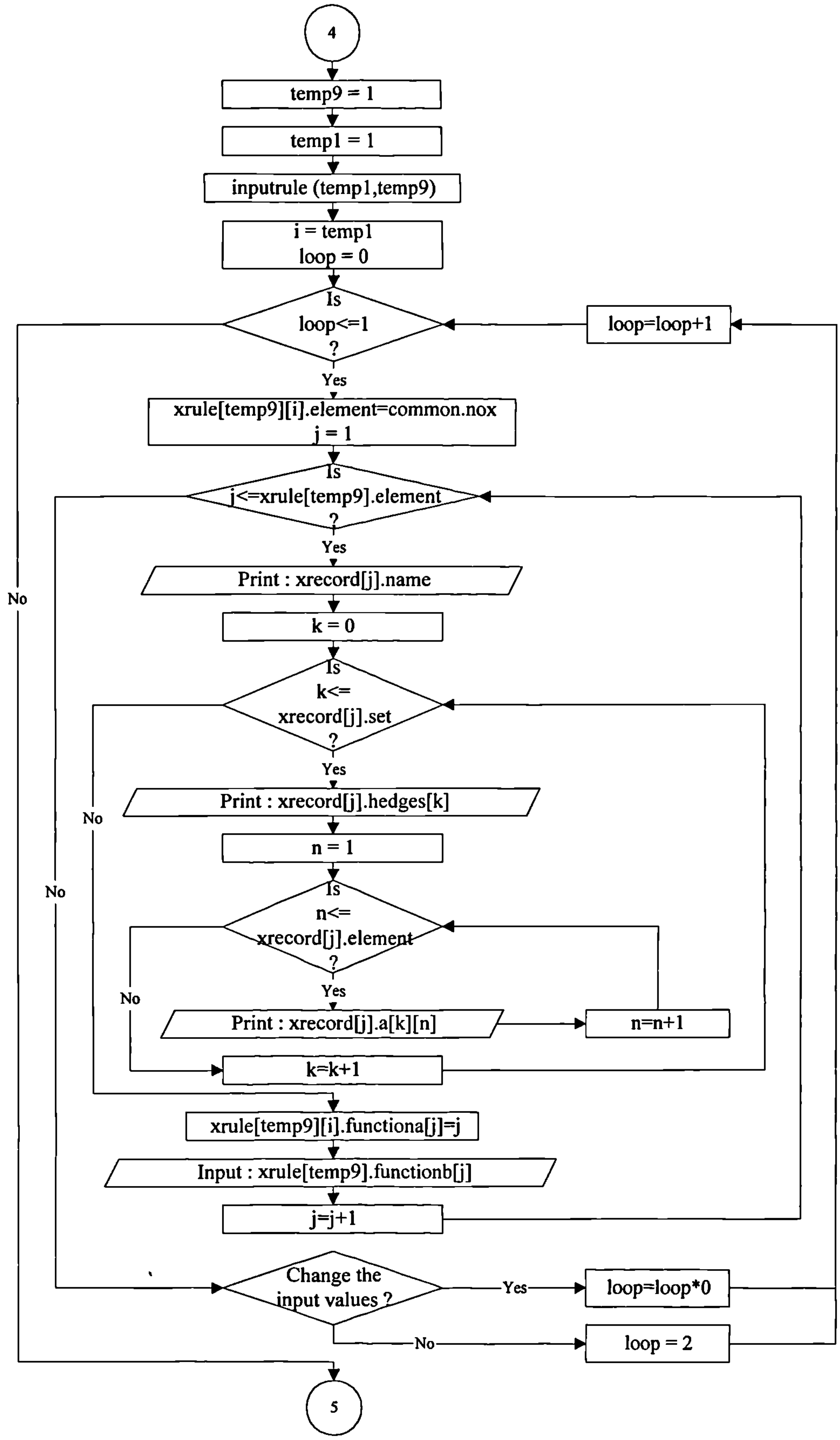

START
main ( )
play = 0
play1 = 0
loop = 0
END
No
Is
loop <= 1
?
Yes
loop = loop * 0
screen ( )
Is
play1 = 0
?
No
Yes
Print :
FCRIS
play1=1
Print :
Fuzzy Customer Requirements inference system
1. Create a new fuzzy model
2. Activate existing fuzzy model
3. Run the fuzzy inference program
4. Data display of the fuzzy model
5. Save the current fuzzy model
6. Amend the current fuzzy model
0. Quit
Print :
Fuzzy Customer Requirements inference system
1. Create a new fuzzy model
2. Activate existing fuzzy model
0. Quit
Input
jumpa
Input
jumpa
If jumpa = 0
return to main ( )
If jumpa = 0
return to main ( )
If jumpa = 1
Go to inputnew ( )
If jumpa = 1
Go to inputnew ( )
If jumpa = 2
Go to openfile ( )
If jumpa = 2
Go to openfile ( )
If jumpa = 3
Go to run ( )
If jumpa = 4
Go to display ( )
If jumpa = 5
Go to savefile ( )
If jumpa = 6
Go to dataamend ( )
a
b
c
d
e
f
a
b
Print :
End of the Program
Press [ENTER]
loop = 1
loop=loop+1


a
inputnew ( )
getdata ( )
loop = 0
Is loop<=1 ?
loop=loop+1
Yes
No
Input : common.nox common.noy common.nor
Change the input values ?
Yes
loop=loop*0
No
loop = 2
return to input ( )
temp1 = 1
inputx (temp1)
temp1 = i
loop = 0
Is loop<=1 ?
loop=loop+1
Yes
No
Input : xrecord[i].name xrecord[i].unit xrecord[i].mini xrecord[i].max xrecord[i].set xrecord[i].element
Change the input values ?
Yes
loop=loop*0
No
loop = 2
1

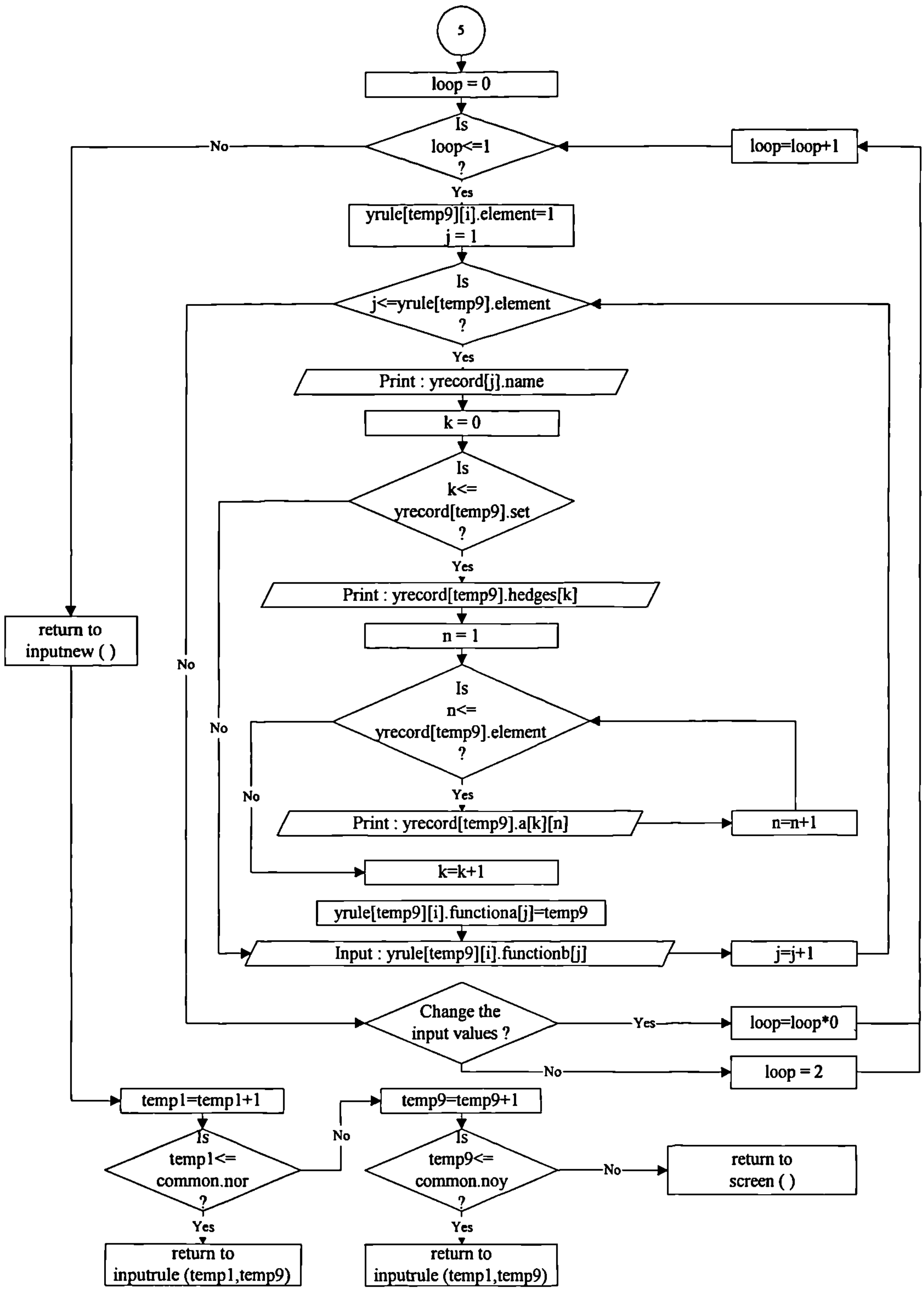

1
loop = 0
k = 1
Is k <= xrecord[i].set ?
Yes
No
Is loop<=1 ?
Yes
No
loop=loop+1
Input : xrecord[i].hedges[k]
h = 1
Is h <= xrecord[i].element ?
Yes
No
Input : xrecord[i].a[k][h]
h=h+1
Change the input values ?
Yes
loop=loop*0
No
loop = 2
xrecord[i].hedges[0]=unit
h = 1
Is h <= xrecord[i].element ?
Yes
No
xrecord[i].a[0][h]=1
h=h+1
k=k+1
temp1=temp1+1
Is temp1 <= common.nox ?
Yes
return to inputx (temp1)
No
return to inputnew ( )
2


2
temp1 = 1
inputy (temp1)
temp1 = i
loop = 0
Is loop<=1 ?
loop=loop+1
No
Yes
Input :
yrecord[i].name
yrecord[i].unit
yrecord[i].mini
yrecord[i].max
yrecord[i].set
yrecord[i].element
Change the input values ?
Yes
loop=loop*0
No
loop = 2
3

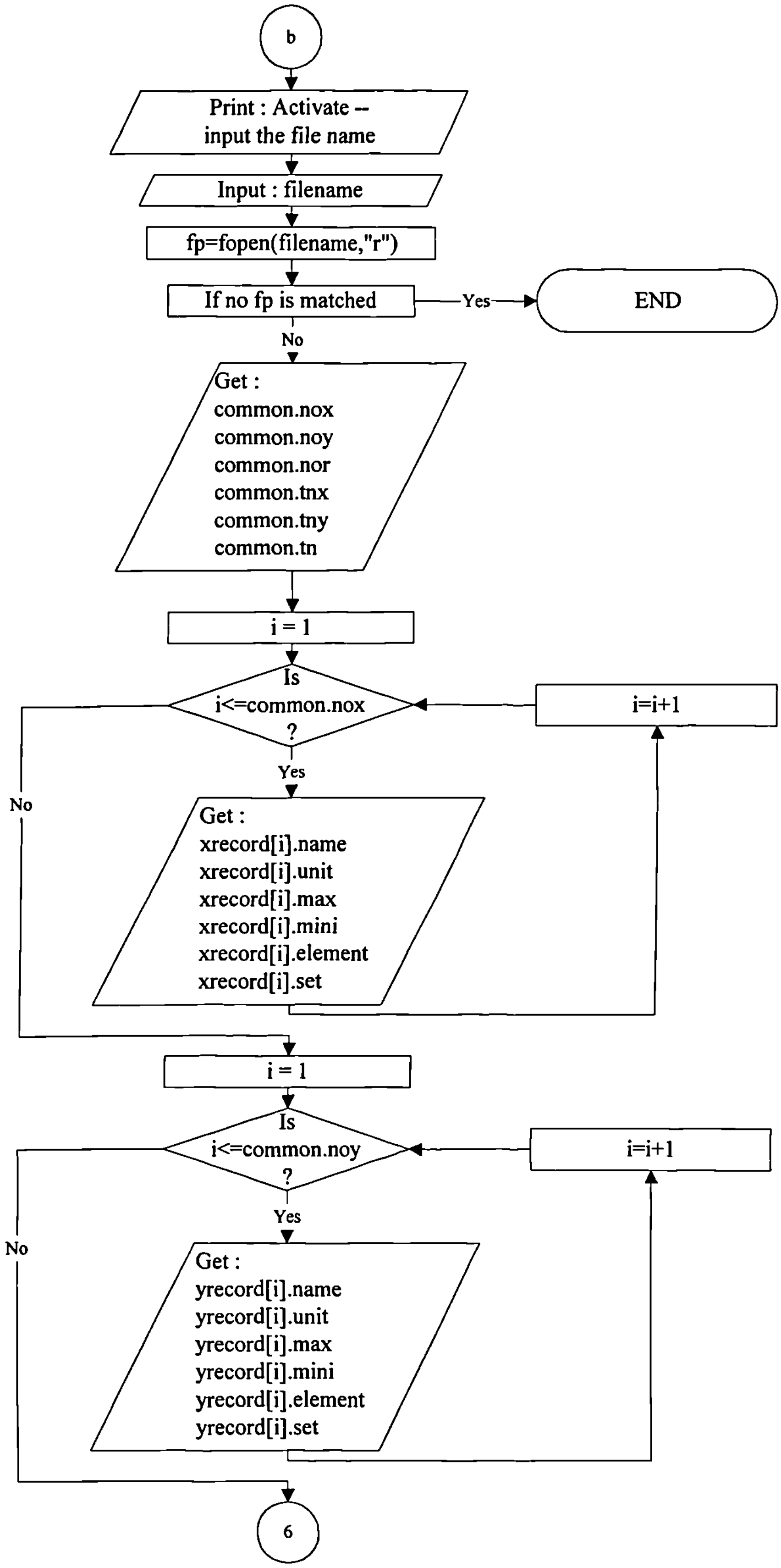

3
loop = 0
k = 1
Is k <= yrecord[i].set ?
Yes
No
Is loop<=1 ?
Yes
No
loop=loop+1
Input : yrecord[i].hedges[k]
h = 1
Is h <= yrecord[i].element ?
Yes
No
h=h+1
Input : yrecord[i].b[k][h]
Change the input values ?
Yes
loop=loop*0
No
loop = 2
yrecord[i].hedges[0]=unit
h = 1
Is h <= yrecord[i].element ?
Yes
No
yrecord[i].b[0][h]=1
h=h+1
k=k+1
temp1=temp1+1
Is temp1 <= common.noy ?
Yes
return to inputy (temp1)
No
return to inputnew ( )
4

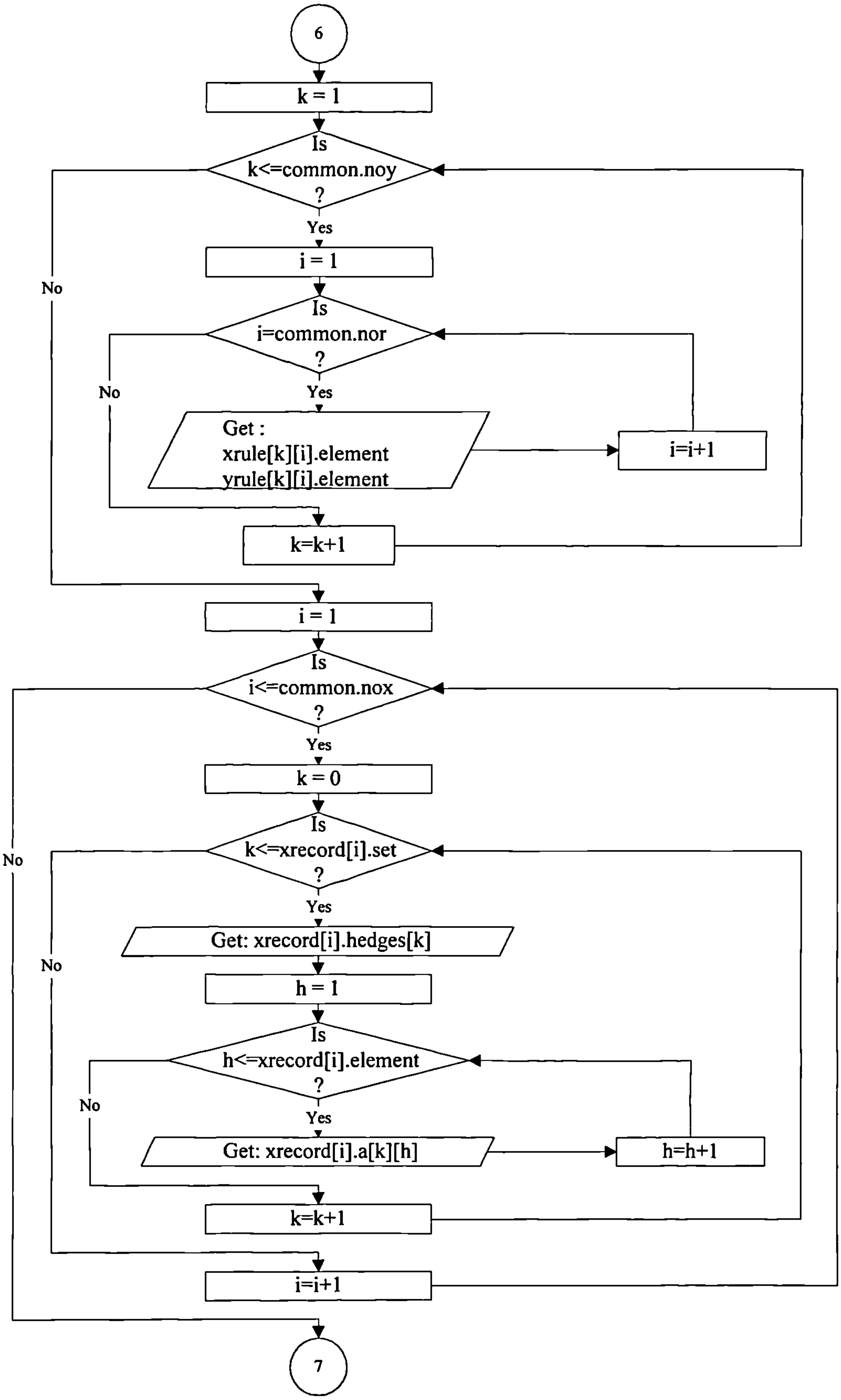


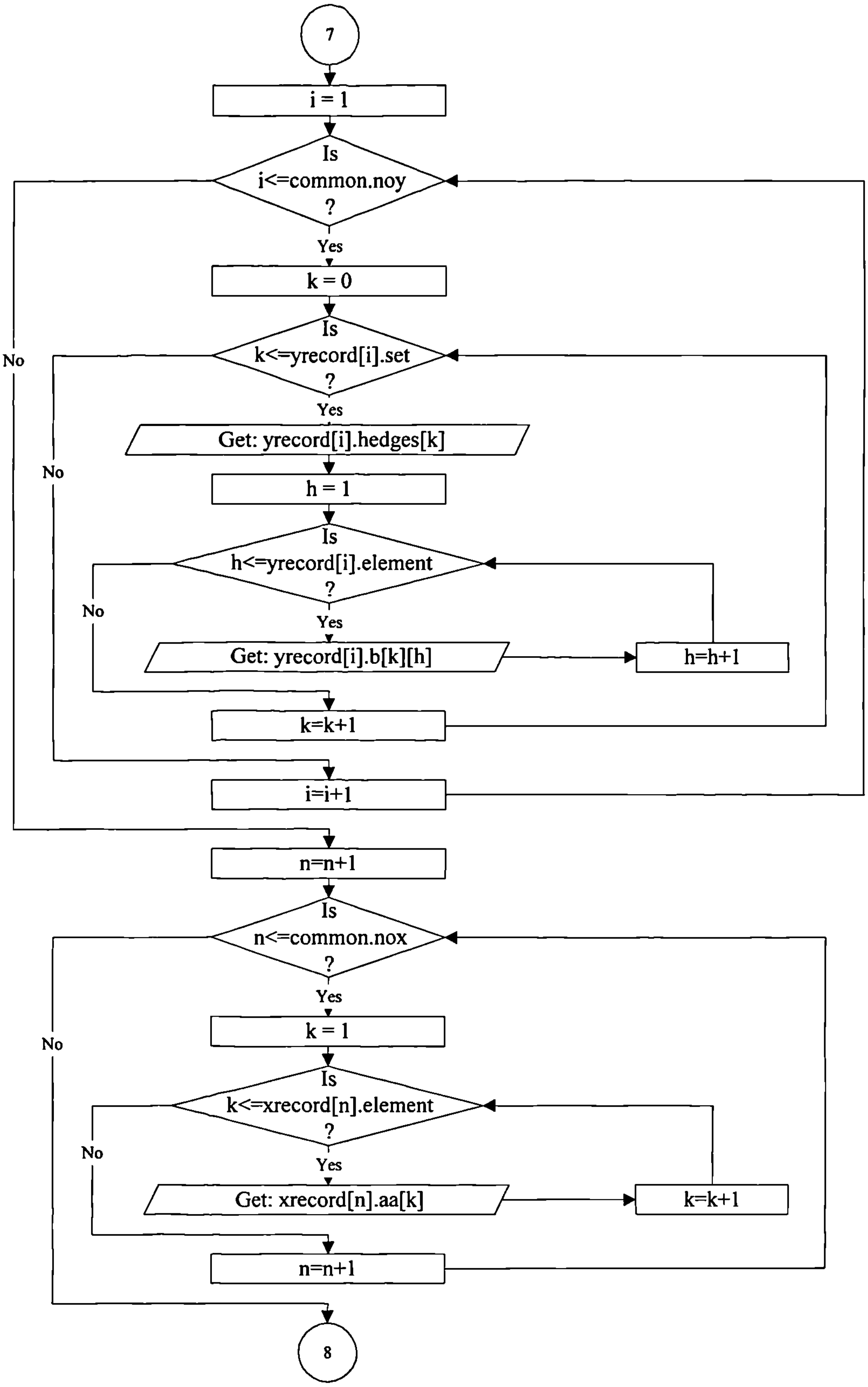
4
temp9 = 1
temp1 = 1
inputrule (temp1,temp9)
i = temp1
loop = 0
Is
loop<=1
?
loop=loop+1
Yes
xrule[temp9][i].element=common.nox
j = 1
Is
j<=xrule[temp9].element
?
Yes
Print : xrecord[j].name
No
k = 0
Is
k<=
xrecord[j].set
?
Yes
Print : xrecord[j].hedges[k]
No
n = 1
No
Is
n<=
xrecord[j].element
?
Yes
No
Print : xrecord[j].a[k][n]
n=n+1
k=k+1
xrule[temp9][i].functiona[j]=j
Input : xrule[temp9].functionb[j]
j=j+1
Change the
input values ?
Yes
loop=loop*0
No
loop = 2
5

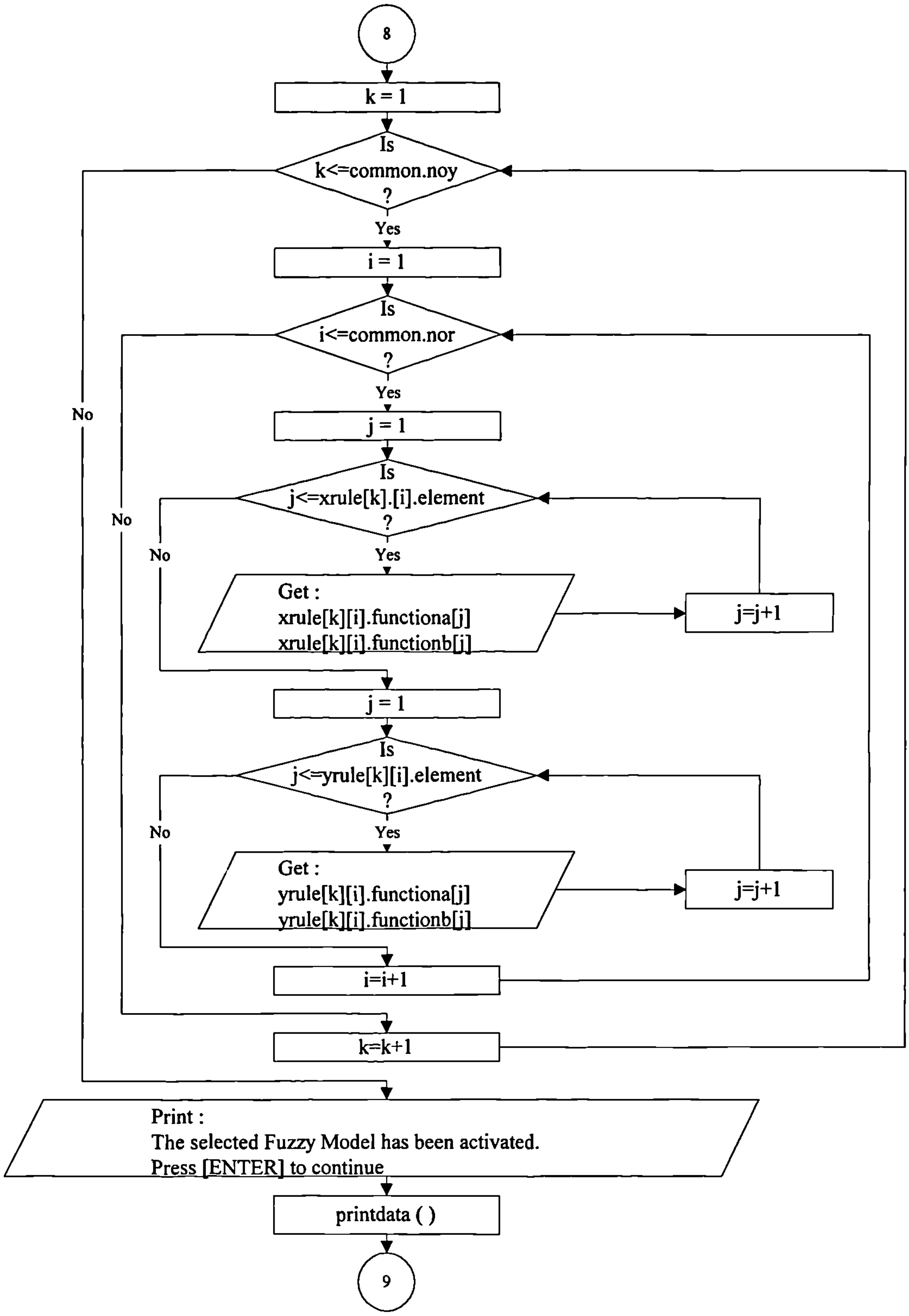


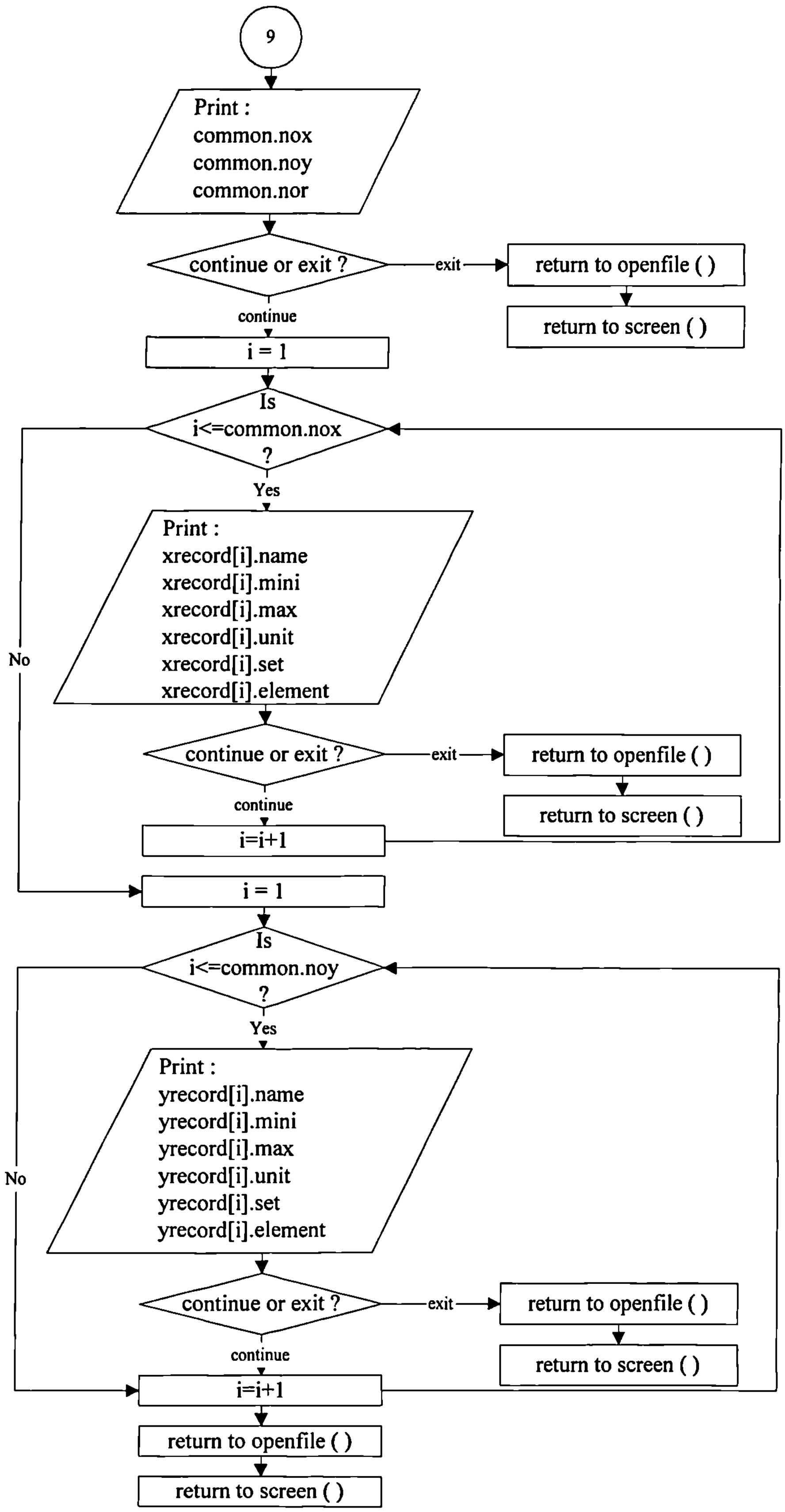
5
loop = 0
Is
loop<=1
?
No
Yes
loop=loop+1
yrule[temp9][i].element=1
j = 1
Is
j<=yrule[temp9].element
?
Yes
Print : yrecord[j].name
k = 0
Is
k<=
yrecord[temp9].set
?
Yes
Print : yrecord[temp9].hedges[k]
n = 1
Is
n<=
yrecord[temp9].element
?
Yes
Print : yrecord[temp9].a[k][n]
n=n+1
k=k+1
yrule[temp9][i].functiona[j]=temp9
Input : yrule[temp9][i].functionb[j]
j=j+1
return to
inputnew ( )
No
No
No
Change the
input values ?
Yes
loop=loop*0
No
loop = 2
temp1=temp1+1
Is
temp1<=
common.nor
?
Yes
return to
inputrule (temp1,temp9)
No
temp9=temp9+1
Is
temp9<=
common.noy
?
Yes
return to
inputrule (temp1,temp9)
No
return to
screen ( )

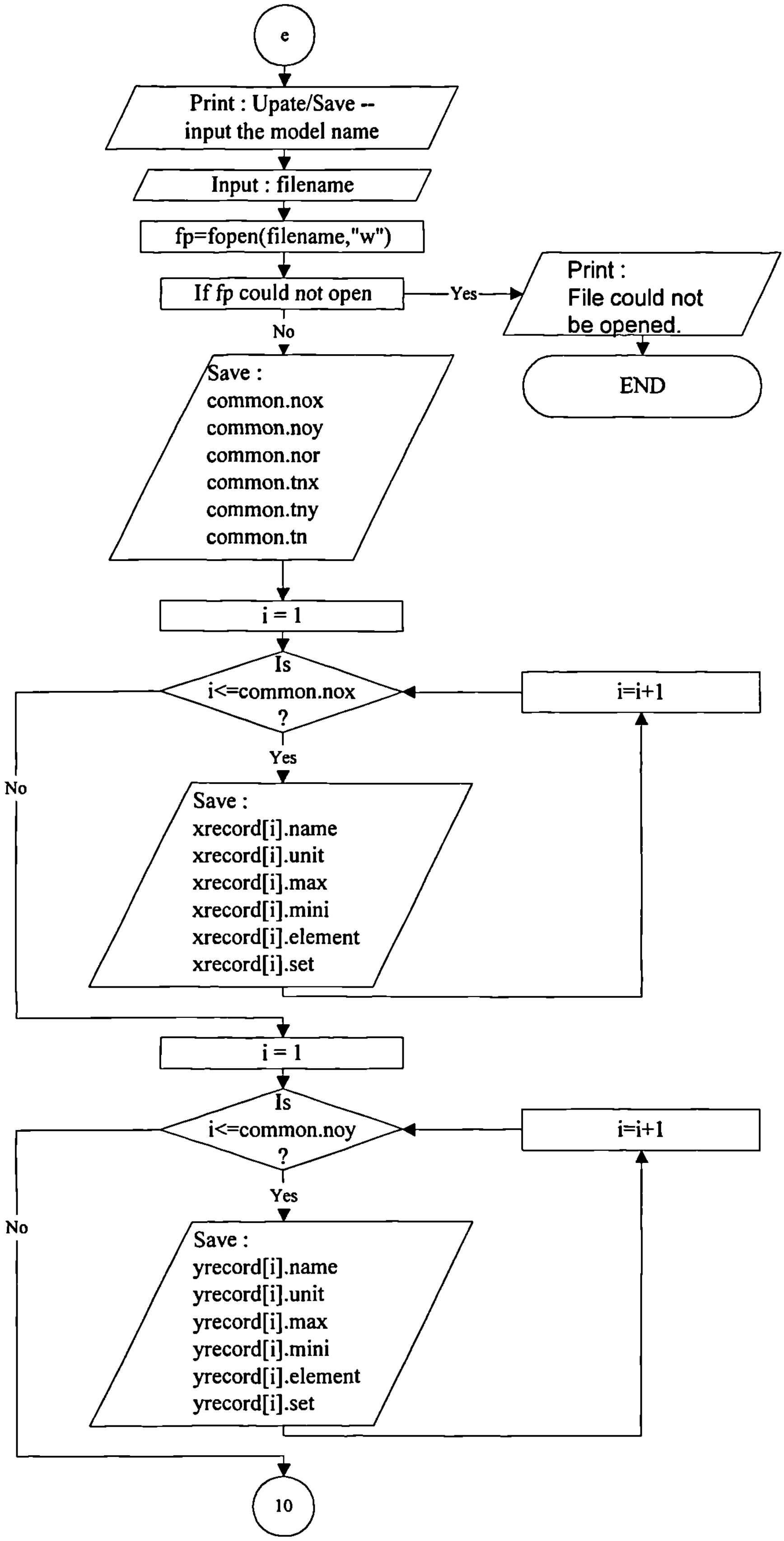

b
Print : Activate --
input the file name
Input : filename
fp=fopen(filename,"r")
If no fp is matched
Yes
END
No
Get :
common.nox
common.noy
common.nor
common.tnx
common.tny
common.tn
i = 1
Is
i<=common.nox
?
i=i+1
Yes
No
Get :
xrecord[i].name
xrecord[i].unit
xrecord[i].max
xrecord[i].mini
xrecord[i].element
xrecord[i].set
i = 1
Is
i<=common.noy
?
i=i+1
Yes
No
Get :
yrecord[i].name
yrecord[i].unit
yrecord[i].max
yrecord[i].mini
yrecord[i].element
yrecord[i].set
6


6
k = 1
Is
k<=common.noy
?
Yes
No
i = 1
Is
i=common.nor
?
No
Yes
Get :
xrule[k][i].element
yrule[k][i].element
i=i+1
k=k+1
i = 1
Is
i<=common.nox
?
Yes
k = 0
Is
k<=xrecord[i].set
?
No
Yes
Get: xrecord[i].hedges[k]
No
h = 1
Is
h<=xrecord[i].element
?
No
Yes
Get: xrecord[i].a[k][h]
h=h+1
k=k+1
i=i+1
7

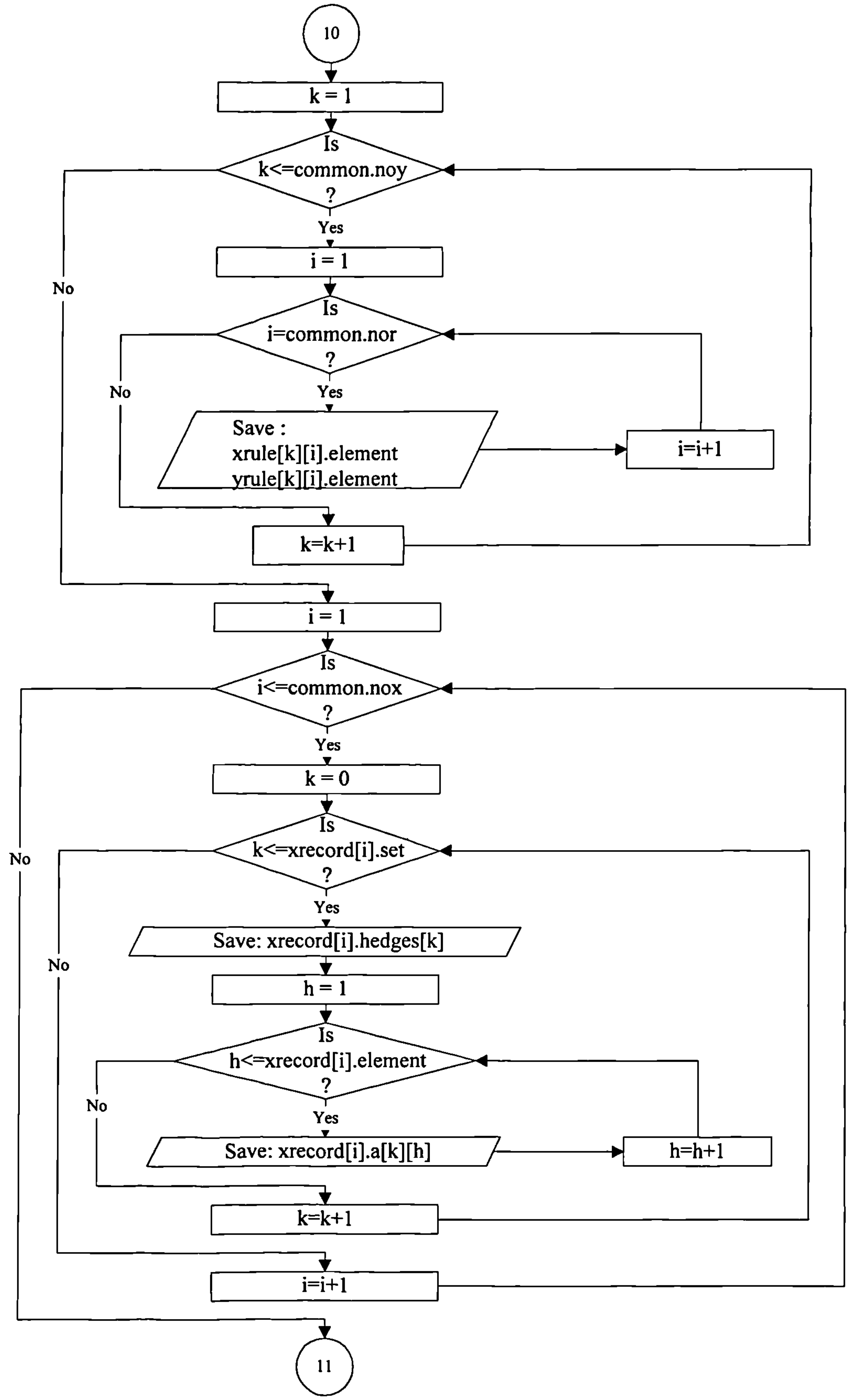

7
i = 1
Is
i<=common.noy
?
Yes
k = 0
Is
k<=yrecord[i].set
?
Yes
Get: yrecord[i].hedges[k]
h = 1
Is
h<=yrecord[i].element
?
Yes
Get: yrecord[i].b[k][h]
h=h+1
No
k=k+1
No
i=i+1
No
n=n+1
Is
n<=common.nox
?
Yes
k = 1
Is
k<=xrecord[n].element
?
Yes
Get: xrecord[n].aa[k]
k=k+1
No
n=n+1
No
8

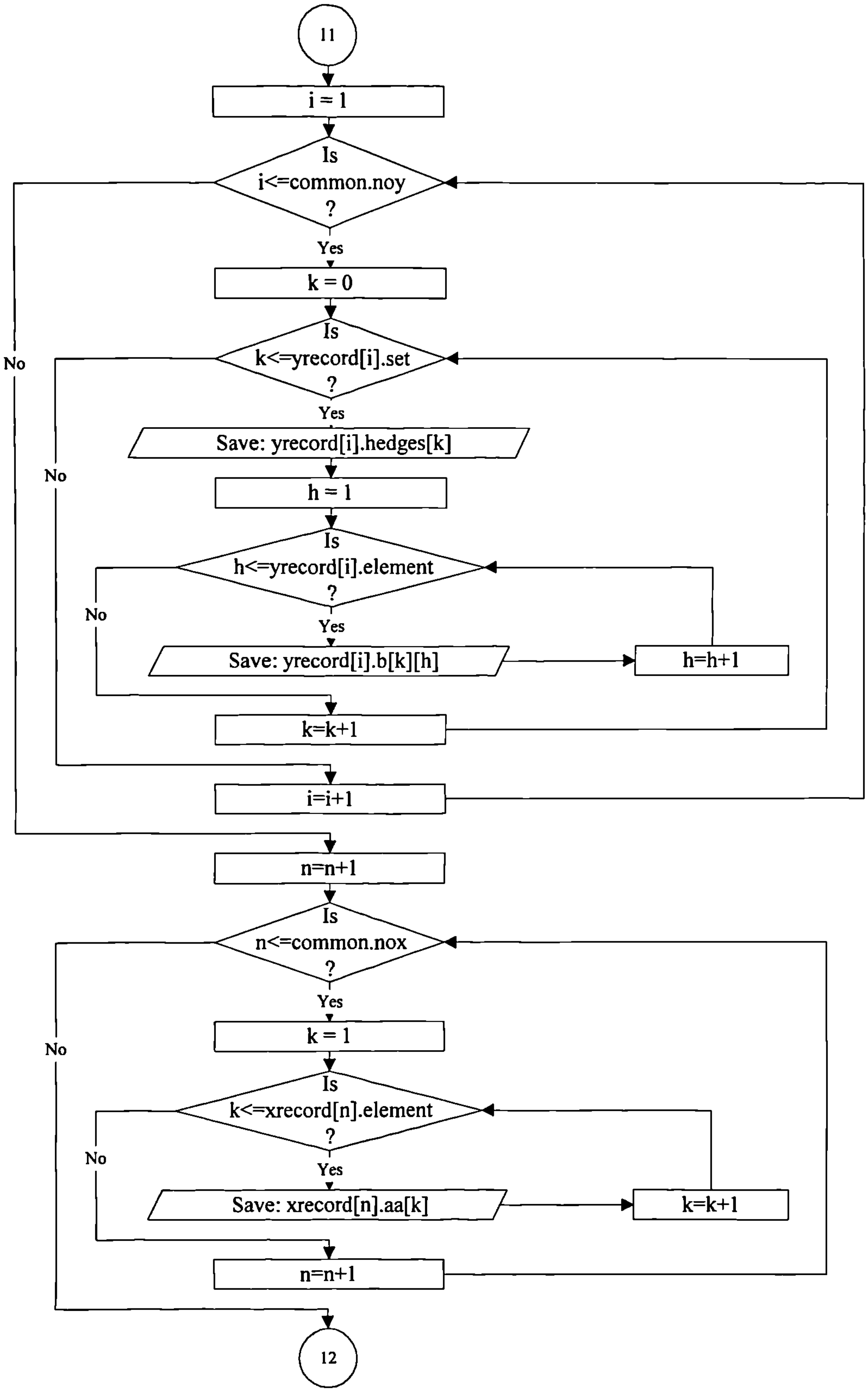

8
k = 1
Is
k<=common.noy
?
Yes
No
i = 1
Is
i<=common.nor
?
Yes
No
j = 1
Is
j<=xrule[k].[i].element
?
Yes
No
Get :
xrule[k][i].functiona[j]
xrule[k][i].functionb[j]
j=j+1
j = 1
Is
j<=yrule[k][i].element
?
Yes
No
Get :
yrule[k][i].functiona[j]
yrule[k][i].functionb[j]
j=j+1
i=i+1
k=k+1
Print :
The selected Fuzzy Model has been activated.
Press [ENTER] to continue
printdata ( )
9


9
Print :
common.nox
common.noy
common.nor
continue or exit ?
exit
return to openfile ( )
return to screen ( )
continue
i = 1
Is
i<=common.nox
?
Yes
No
Print :
xrecord[i].name
xrecord[i].mini
xrecord[i].max
xrecord[i].unit
xrecord[i].set
xrecord[i].element
continue or exit ?
exit
return to openfile ( )
return to screen ( )
continue
i=i+1
i = 1
Is
i<=common.noy
?
Yes
No
Print :
yrecord[i].name
yrecord[i].mini
yrecord[i].max
yrecord[i].unit
yrecord[i].set
yrecord[i].element
continue or exit ?
exit
return to openfile ( )
return to screen ( )
continue
i=i+1
return to openfile ( )
return to screen ( )

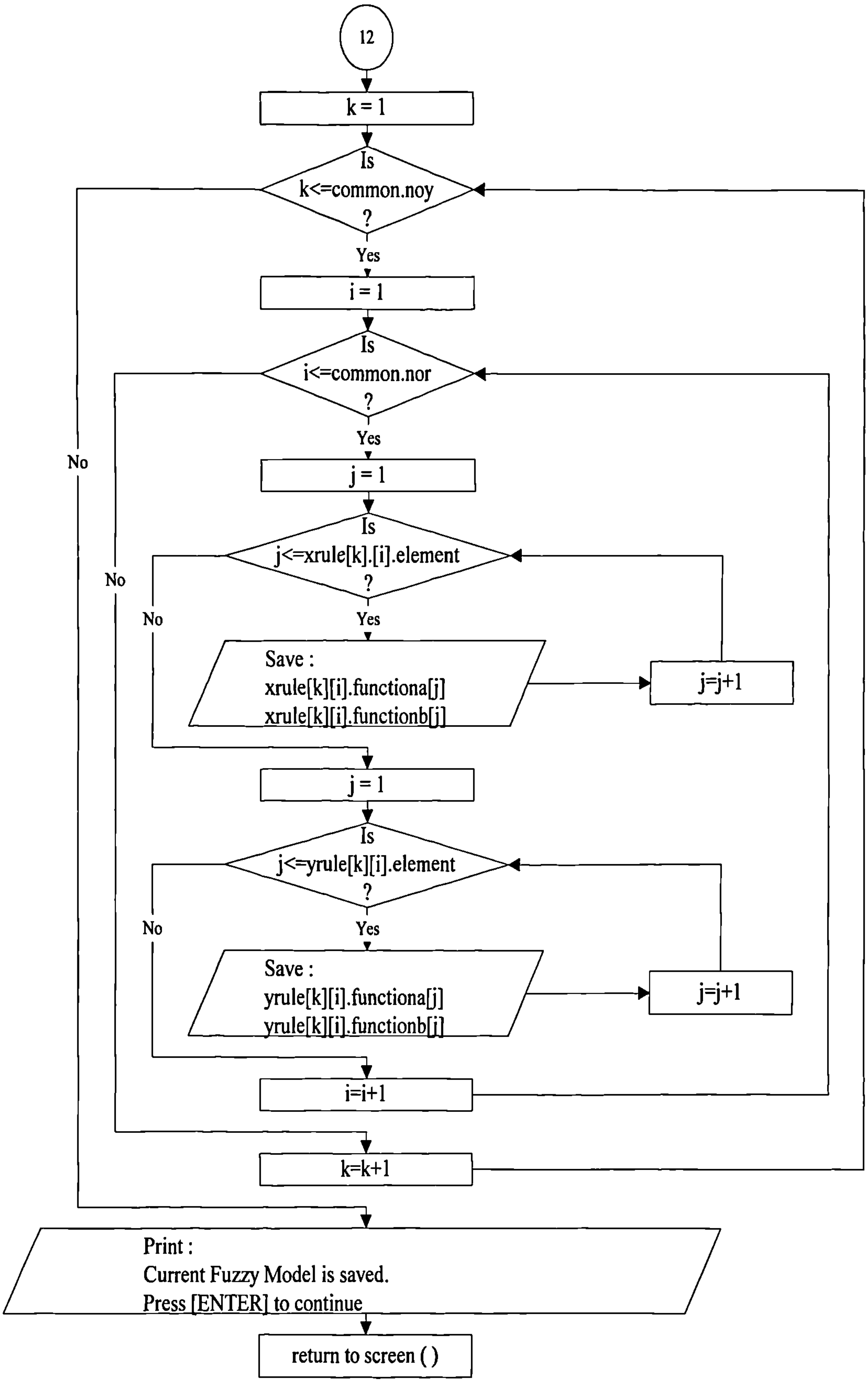


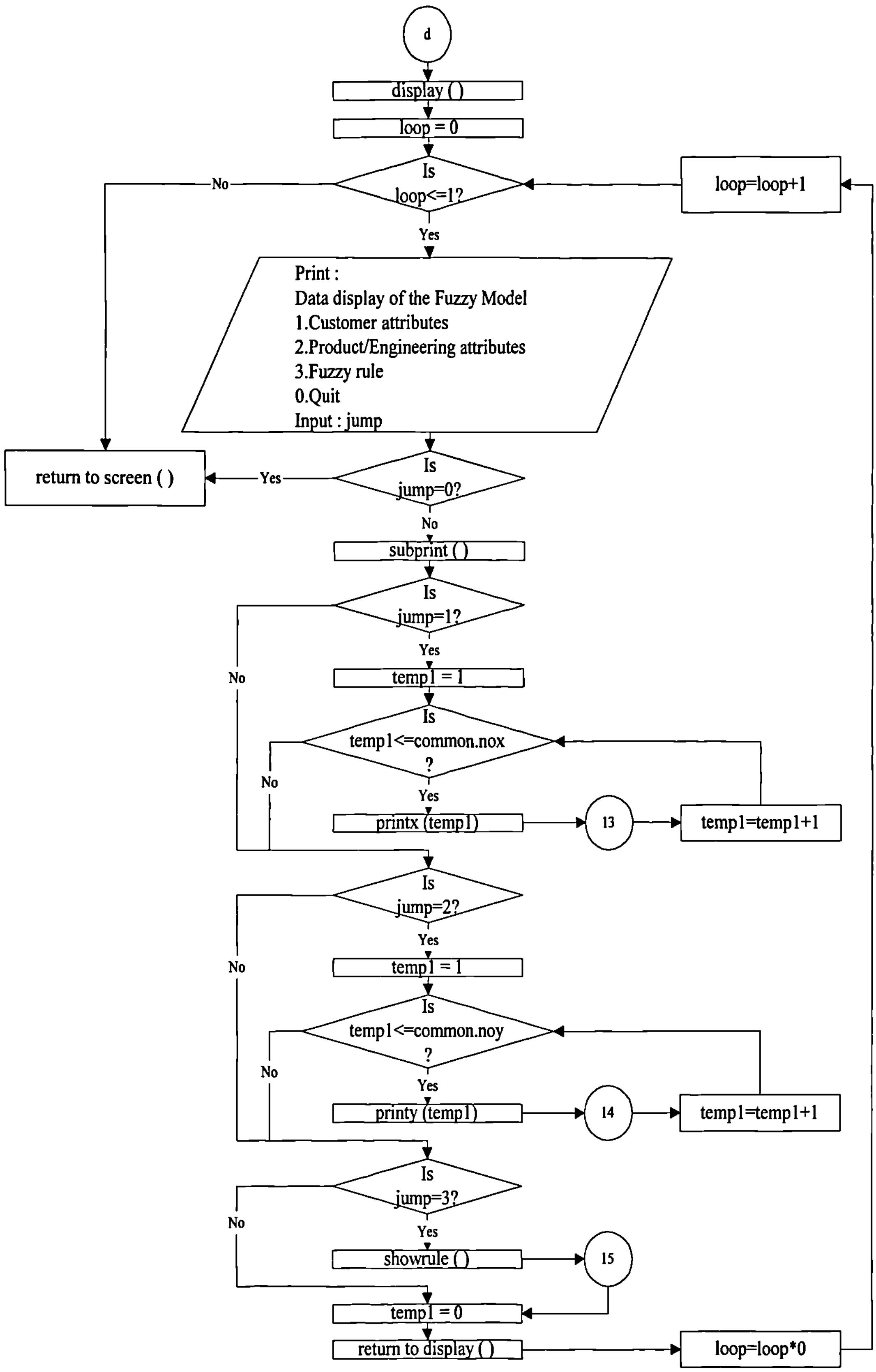
e
Print : Upate/Save -- input the model name
Input : filename
fp=fopen(filename,"w")
If fp could not open
Yes
Print : File could not be opened.
END
No
Save : common.nox common.noy common.nor common.tnx common.tny common.tn
i = 1
Is i<=common.nox ?
i=i+1
Yes
No
Save : xrecord[i].name xrecord[i].unit xrecord[i].max xrecord[i].mini xrecord[i].element xrecord[i].set
i = 1
Is i<=common.noy ?
i=i+1
Yes
No
Save : yrecord[i].name yrecord[i].unit yrecord[i].max yrecord[i].mini yrecord[i].element yrecord[i].set
10

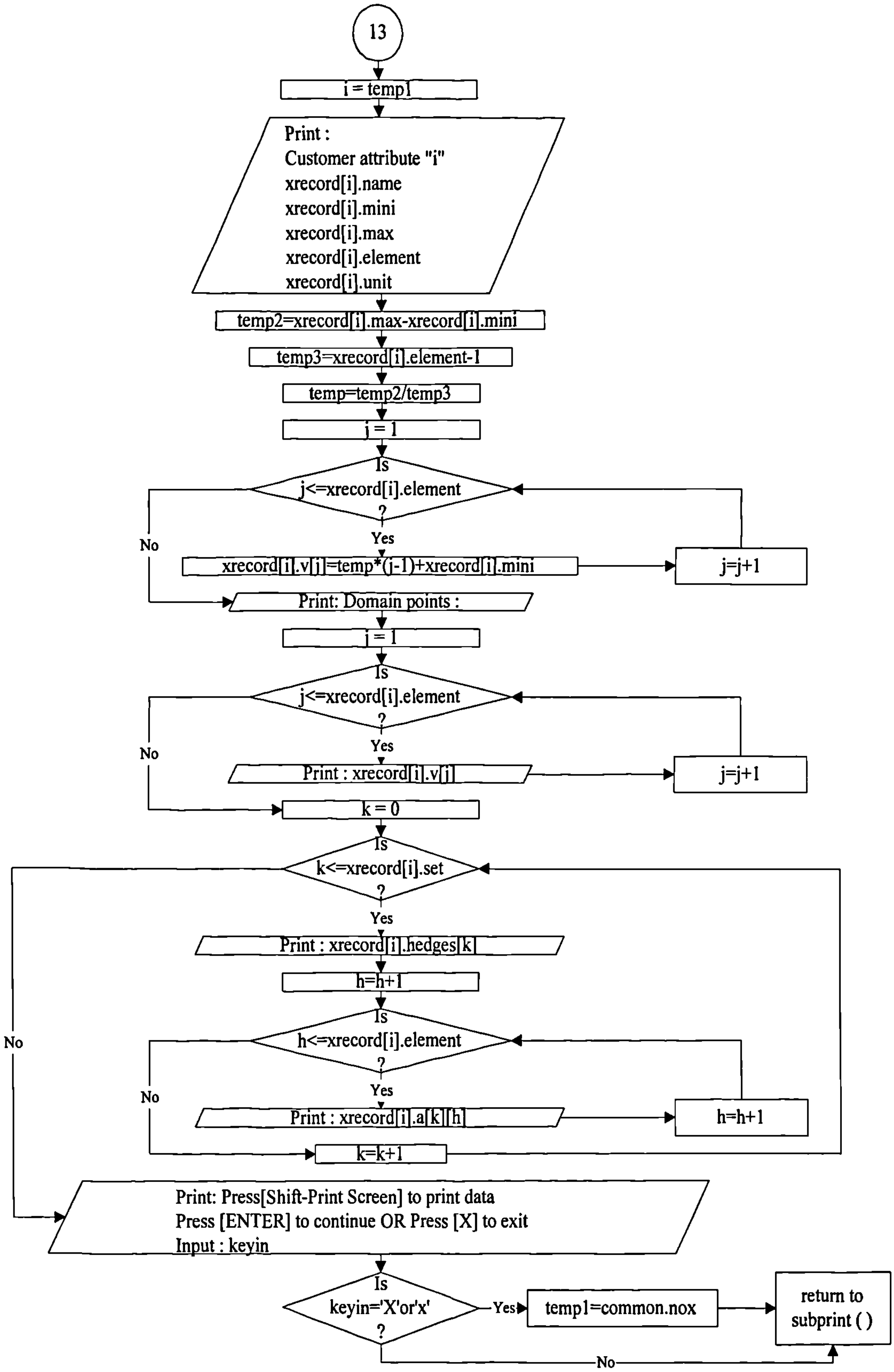

10
k = 1
Is
k<=common.noy
?
Yes
No
i = 1
Is
i=common.nor
?
No
Yes
Save :
xrule[k][i].element
yrule[k][i].element
i=i+1
k=k+1
i = 1
Is
i<=common.nox
?
Yes
No
k = 0
Is
k<=xrecord[i].set
?
Yes
No
Save: xrecord[i].hedges[k]
h = 1
Is
h<=xrecord[i].element
?
No
Yes
Save: xrecord[i].a[k][h]
h=h+1
k=k+1
i=i+1
11

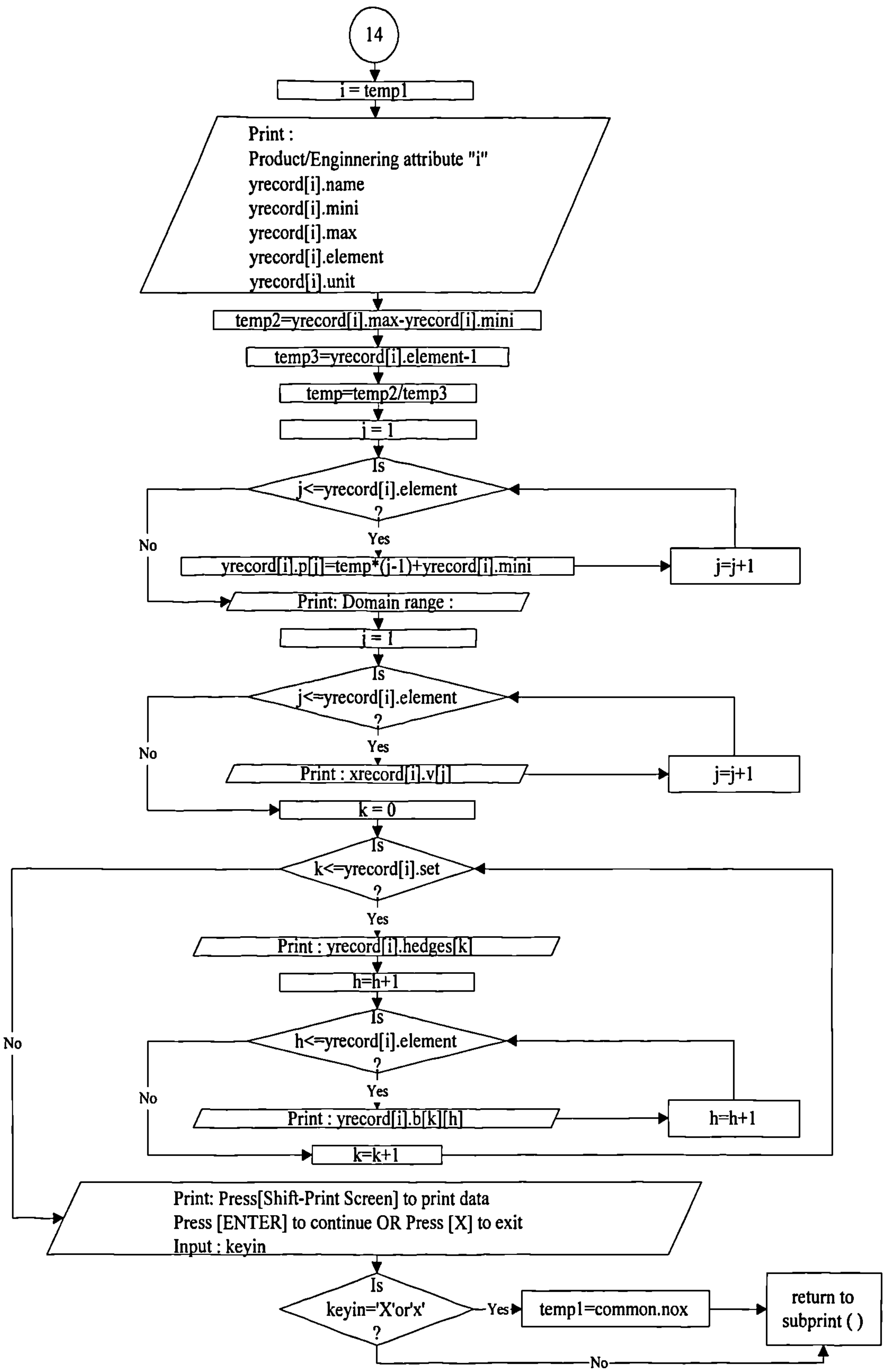


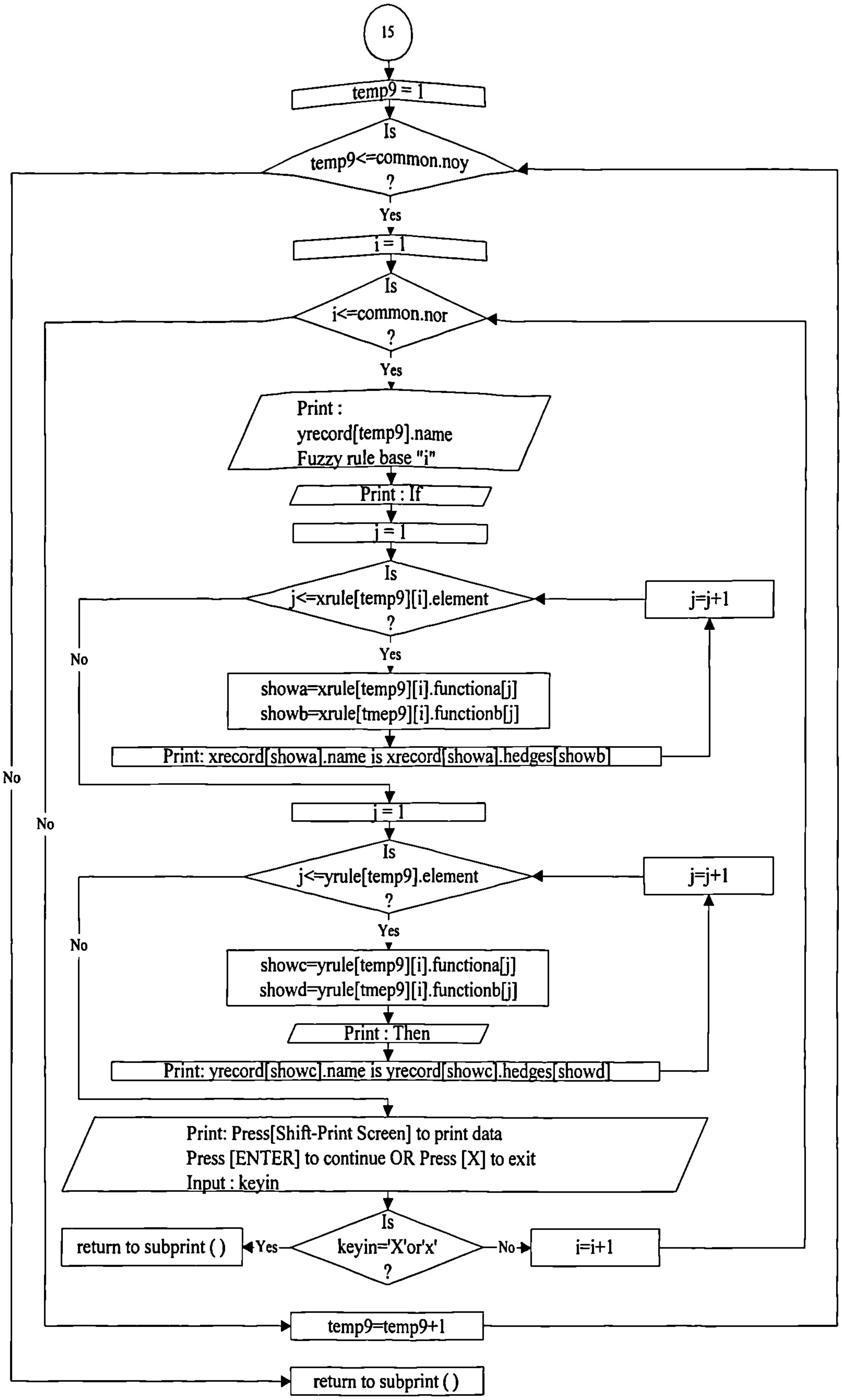
11
i = 1
Is
i<=common.noy
?
Yes
No
k = 0
Is
k<=yrecord[i].set
?
Yes
No
Save: yrecord[i].hedges[k]
h = 1
Is
h<=yrecord[i].element
?
Yes
No
Save: yrecord[i].b[k][h]
h=h+1
k=k+1
i=i+1
n=n+1
Is
n<=common.nox
?
Yes
No
k = 1
Is
k<=xrecord[n].element
?
Yes
No
Save: xrecord[n].aa[k]
k=k+1
n=n+1
12


12
k = 1
Is
k<=common.noy
?
Yes
i = 1
Is
i<=common.nor
?
Yes
j = 1
Is
j<=xrule[k].[i].element
?
Yes
Save :
xrule[k][i].functiona[j]
xrule[k][i].functionb[j]
j=j+1
No
j = 1
Is
j<=yrule[k][i].element
?
Yes
Save :
yrule[k][i].functiona[j]
yrule[k][i].functionb[j]
j=j+1
No
i=i+1
No
k=k+1
No
Print :
Current Fuzzy Model is saved.
Press [ENTER] to continue
return to screen ( )

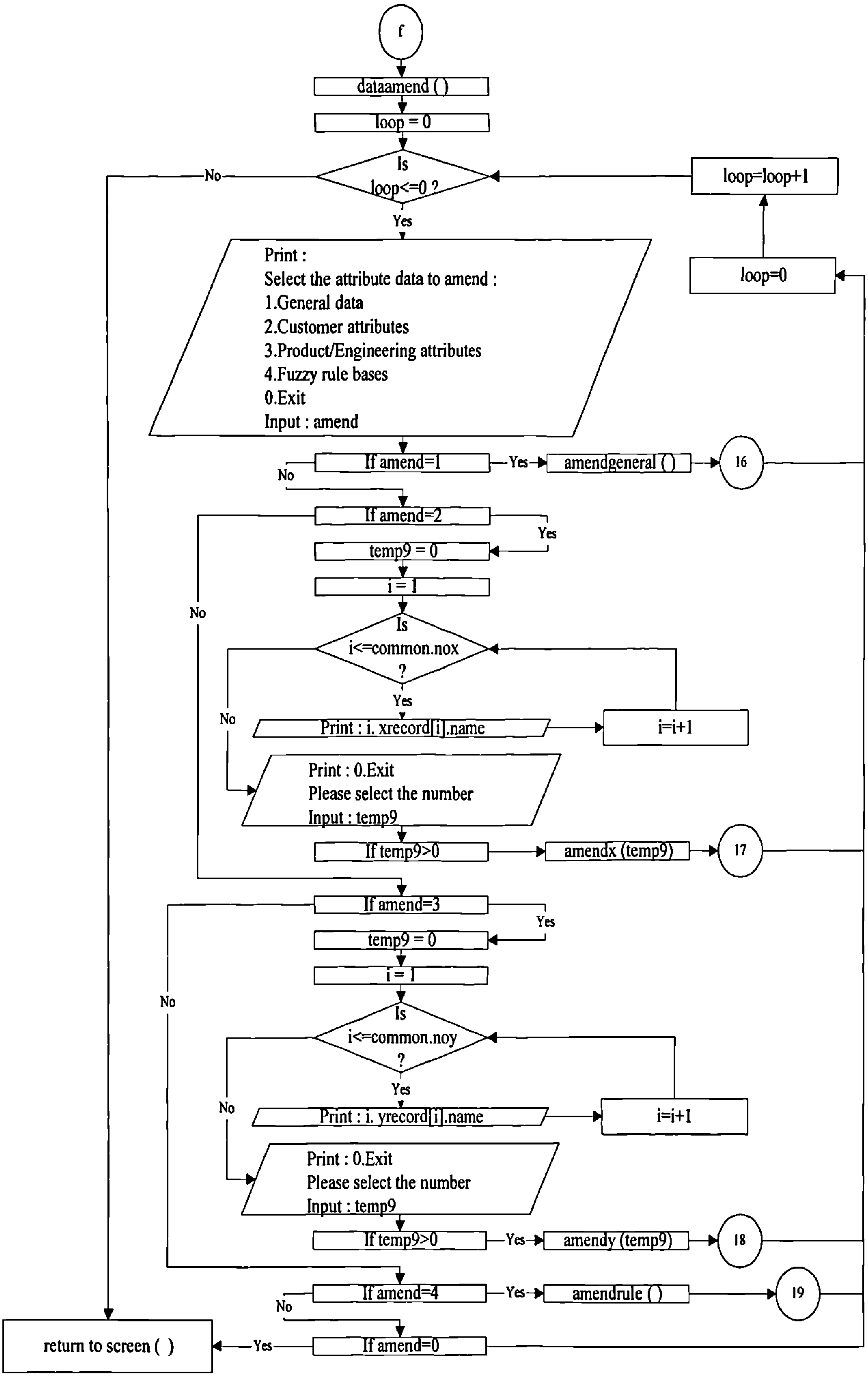

d
display ()
loop = 0
Is
loop<=1?
No
Yes
loop=loop+1
Print :
Data display of the Fuzzy Model
1.Customer attributes
2.Product/Engineering attributes
3.Fuzzy rule
0.Quit
Input : jump
return to screen ( )
Yes
Is
jump=0?
No
subprint ( )
Is
jump=1?
Yes
No
temp1 = 1
Is
temp1<=common.nox
?
No
Yes
printx (temp1)
13
temp1=temp1+1
Is
jump=2?
Yes
No
temp1 = 1
Is
temp1<=common.noy
?
No
Yes
printy (temp1)
14
temp1=temp1+1
Is
jump=3?
No
Yes
showrule ( )
15
temp1 = 0
return to display ( )
loop=loop*0

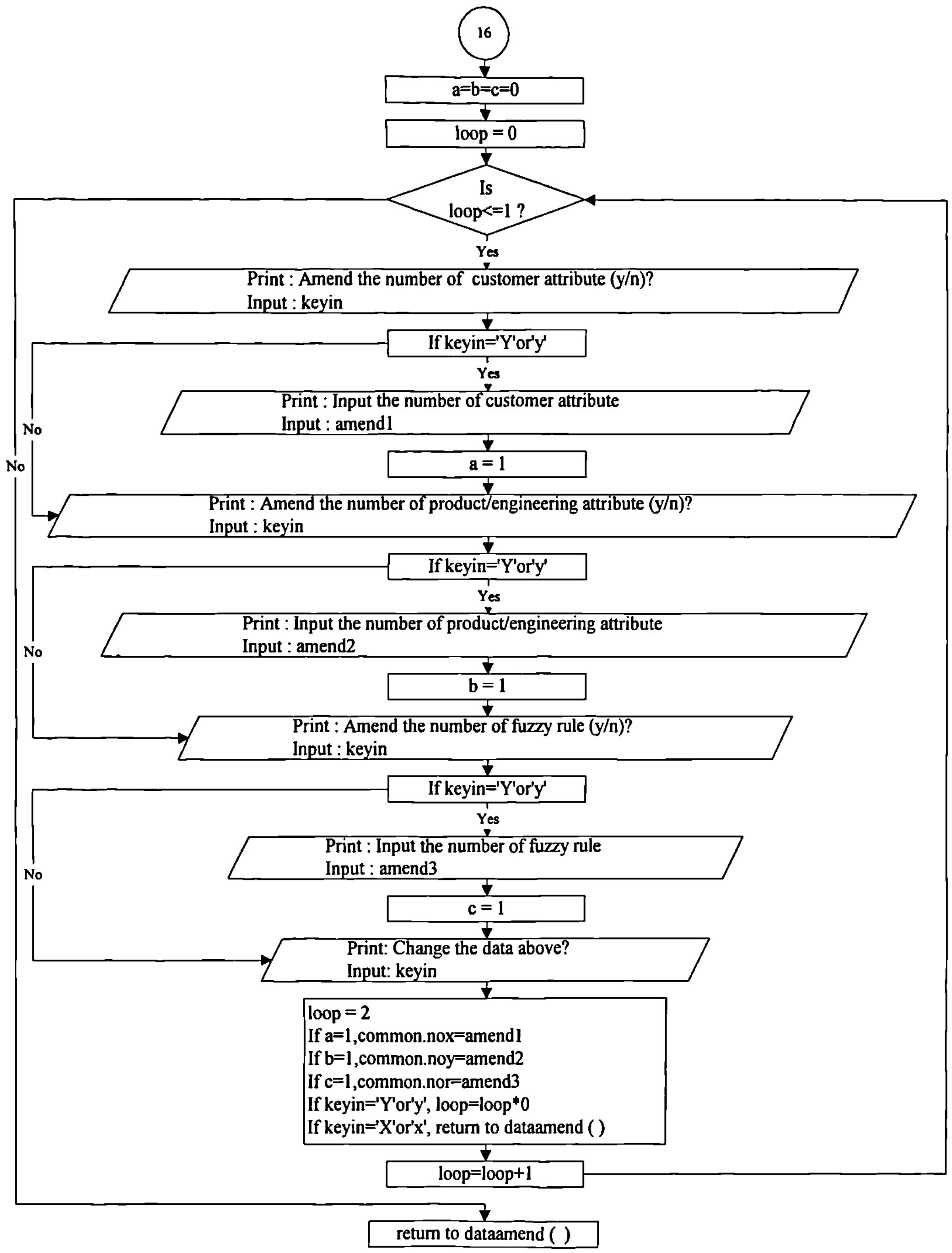

13
i = temp1
Print :
Customer attribute "i"
xrecord[i].name
xrecord[i].mini
xrecord[i].max
xrecord[i].element
xrecord[i].unit
temp2=xrecord[i].max-xrecord[i].mini
temp3=xrecord[i].element-1
temp=temp2/temp3
j = 1
Is j<=xrecord[i].element ?
Yes
No
xrecord[i].v[j]=temp*(j-1)+xrecord[i].mini
j=j+1
Print: Domain points :
j = 1
Is j<=xrecord[i].element ?
Yes
No
Print : xrecord[i].v[j]
j=j+1
k = 0
Is k<=xrecord[i].set ?
Yes
No
Print : xrecord[i].hedges[k]
h=h+1
Is h<=xrecord[i].element ?
Yes
No
Print : xrecord[i].a[k][h]
h=h+1
k=k+1
Print: Press[Shift-Print Screen] to print data
Press [ENTER] to continue OR Press [X] to exit
Input : keyin
Is keyin='X'or'x' ?
Yes
temp1=common.nox
return to subprint ( )
No

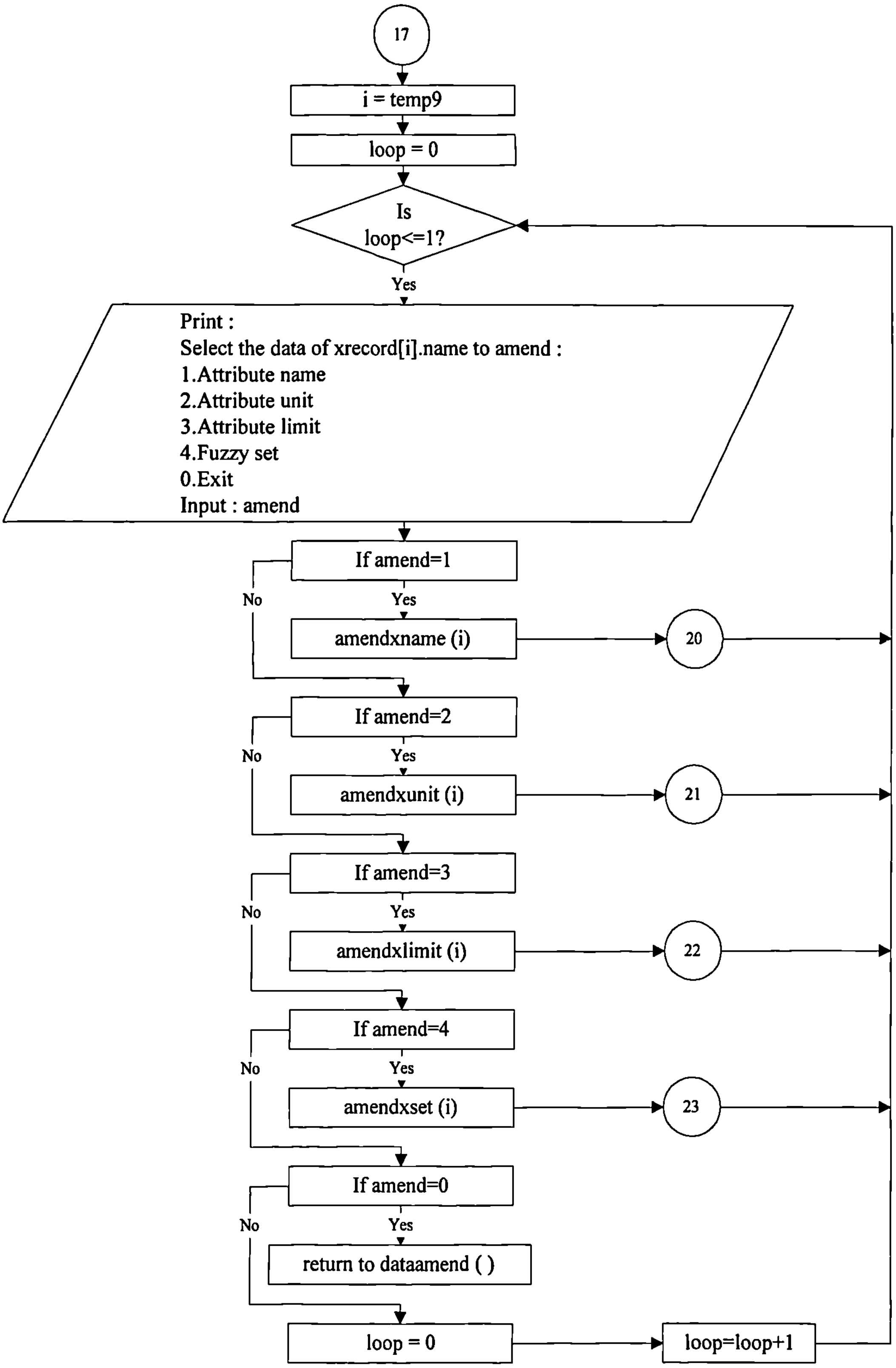

14
i = temp1
Print :
Product/Enginnering attribute "i"
yrecord[i].name
yrecord[i].mini
yrecord[i].max
yrecord[i].element
yrecord[i].unit
temp2=yrecord[i].max-yrecord[i].mini
temp3=yrecord[i].element-1
temp=temp2/temp3
j = 1
Is j<=yrecord[i].element ?
Yes
No
yrecord[i].p[j]=temp*(j-1)+yrecord[i].mini
j=j+1
Print: Domain range :
j = 1
Is j<=yrecord[i].element ?
Yes
No
Print : xrecord[i].v[j]
j=j+1
k = 0
Is k<=yrecord[i].set ?
Yes
No
Print : yrecord[i].hedges[k]
h=h+1
Is h<=yrecord[i].element ?
Yes
No
Print : yrecord[i].b[k][h]
h=h+1
k=k+1
Print: Press[Shift-Print Screen] to print data
Press [ENTER] to continue OR Press [X] to exit
Input : keyin
Is keyin='X'or'x' ?
Yes
temp1=common.nox
return to subprint ( )
No

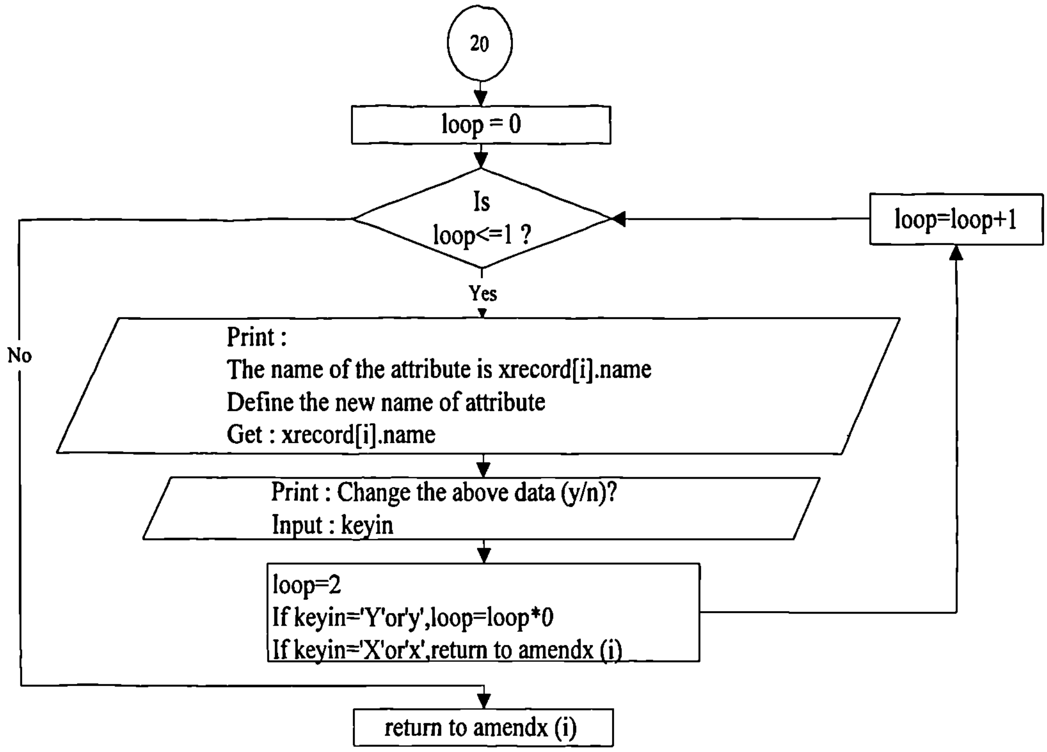


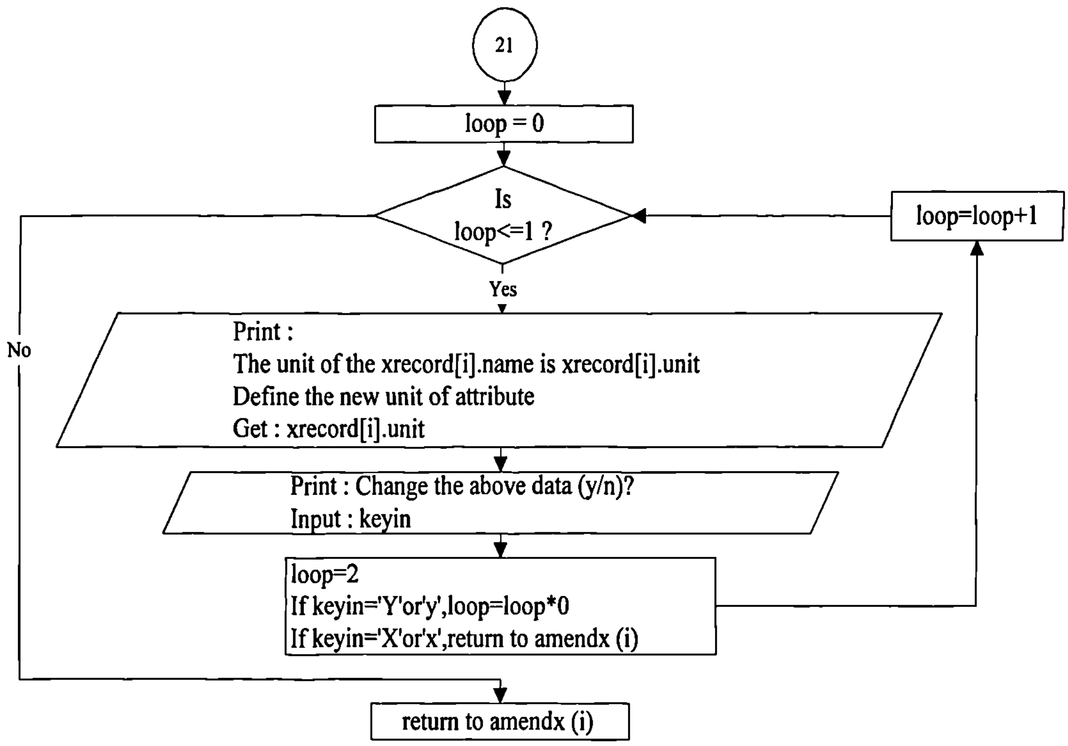
15
temp9 = 1
Is
temp9<=common.noy
?
Yes
i = 1
Is
i<=common.nor
?
Yes
Print :
yrecord[temp9].name
Fuzzy rule base "i"
Print : If
j = 1
Is
j<=xrule[temp9][i].element
?
Yes
j=j+1
No
showa=xrule[temp9][i].functiona[j]
showb=xrule[tmep9][i].functionb[j]
Print: xrecord[showa].name is xrecord[showa].hedges[showb]
No
No
j = 1
Is
j<=yrule[temp9].element
?
Yes
j=j+1
No
showc=yrule[temp9][i].functiona[j]
showd=yrule[tmep9][i].functionb[j]
Print : Then
Print: yrecord[showc].name is yrecord[showc].hedges[showd]
Print: Press[Shift-Print Screen] to print data
Press [ENTER] to continue OR Press [X] to exit
Input : keyin
return to subprint ( )
Yes
Is
keyin='X'or'x'
?
No
i=i+1
temp9=temp9+1
return to subprint ( )

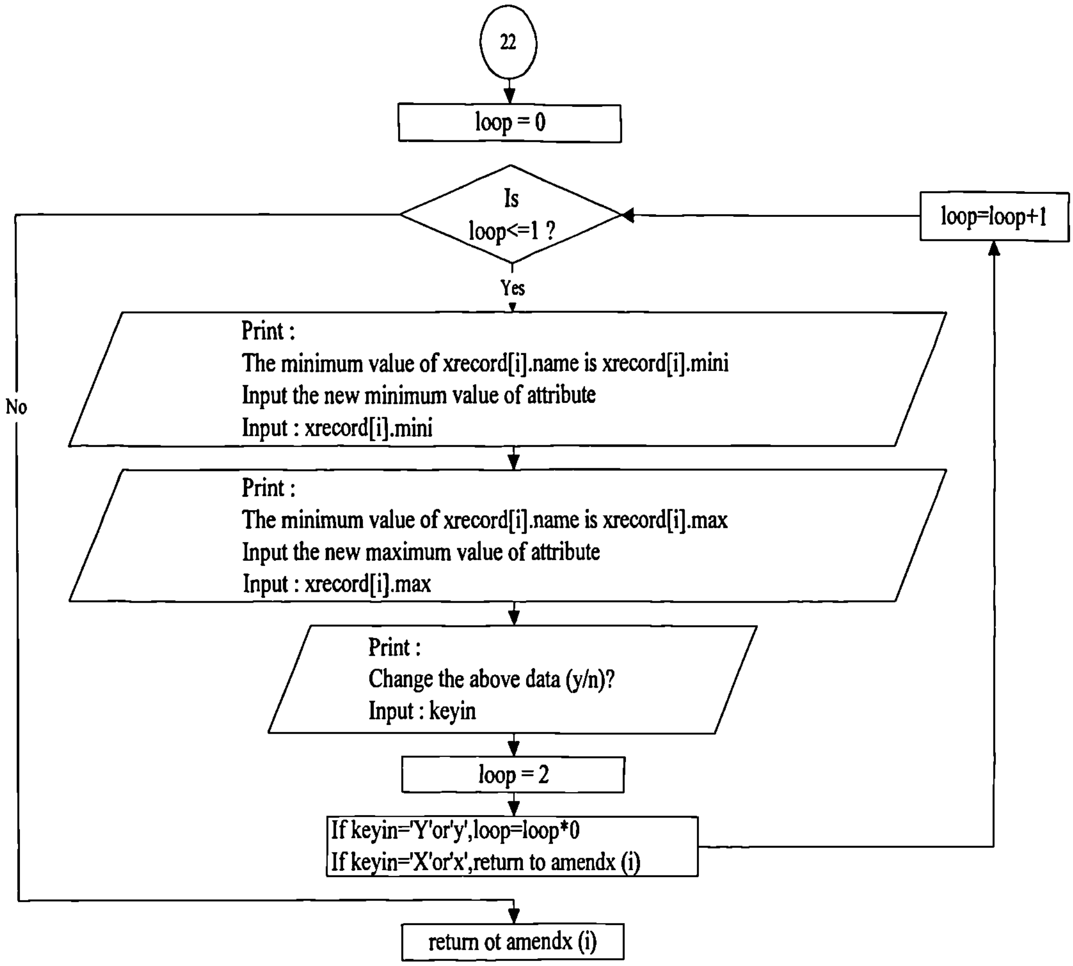

f
dataamend ( )
loop = 0
Is loop<=0 ?
No
Yes
loop=loop+1
loop=0
Print :
Select the attribute data to amend :
1.General data
2.Customer attributes
3.Product/Engineering attributes
4.Fuzzy rule bases
0.Exit
Input : amend
If amend=1
amendgeneral ( )
16
If amend=2
temp9 = 0
i = 1
Is i<=common.nox ?
Print : i. xrecord[i].name
i=i+1
Print : 0.Exit
Please select the number
Input : temp9
If temp9>0
amendx (temp9)
17
If amend=3
temp9 = 0
i = 1
Is i<=common.noy ?
Print : i. yrecord[i].name
i=i+1
Print : 0.Exit
Please select the number
Input : temp9
If temp9>0
amendy (temp9)
18
If amend=4
amendrule ( )
19
If amend=0
return to screen ( )

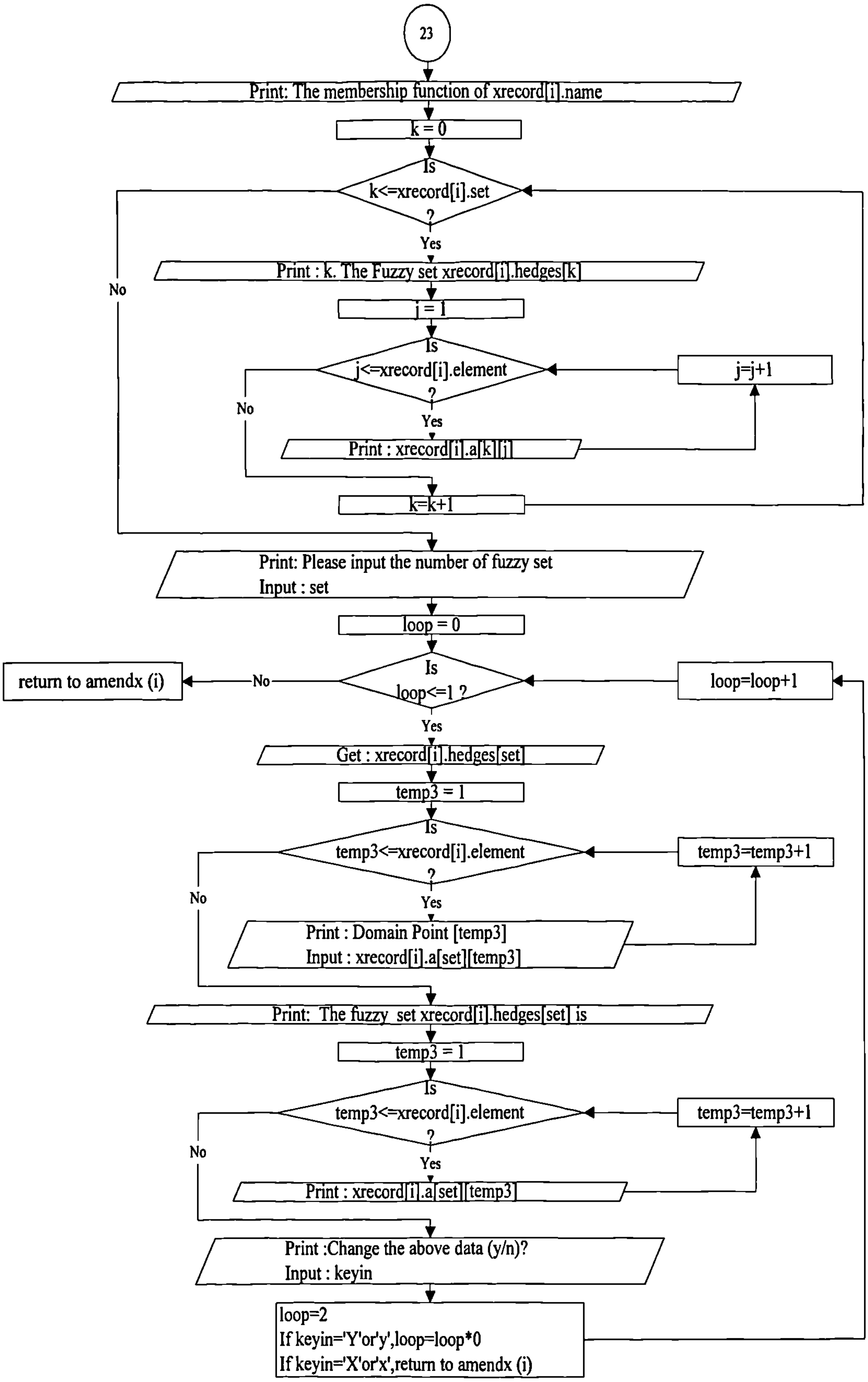

16
a=b=c=0
loop = 0
Is loop<=1 ?
Yes
Print : Amend the number of customer attribute (y/n)?
Input : keyin
If keyin='Y'or'y'
Yes
Print : Input the number of customer attribute
Input : amend1
a = 1
No
No
Print : Amend the number of product/engineering attribute (y/n)?
Input : keyin
If keyin='Y'or'y'
Yes
Print : Input the number of product/engineering attribute
Input : amend2
No
b = 1
Print : Amend the number of fuzzy rule (y/n)?
Input : keyin
If keyin='Y'or'y'
Yes
Print : Input the number of fuzzy rule
Input : amend3
No
c = 1
Print: Change the data above?
Input: keyin
loop = 2
If a=1,common.nox=amend1
If b=1,common.noy=amend2
If c=1,common.nor=amend3
If keyin='Y'or'y', loop=loop*0
If keyin='X'or'x', return to dataamend ( )
loop=loop+1
return to dataamend ( )

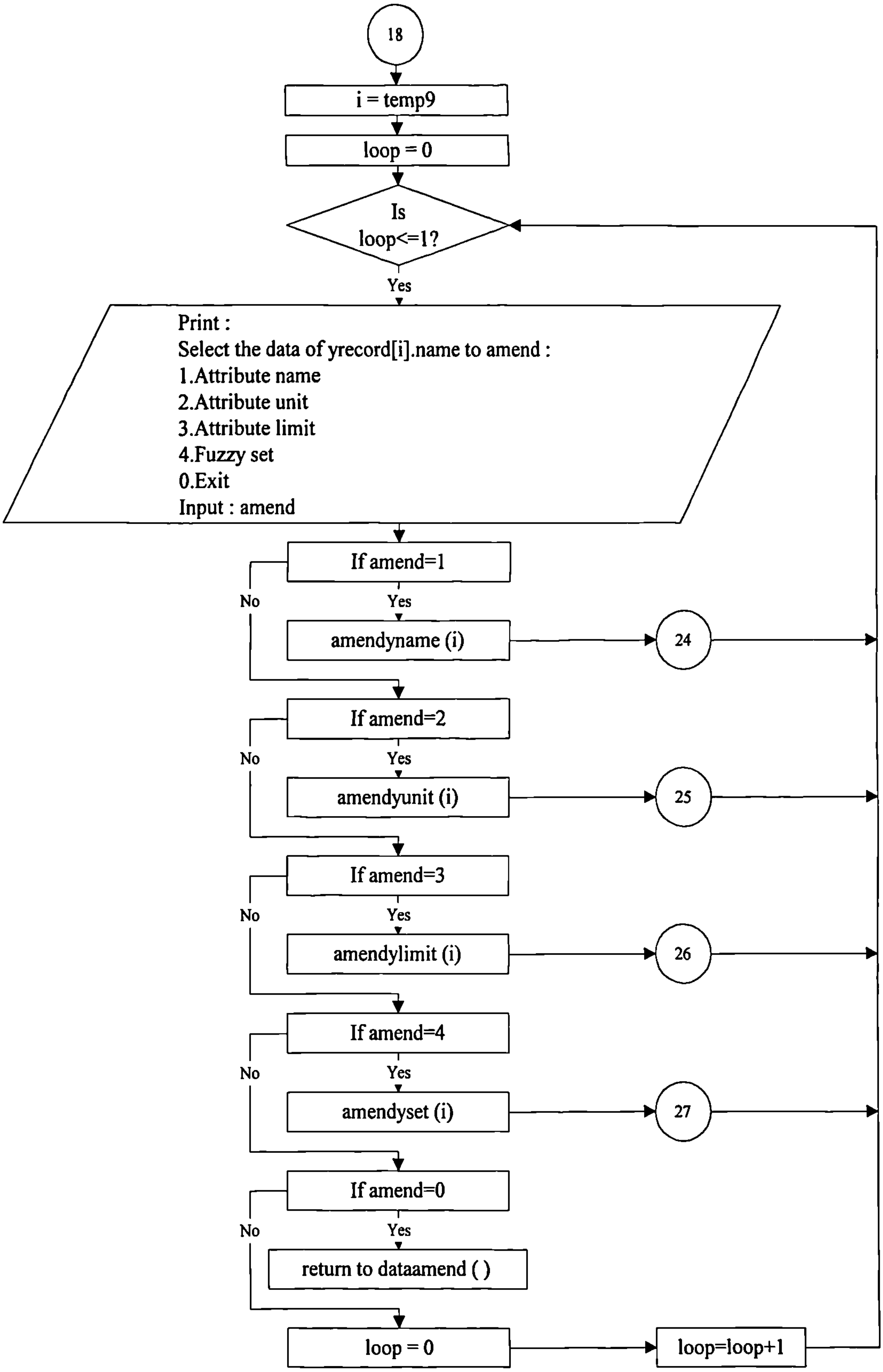

17
i = temp9
loop = 0
Is
loop<=1?
Yes
Print :
Select the data of xrecord[i].name to amend :
1.Attribute name
2.Attribute unit
3.Attribute limit
4.Fuzzy set
0.Exit
Input : amend
If amend=1
No
Yes
amendxname (i)
20
If amend=2
No
Yes
amendxunit (i)
21
If amend=3
No
Yes
amendxlimit (i)
22
If amend=4
No
Yes
amendxset (i)
23
If amend=0
No
Yes
return to dataamend ( )
loop = 0
loop=loop+1

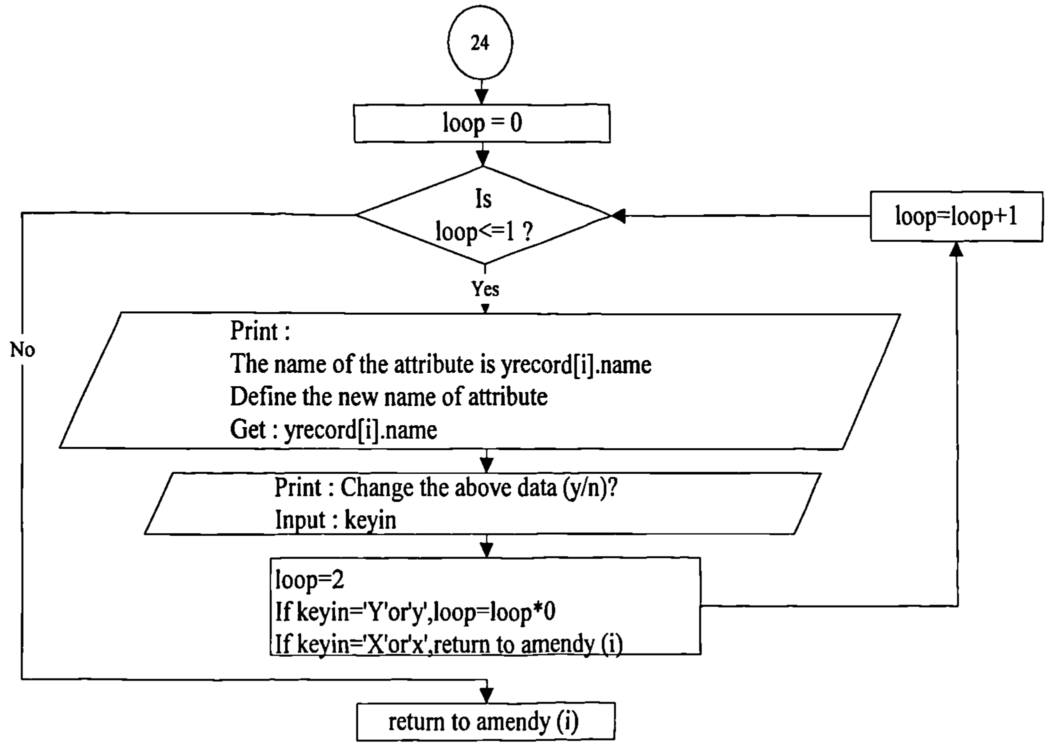

20
loop = 0
Is
loop<=1 ?
loop=loop+1
Yes
No
Print :
The name of the attribute is xrecord[i].name
Define the new name of attribute
Get : xrecord[i].name
Print : Change the above data (y/n)?
Input : keyin
loop=2
If keyin='Y'or'y',loop=loop*0
If keyin='X'or'x',return to amendx (i)
return to amendx (i)

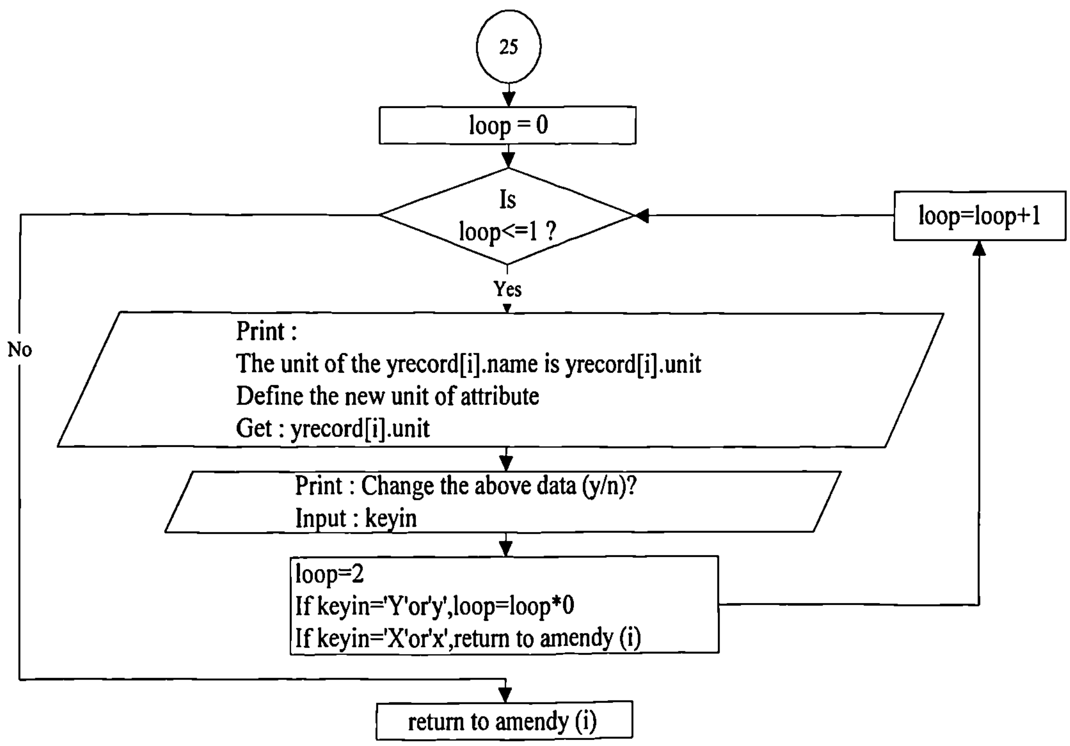

21
loop = 0
Is
loop<=1 ?
loop=loop+1
Yes
No
Print :
The unit of the xrecord[i].name is xrecord[i].unit
Define the new unit of attribute
Get : xrecord[i].unit
Print : Change the above data (y/n)?
Input : keyin
loop=2
If keyin='Y'or'y',loop=loop*0
If keyin='X'or'x',return to amendx (i)
return to amendx (i)

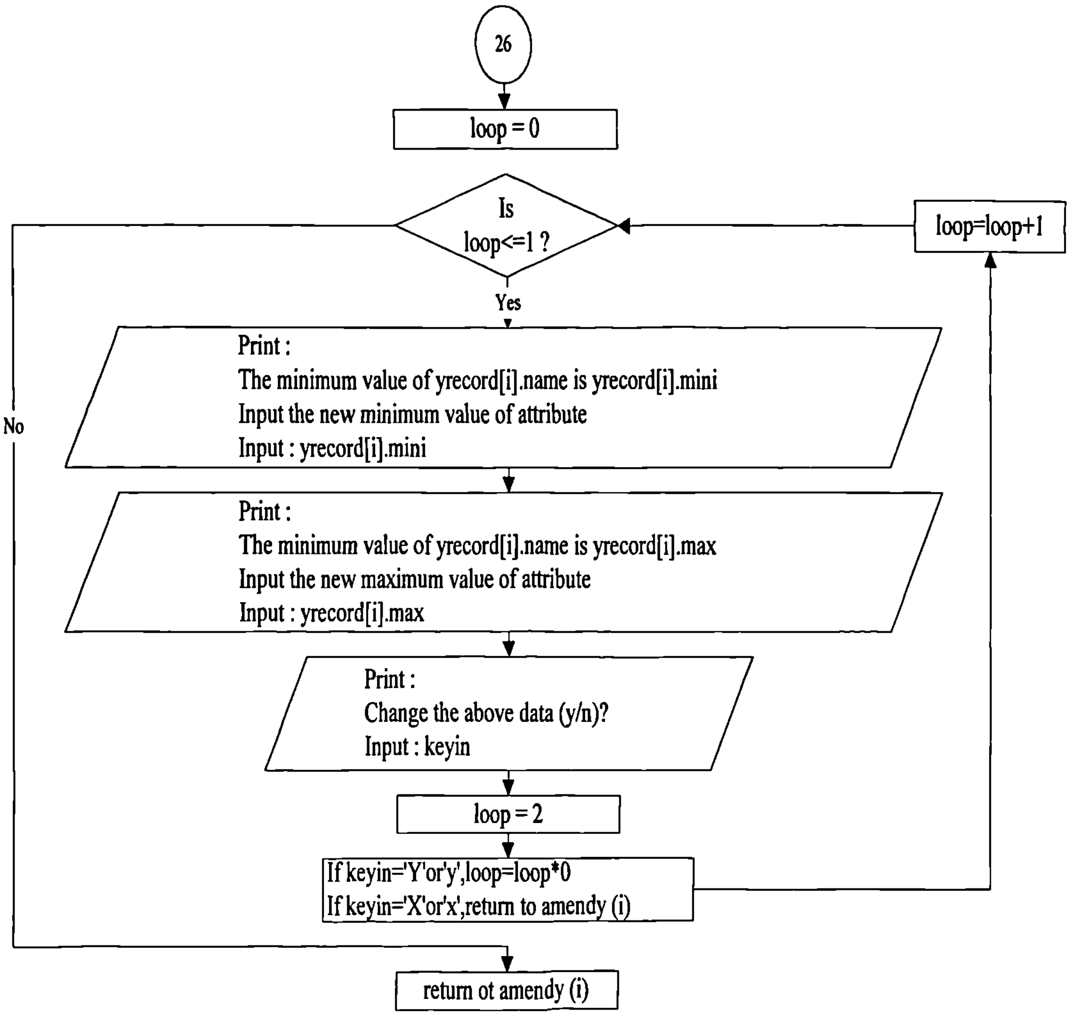

22
loop = 0
Is
loop<=1 ?
Yes
No
loop=loop+1
Print :
The minimum value of xrecord[i].name is xrecord[i].mini
Input the new minimum value of attribute
Input : xrecord[i].mini
Print :
The minimum value of xrecord[i].name is xrecord[i].max
Input the new maximum value of attribute
Input : xrecord[i].max
Print :
Change the above data (y/n)?
Input : keyin
loop = 2
If keyin='Y'or'y',loop=loop*0
If keyin='X'or'x',return to amendx (i)
return ot amendx (i)

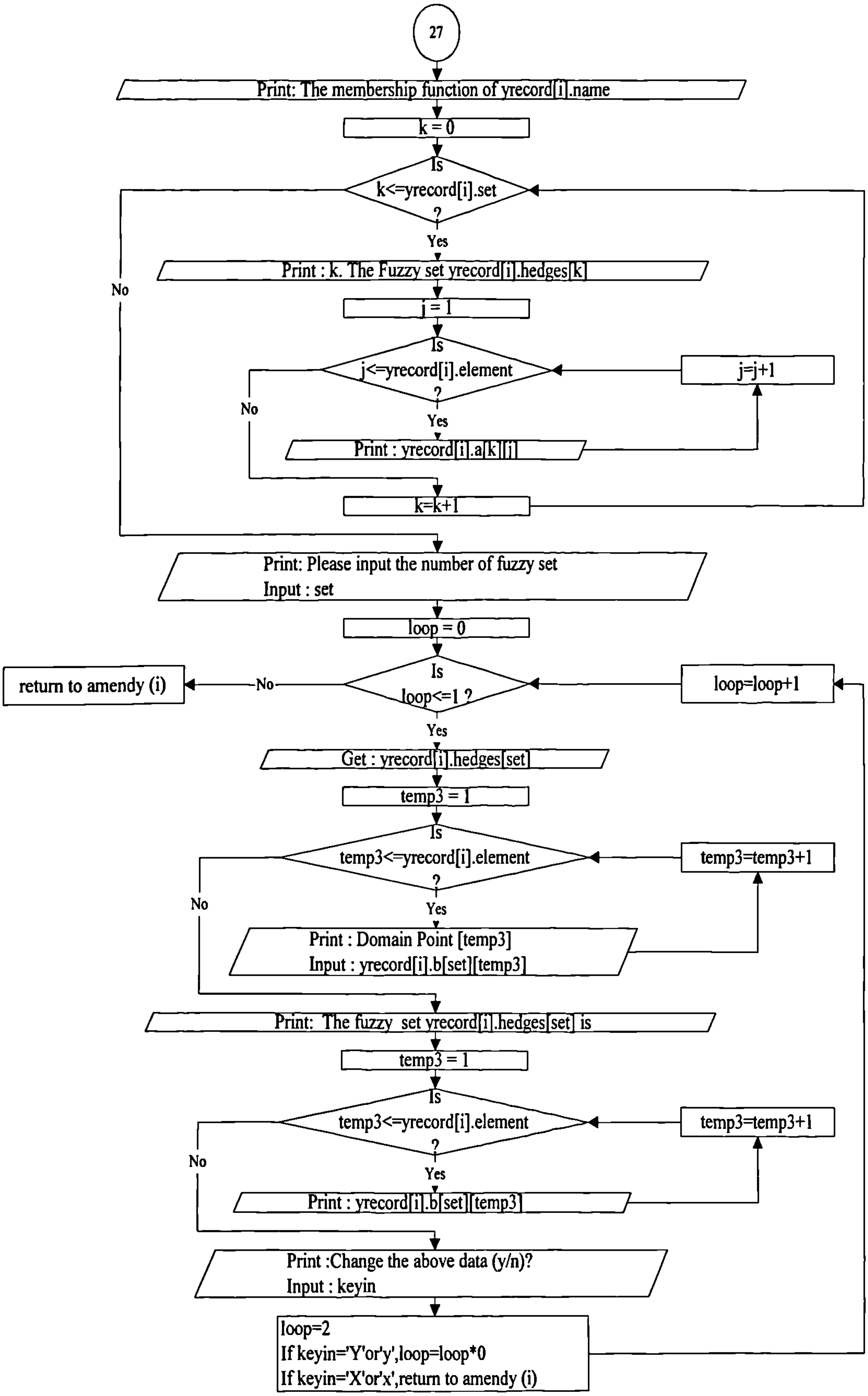

23
Print: The membership function of xrecord[i].name
k = 0
Is k<=xrecord[i].set ?
Yes
No
Print : k. The Fuzzy set xrecord[i].hedges[k]
j = 1
Is j<=xrecord[i].element ?
j=j+1
No
Yes
Print : xrecord[i].a[k][j]
k=k+1
Print: Please input the number of fuzzy set
Input : set
loop = 0
Is loop<=1 ?
return to amendx (i)
No
loop=loop+1
Yes
Get : xrecord[i].hedges[set]
temp3 = 1
Is temp3<=xrecord[i].element ?
temp3=temp3+1
No
Yes
Print : Domain Point [temp3]
Input : xrecord[i].a[set][temp3]
Print: The fuzzy set xrecord[i].hedges[set] is
temp3 = 1
Is temp3<=xrecord[i].element ?
temp3=temp3+1
No
Yes
Print : xrecord[i].a[set][temp3]
Print :Change the above data (y/n)?
Input : keyin
loop=2
If keyin='Y'or'y',loop=loop*0
If keyin='X'or'x',return to amendx (i)

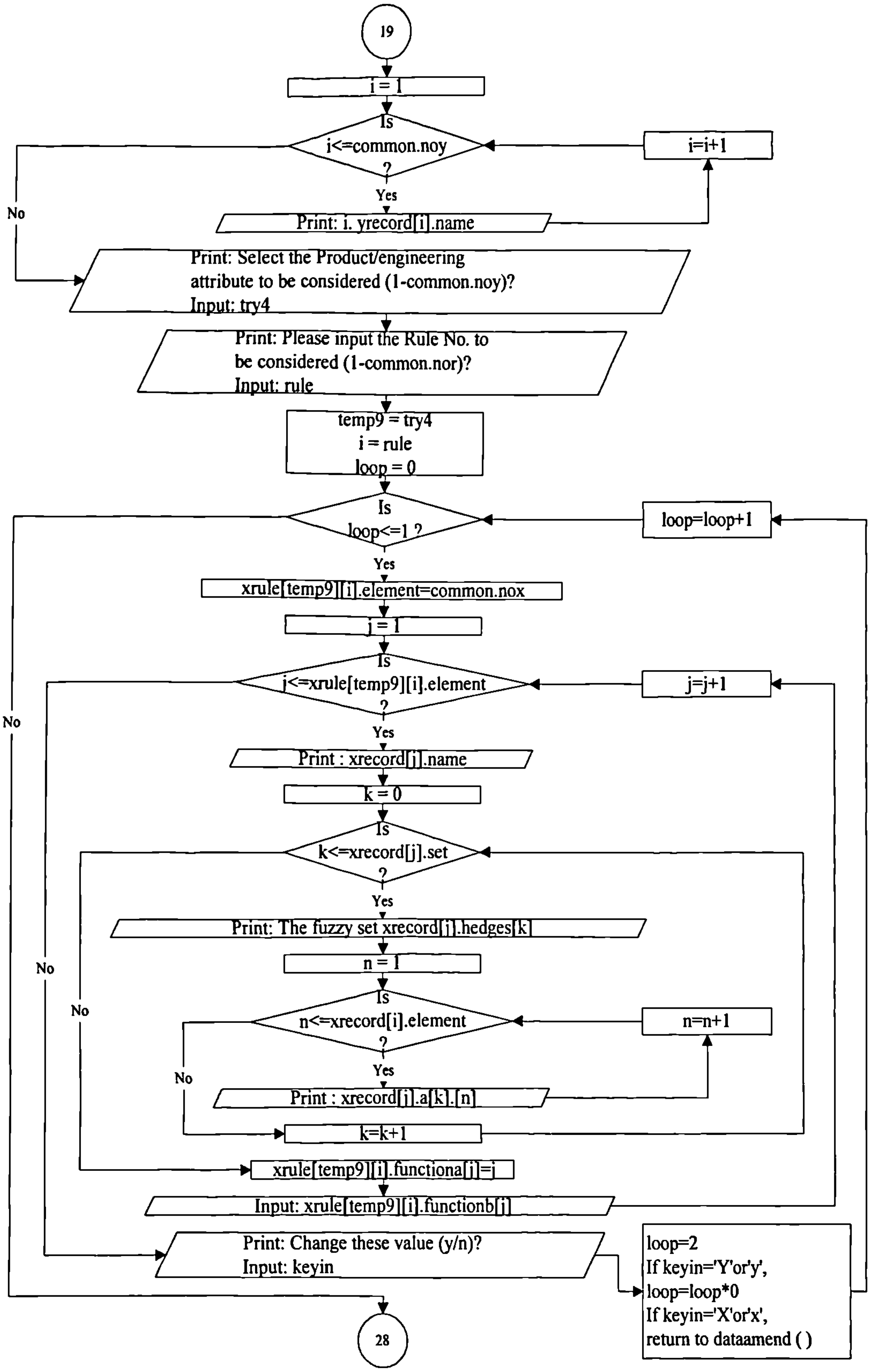

18
i = temp9
loop = 0
Is loop<=1?
Yes
Print :
Select the data of yrecord[i].name to amend :
1.Attribute name
2.Attribute unit
3.Attribute limit
4.Fuzzy set
0.Exit
Input : amend
If amend=1
No
Yes
amendyname (i)
24
If amend=2
No
Yes
amendyunit (i)
25
If amend=3
No
Yes
amendylimit (i)
26
If amend=4
No
Yes
amendyset (i)
27
If amend=0
No
Yes
return to dataamend ( )
loop = 0
loop=loop+1

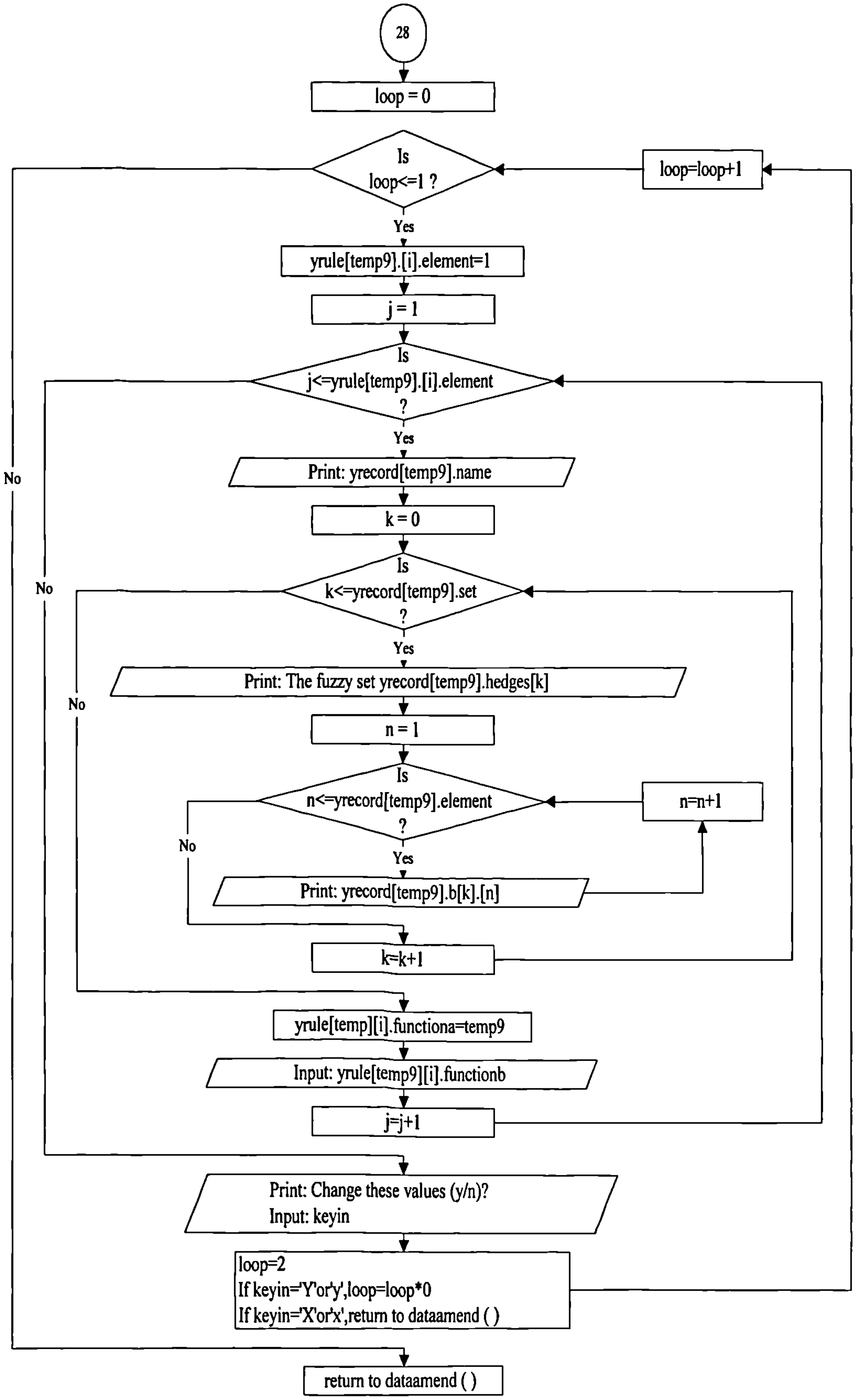

24
loop = 0
Is
loop<=1 ?
loop=loop+1
Yes
No
Print :
The name of the attribute is yrecord[i].name
Define the new name of attribute
Get : yrecord[i].name
Print : Change the above data (y/n)?
Input : keyin
loop=2
If keyin='Y'or'y',loop=loop*0
If keyin='X'or'x',return to amendy (i)
return to amendy (i)

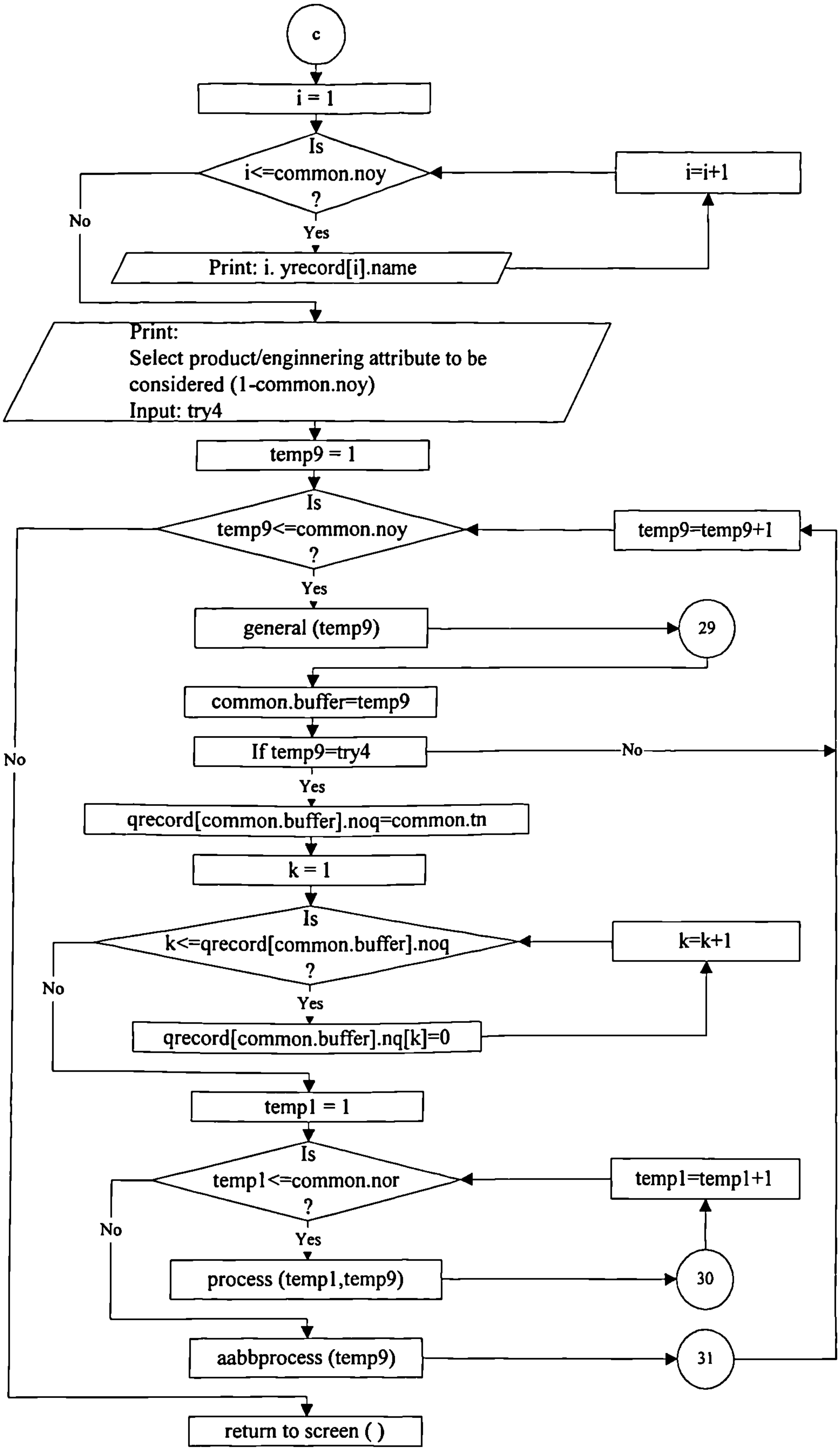

25
loop = 0
Is
loop<=1 ?
loop=loop+1
Yes
No
Print :
The unit of the yrecord[i].name is yrecord[i].unit
Define the new unit of attribute
Get : yrecord[i].unit
Print : Change the above data (y/n)?
Input : keyin
loop=2
If keyin='Y'or'y',loop=loop*0
If keyin='X'or'x',return to amendy (i)
return to amendy (i)

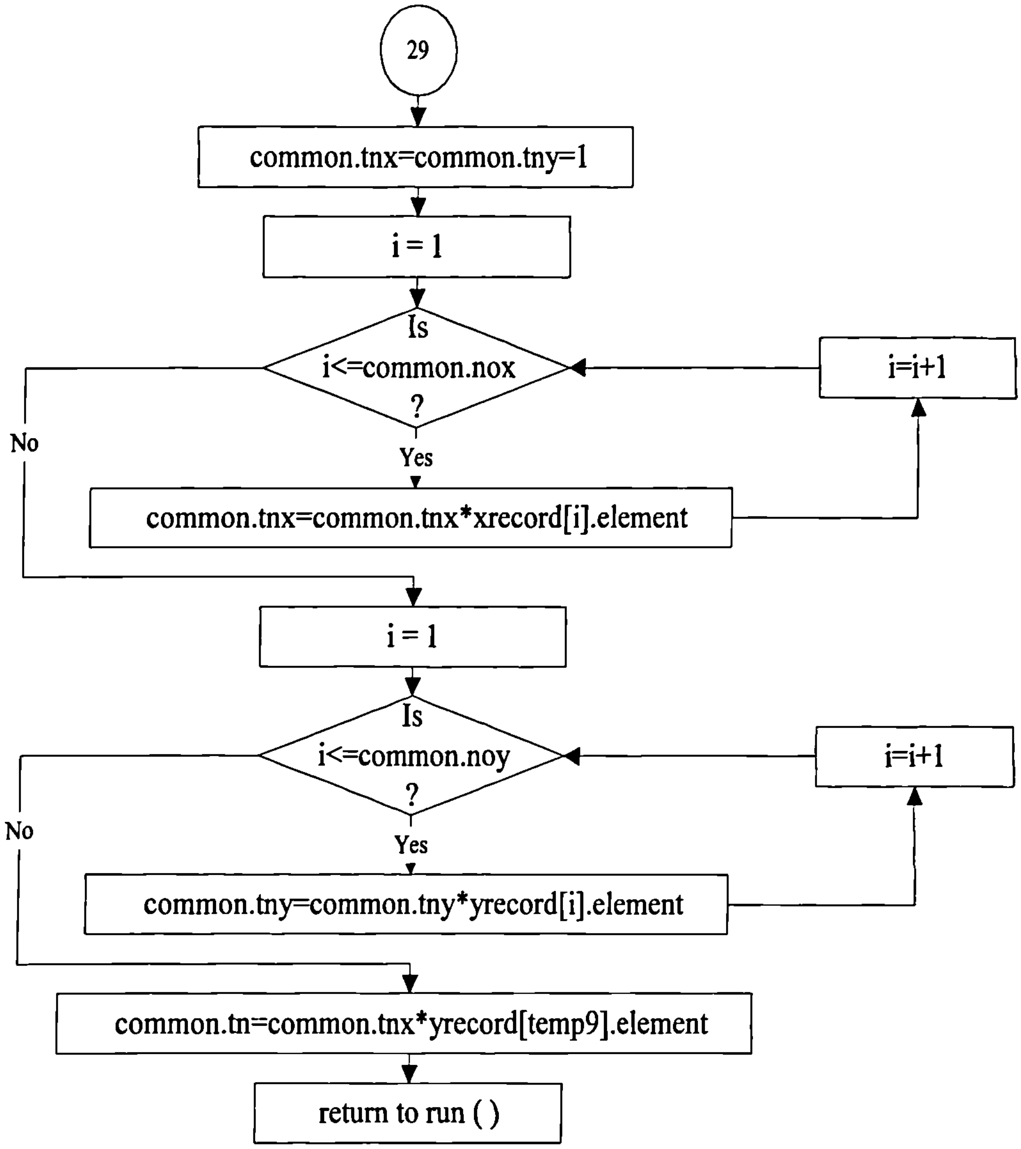

26
loop = 0
Is
loop<=1 ?
loop=loop+1
Yes
No
Print :
The minimum value of yrecord[i].name is yrecord[i].mini
Input the new minimum value of attribute
Input : yrecord[i].mini
Print :
The minimum value of yrecord[i].name is yrecord[i].max
Input the new maximum value of attribute
Input : yrecord[i].max
Print :
Change the above data (y/n)?
Input : keyin
loop = 2
If keyin='Y'or'y',loop=loop*0
If keyin='X'or'x',return to amendy (i)
return ot amendy (i)

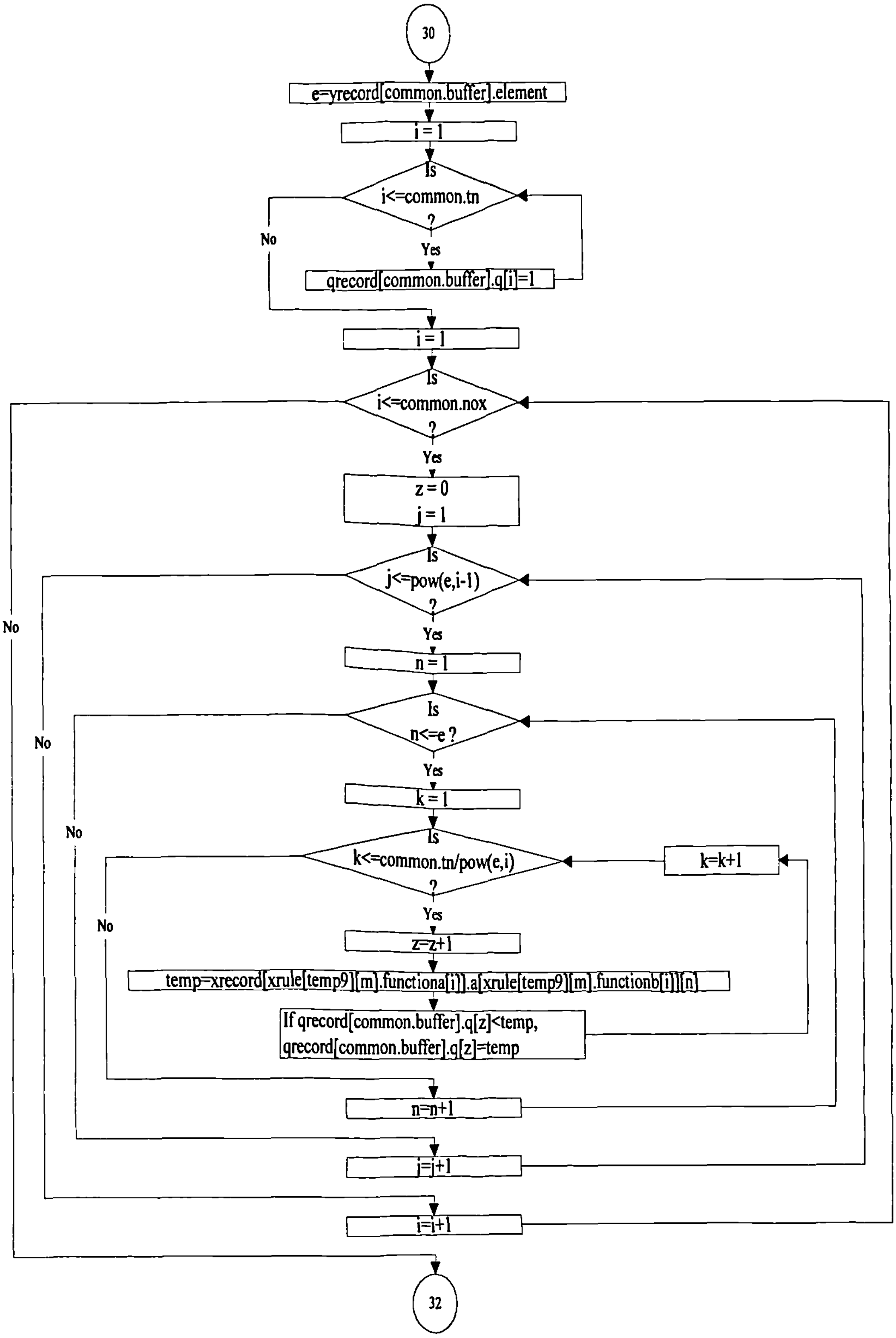

27
Print: The membership function of yrecord[i].name
k = 0
Is k<=yrecord[i].set ?
Yes
No
Print : k. The Fuzzy set yrecord[i].hedges[k]
j = 1
Is j<=yrecord[i].element ?
j=j+1
No
Yes
Print : yrecord[i].a[k][j]
k=k+1
Print: Please input the number of fuzzy set
Input : set
loop = 0
Is loop<=1 ?
return to amendy (i)
No
loop=loop+1
Yes
Get : yrecord[i].hedges[set]
temp3 = 1
Is temp3<=yrecord[i].element ?
temp3=temp3+1
No
Yes
Print : Domain Point [temp3]
Input : yrecord[i].b[set][temp3]
Print: The fuzzy set yrecord[i].hedges[set] is
temp3 = 1
Is temp3<=yrecord[i].element ?
temp3=temp3+1
No
Yes
Print : yrecord[i].b[set][temp3]
Print :Change the above data (y/n)?
Input : keyin
loop=2
If keyin='Y'or'y',loop=loop*0
If keyin='X'or'x',return to amendy (i)

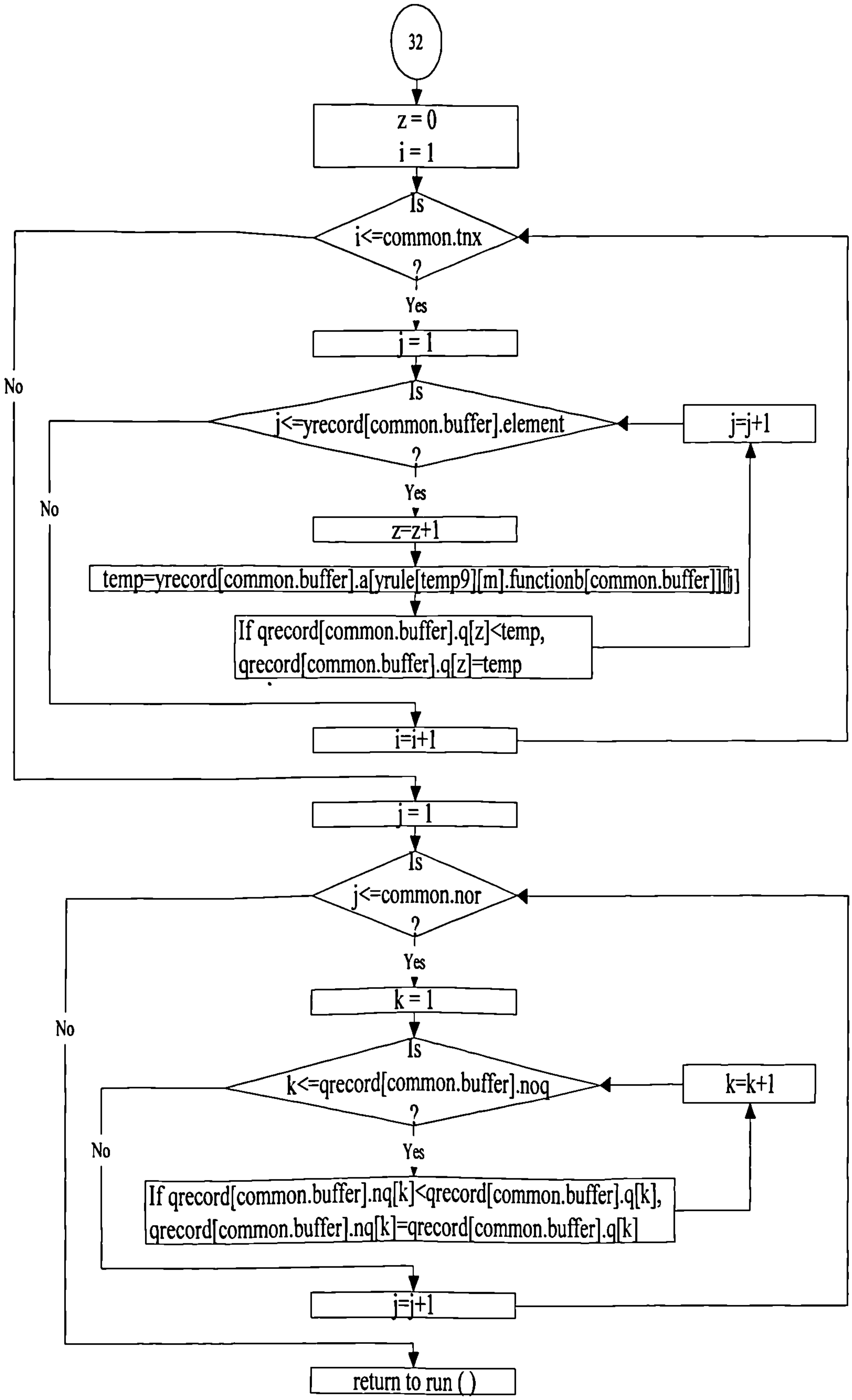

19
i = 1
Is
i<=common.noy
?
Yes
No
i=i+1
Print: i. yrecord[i].name
Print: Select the Product/engineering
attribute to be considered (1-common.noy)?
Input: try4
Print: Please input the Rule No. to
be considered (1-common.nor)?
Input: rule
temp9 = try4
i = rule
loop = 0
Is
loop<=1 ?
Yes
No
loop=loop+1
xrule[temp9][i].element=common.nox
j = 1
Is
j<=xrule[temp9][i].element
?
Yes
No
j=j+1
Print : xrecord[j].name
k = 0
Is
k<=xrecord[j].set
?
Yes
No
Print: The fuzzy set xrecord[j].hedges[k]
n = 1
Is
n<=xrecord[i].element
?
Yes
No
n=n+1
Print : xrecord[j].a[k].[n]
k=k+1
xrule[temp9][i].functiona[j]=j
Input: xrule[temp9][i].functionb[j]
Print: Change these value (y/n)?
Input: keyin
loop=2
If keyin='Y'or'y',
loop=loop*0
If keyin='X'or'x',
return to dataamend ( )
28

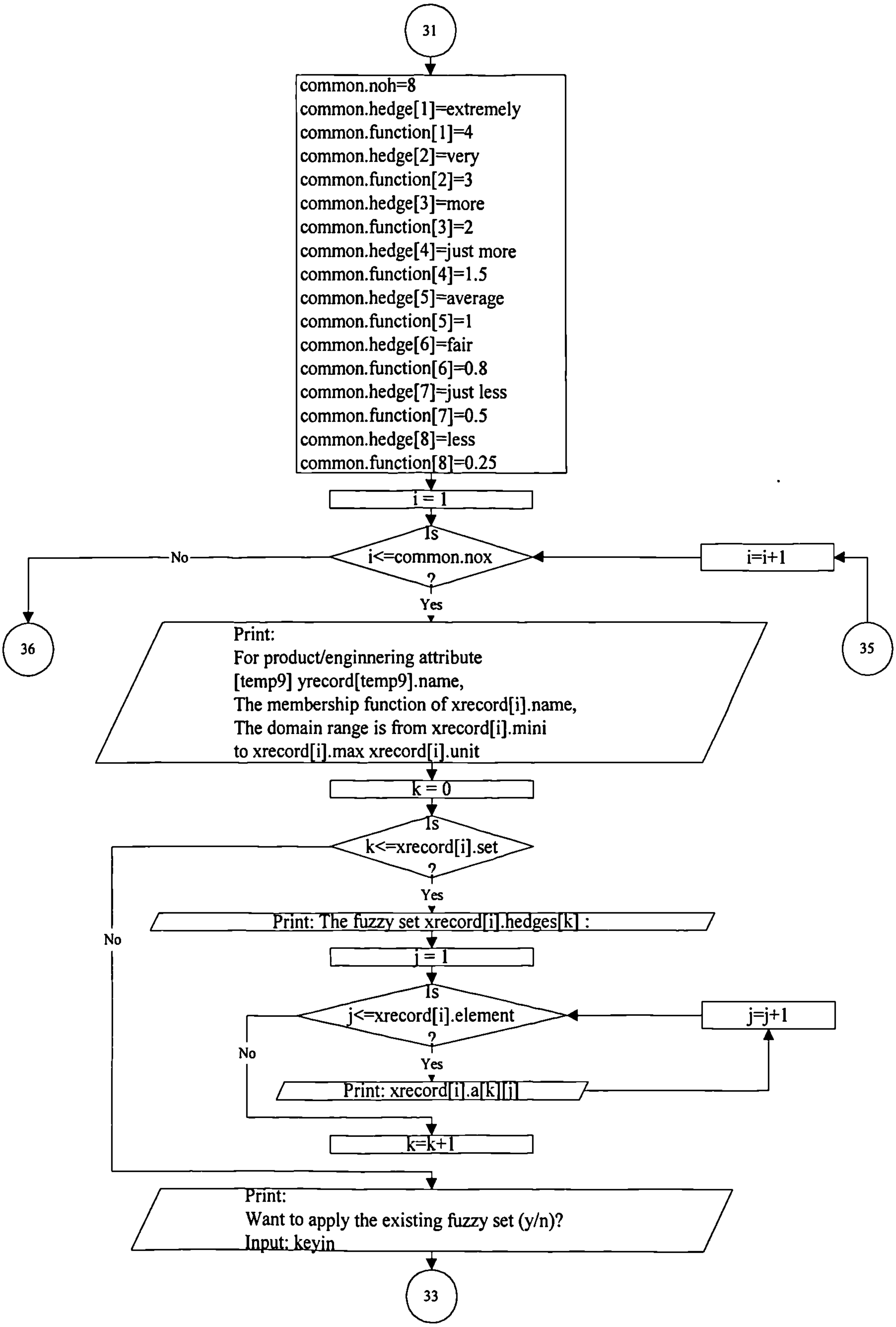

28
loop = 0
Is
loop<=1 ?
loop=loop+1
Yes
No
yrule[temp9].[i].element=1
j = 1
Is
j<=yrule[temp9].[i].element
?
Yes
No
Print: yrecord[temp9].name
k = 0
Is
k<=yrecord[temp9].set
?
Yes
No
Print: The fuzzy set yrecord[temp9].hedges[k]
n = 1
Is
n<=yrecord[temp9].element
?
n=n+1
Yes
No
Print: yrecord[temp9].b[k].[n]
k=k+1
yrule[temp][i].functiona=temp9
Input: yrule[temp9][i].functionb
j=j+1
Print: Change these values (y/n)?
Input: keyin
loop=2
If keyin='Y'or'y',loop=loop*0
If keyin='X'or'x',return to dataamend ( )
return to dataamend ( )

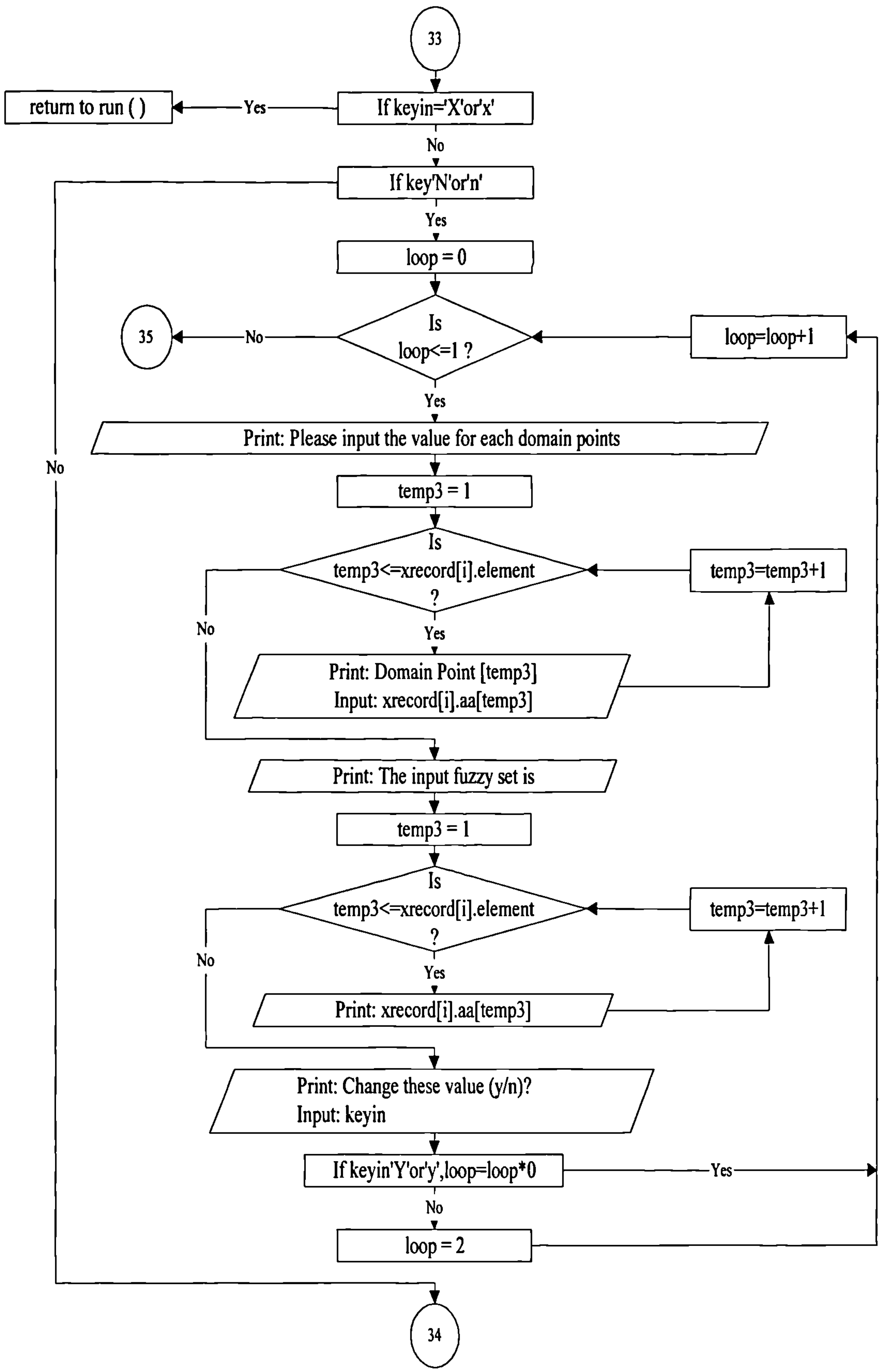

c
i = 1
Is
i<=common.noy
?
No
Yes
i=i+1
Print: i. yrecord[i].name
Print:
Select product/enginnering attribute to be
considered (1-common.noy)
Input: try4
temp9 = 1
Is
temp9<=common.noy
?
Yes
temp9=temp9+1
general (temp9)
29
common.buffer=temp9
If temp9=try4
No
No
Yes
qrecord[common.buffer].noq=common.tn
k = 1
Is
k<=qrecord[common.buffer].noq
?
No
Yes
k=k+1
qrecord[common.buffer].nq[k]=0
temp1 = 1
Is
temp1<=common.nor
?
No
Yes
temp1=temp1+1
process (temp1,temp9)
30
aabbprocess (temp9)
31
return to screen ( )


29
common.tnx=common.tny=1
i = 1
Is
i<=common.nox
?
No
Yes
i=i+1
common.tnx=common.tnx*xrecord[i].element
i = 1
Is
i<=common.noy
?
No
Yes
i=i+1
common.tny=common.tny*yrecord[i].element
common.tn=common.tnx*yrecord[temp9].element
return to run ( )

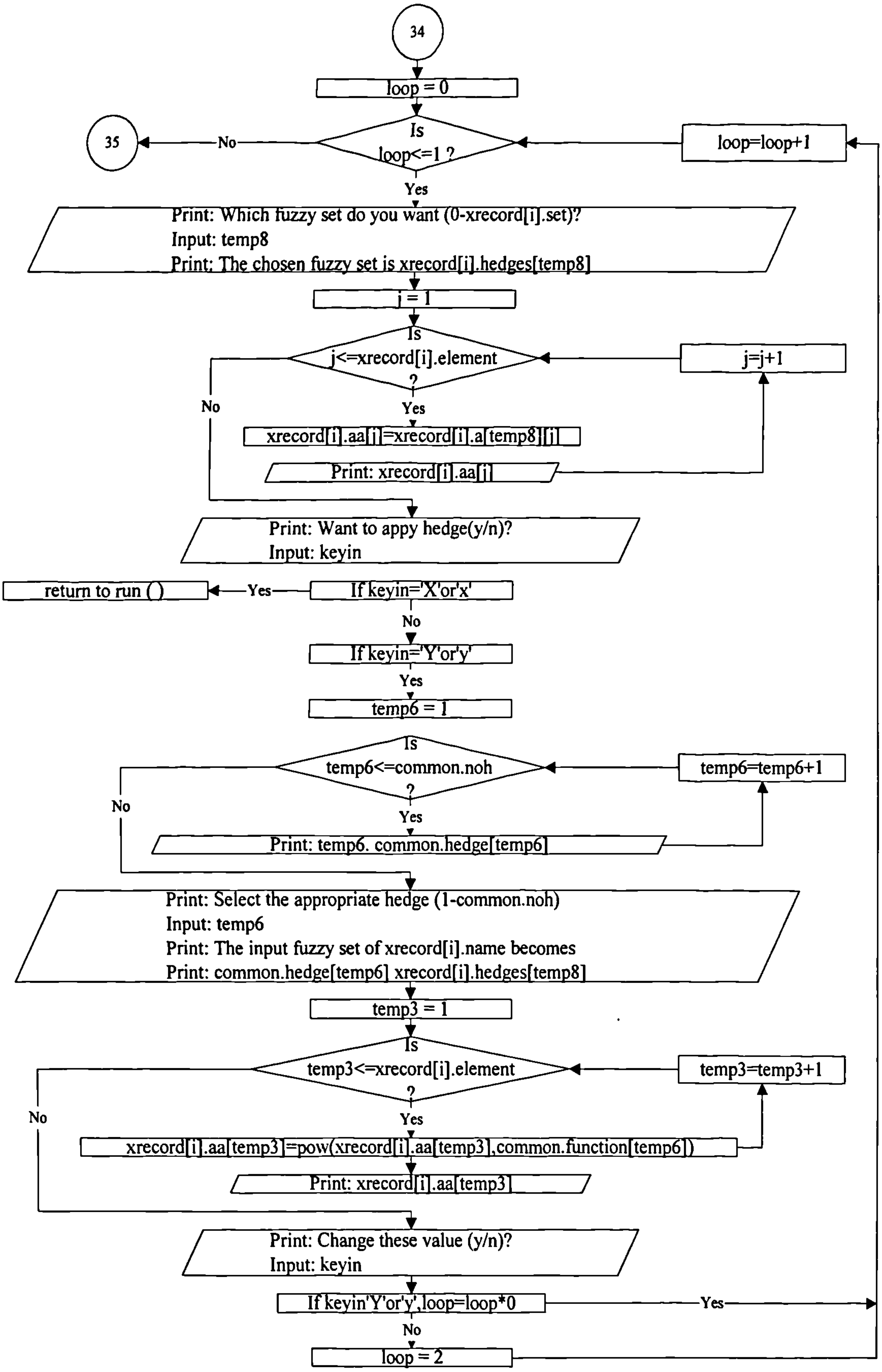

30
e=yrecord[common.buffer].element
i = 1
Is
i<=common.tn
?
No
Yes
qrecord[common.buffer].q[i]=1
i = 1
Is
i<=common.nox
?
Yes
z = 0
j = 1
Is
j<=pow(e,i-1)
?
No
Yes
n = 1
Is
n<=e ?
No
Yes
k = 1
No
Is
k<=common.tn/pow(e,i)
?
k=k+1
Yes
No
z=z+1
temp=xrecord[xrule[temp9][m].functiona[i]].a[xrule[temp9][m].functionb[i]][n]
If qrecord[common.buffer].q[z]<temp,
qrecord[common.buffer].q[z]=temp
n=n+1
j=j+1
i=i+1
32


32
z = 0
i = 1
Is
i<=common.tnx
?
Yes
No
j = 1
Is
j<=yrecord[common.buffer].element
?
j=j+1
Yes
No
z=z+1
temp=yrecord[common.buffer].a[yrule[temp9][m].functionb[common.buffer]][j]
If qrecord[common.buffer].q[z]<temp,
qrecord[common.buffer].q[z]=temp
i=i+1
j = 1
Is
j<=common.nor
?
Yes
No
k = 1
Is
k<=qrecord[common.buffer].noq
?
k=k+1
No
Yes
If qrecord[common.buffer].nq[k]<qrecord[common.buffer].q[k],
qrecord[common.buffer].nq[k]=qrecord[common.buffer].q[k]
j=j+1
return to run ( )

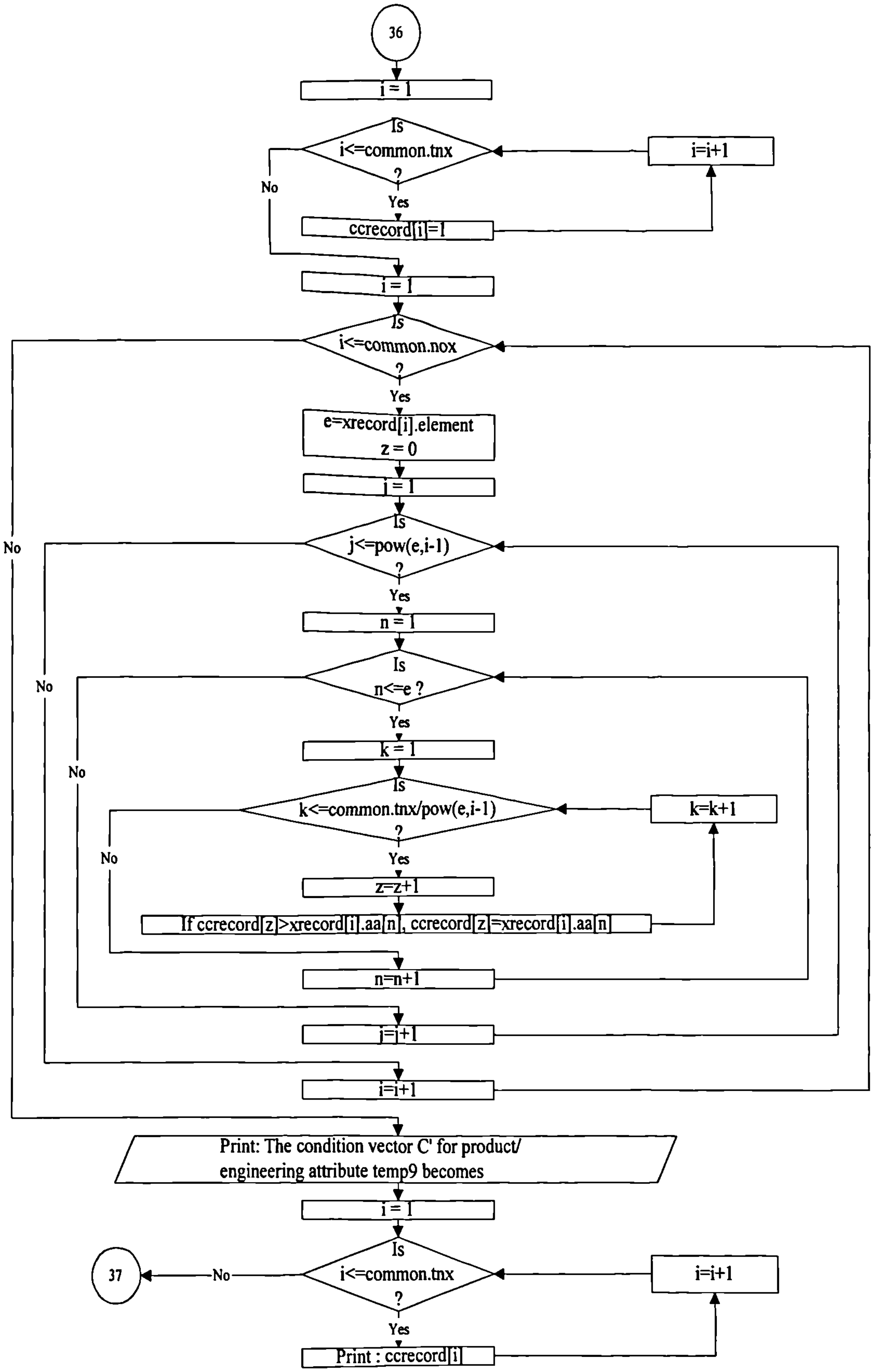

31
common.noh=8
common.hedge[1]=extremely
common.function[1]=4
common.hedge[2]=very
common.function[2]=3
common.hedge[3]=more
common.function[3]=2
common.hedge[4]=just more
common.function[4]=1.5
common.hedge[5]=average
common.function[5]=1
common.hedge[6]=fair
common.function[6]=0.8
common.hedge[7]=just less
common.function[7]=0.5
common.hedge[8]=less
common.function[8]=0.25
i = 1
Is i<=common.nox ?
No
Yes
i=i+1
36
35
Print:
For product/enginnering attribute
[temp9] yrecord[temp9].name,
The membership function of xrecord[i].name,
The domain range is from xrecord[i].mini
to xrecord[i].max xrecord[i].unit
k = 0
Is k<=xrecord[i].set ?
No
Yes
Print: The fuzzy set xrecord[i].hedges[k] :
j = 1
Is j<=xrecord[i].element ?
No
Yes
j=j+1
Print: xrecord[i].a[k][j]
k=k+1
Print:
Want to apply the existing fuzzy set (y/n)?
Input: keyin
33

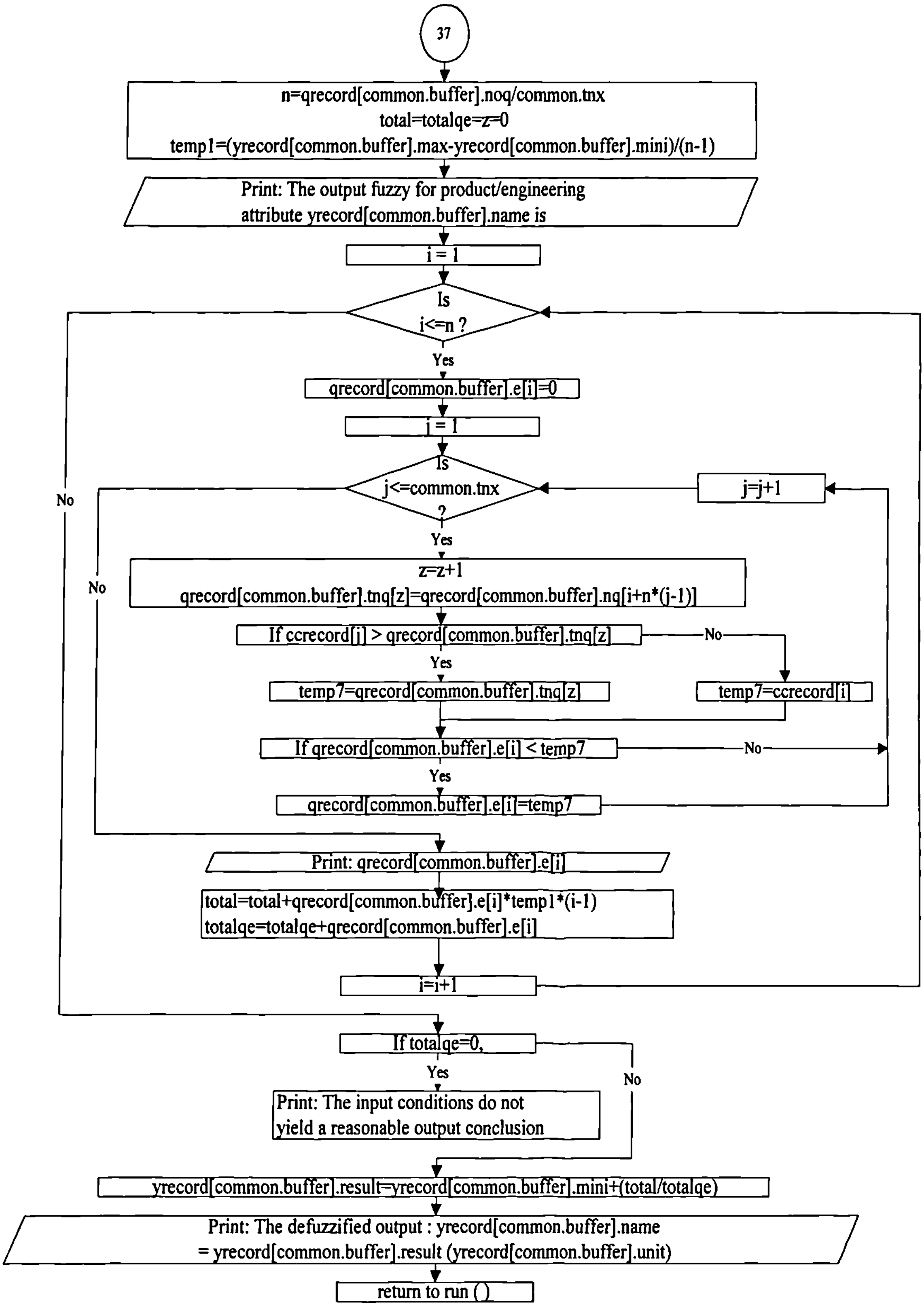


33
If keyin='X'or'x'
Yes
return to run ( )
No
If key'N'or'n'
Yes
loop = 0
Is
loop<=1 ?
No
35
loop=loop+1
Yes
Print: Please input the value for each domain points
No
temp3 = 1
Is
temp3<=xrecord[i].element
?
temp3=temp3+1
No
Yes
Print: Domain Point [temp3]
Input: xrecord[i].aa[temp3]
Print: The input fuzzy set is
temp3 = 1
Is
temp3<=xrecord[i].element
?
temp3=temp3+1
No
Yes
Print: xrecord[i].aa[temp3]
Print: Change these value (y/n)?
Input: keyin
If keyin'Y'or'y',loop=loop*0
Yes
No
loop = 2
34



34
loop = 0
Is loop<=1 ?
No
35
loop=loop+1
Yes
Print: Which fuzzy set do you want (0-xrecord[i].set)?
Input: temp8
Print: The chosen fuzzy set is xrecord[i].hedges[temp8]
j = 1
Is j<=xrecord[i].element ?
j=j+1
No
Yes
xrecord[i].aa[j]=xrecord[i].a[temp8][j]
Print: xrecord[i].aa[j]
Print: Want to appy hedge(y/n)?
Input: keyin
return to run ()
Yes
If keyin='X'or'x'
No
If keyin='Y'or'y'
Yes
temp6 = 1
Is temp6<=common.noh ?
temp6=temp6+1
No
Yes
Print: temp6. common.hedge[temp6]
Print: Select the appropriate hedge (1-common.noh)
Input: temp6
Print: The input fuzzy set of xrecord[i].name becomes
Print: common.hedge[temp6] xrecord[i].hedges[temp8]
temp3 = 1
Is temp3<=xrecord[i].element ?
temp3=temp3+1
No
Yes
xrecord[i].aa[temp3]=pow(xrecord[i].aa[temp3],common.function[temp6])
Print: xrecord[i].aa[temp3]
Print: Change these value (y/n)?
Input: keyin
If keyin'Y'or'y',loop=loop*0
Yes
No
loop = 2


36
i = 1
Is i<=common.tnx ?
No
Yes
ccrecord[i]=1
i=i+1
i = 1
Is i<=common.nox ?
Yes
e=xrecord[i].element
z = 0
j = 1
Is j<=pow(e,i-1) ?
Yes
n = 1
Is n<=e ?
Yes
k = 1
Is k<=common.tnx/pow(e,i-1) ?
Yes
z=z+1
If ccrecord[z]>xrecord[i].aa[n], ccrecord[z]=xrecord[i].aa[n]
k=k+1
n=n+1
j=j+1
i=i+1
No
Print: The condition vector C' for product/ engineering attribute temp9 becomes
i = 1
Is i<=common.tnx ?
37
No
Yes
Print : ccrecord[i]
i=i+1

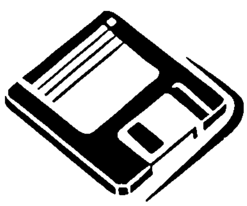


End of Flow Diagrams

APPENDIX II

Fuzzy
Customer
Requirement
Inference
System

▲USER GUIDE▲



CONTENTS

SECTION 1. -- INTRODUCTION (Starting FCRIS)

1.1 To start the programme from Microsoft Windows or from the appropriate directory, invoke '**FCRIS**', and the following systems screen will be displayed:

```
**********************************************************************
*                                                                    *
*     FFFFFFFF    CCCC      RRRRRR     IIIIII    SSSS                *
*     F          C     C   R      R      I     S     S               *
*     F          C       C R        R    I   S         S             *
*     F          C         R        R    I   S                       *
*     F          C         R        R    I   S                       *
*     F          C         R      R      I     S                     *
*     FFFFF      C         RRRRRR        I       SSSS                *
*     F          C         R    R        I             S             *
*     F          C         R    R        I               S           *
*     F          C         R      R      I               S           *
*     F          C      C  R      R      I   S           S           *
*     F          C    C    R        R    I     S      S              *
*     F            CCCC    R        R  IIIIII    SSSS                *
*                                                                    *
**********************************************************************
```

Press any key to continue.

1.2. After screen '**FCRIS**' has been displayed, then press any key. The Main Menu of the programme is shown as follows:

Fuzzy Customer Requirements Inference System

---

1. CREATE A NEW FUZZY MODEL

2. ACTIVATE AN EXISTING FUZZY MODEL

0. QUIT

PLEASE SELECT THE OPTION REQUIRED :

SECTION 2. -- ESTABLISH THE DATA BASES

2. Select option '1' or '2' and press 'Enter' at the Main Menu to create or retrieve the data bases for the programme.

2.1 If the option '1' is selected, the following screen will be shown for Model Parameters specification.

```
CREATE A NEW FUZZY MODEL

      MODEL PARAMETERS SPECIFICATION

How many Customer Attributes are involved ? 2

How many Product Attributes are involved ? 1

How many Fuzzy Rules are involved ? 4

Would you like change these values (Y=Yes, N=No(default))?
```

2.1.1. After that, enter the names and other parameters of the all the relevant Customer Attributes.

```
CREATE A NEW FUZZY MODEL

      CUSTOMER ATTRIBUTE 1

Define the Attribute 1                      : Top Speed

Input the unit of measure                   : km/hr

Input the minimum value                     : 0

Input the maximum value                     : 250

Input the number of fuzzy sets involved     : 4

Input the no. of domain points in each set  : 6

Would you like change these values (Y=Yes, N=No(default))?
```

2.1.2. Then, define the labels and the grade of membership against each domain point for the related Fuzzy Sets.

```
CREATE A NEW FUZZY MODEL

      CUSTOMER ATTRIBUTE 1

Input the Membership Function for the Fuzzy Set [1]        : slow

Input the value for each domain point:

Domain Point [1] -- 1

Domain Point [2] -- 0.5

Domain Point [3] -- 0

Domain Point [4] -- 0

Domain Point [5] -- 0

Domain Point [6] -- 0

Would you like change these values (Y=Yes, N=No(default))?
```

2.1.3. Repeat the step 2.1.1. and 2.1.2 for the related Customer and Product Attributes.

2.1.4. Select an appropriate Fuzzy set of each of the Customer and Product Attributes to build the Fuzzy Rule Base

```
CREATE A NEW FUZZY MODEL

Select the fuzzy set for the attribute:
Top Speed

0. The Fuzzy set 'unit' : 1,1,1,1,1,1,
1. The Fuzzy set 'slow' : 1,0.5,0,0,0,0,
2. The Fuzzy set 'medium' : 0,0,1,0,0,0,
3. The Fuzzy set 'normal' : 0,0,0.5,0.5,1,1,
4. The Fuzzy set 'fast' : 0,0,0,0,0.5,1,

Which FUZZY SET is selected? 1
```

2.2. If option '2' is selected from the Main Menu, the following screen will be shown.

```
ACTIVATE AN EXISTING FUZZY MODEL

Activate -- input the name of the Fuzzy Model:  (e.g. FUZZY1)

The selected Fuzzy Model has been activated.

Press [ENTER] to continue.
```

2.2.1. After that, the current parameters in the selected fuzzy model will be displayed. Press 'enter' to show further details or press 'X' to exit.

```
ACTIVATE AN EXISTING FUZZY MODEL


    DISPLAY DETAILS OF THE FUZZY MODEL

    MODEL PARAMETERS

No. of Customer Attributes = 3

No. of Product Attributes = 2

No. of Fuzzy Rules = 4


Press [ENTER] to continue or Press [X] to exit.
```

SECTION 3. -- RUN THE FUZZY INFERENCE PROGRAMME

3. After the required fuzzy model has been specified or activated, the Main Menu will be refreshed, and more options will become available are shown:

```
Fuzzy Customer Requirements Inference System
____________________________________________

1. CREATE A NEW FUZZY MODEL

2. ACTIVATE AN EXISTING FUZZY MODEL

3. RUN THE FUZZY INFERENCE PROGRAMME

4. DISPLAY DETAILS OF THE FUZZY MODEL

5. SAVE THE CURRENT FUZZY MODEL

6. AMEND THE CURRENT FUZZY MODEL

0. QUIT

PLEASE SELECT THE OPTION REQUIRED :
```

3.1. To run the Fuzzy Inference Programme, select the Option required '3', and the following screen will be displayed.

```
RUN THE FUZZY INFERENCE PROGRAMME

Product Attributes :

1. Engine Output Power.

2. Fuel Economy.

Select the Product Attribute to be considered?
```

3.2 Then, select or specify the membership function for each of the Customer and Product Attributes. In this case, an existing fuzzy set is chosen, and a suitable hedge is applied.

RUN THE FUZZY INFERENCE PROGRAMME

For the Product Attribute [1]: Engine Output Power

The membership function for the Customer Attribute, Seating Capacity with domain range covering 2 to 7 seats is chosen from one of the following fuzzy sets:

0. The Fuzzy set 'unit' : 1,1,1,1,1,1,
1. The Fuzzy set 'less ' : 1,0.5,0,0,0,0,
2. The Fuzzy set 'not enough ' : 0,0.5,1,0.5,0,0,
3. The Fuzzy set 'enough' : 0,0,0,0.5,1,0.5,
4. The Fuzzy set 'too much ' : 0,0,0,0,0.5,1,

Do you want to apply an existing fuzzy set (Y=Yes(default) or N=No)? Y
Which fuzzy set do you want (0-4) ? 1

The chosen fuzzy set is 'less ' -- 1,0.5,0,0,0,0

Do you want to apply hedges to the chosen fuzzy set (Y=Yes or N=No(default))? Y

(1. extremely 2. very 3. more 4. just more)
(5. average 6. fair 7. just less 8. less)

Please select the appropriate hedge (1-8). 1

The input fuzzy set of Seating Capacity becomes 'extremely less ' with membership function = 1,0.0625,0,0,0,0

Would you like change these values (Y=Yes, N=No(default))?

Alternatively, if a new fuzzy set is to be defined, the input screen can be illustrated as follows:

```
RUN THE FUZZY INFERENCE PROGRAMME

For the Product Attribute [1]: Engine Output Power,
the membership function for the Customer Attribute, Weight with domain range
covering 700 to 1500 kg can be defined as follows:

0. The Fuzzy set 'unit' : 1,1,1,1,1,1,
1. The Fuzzy set 'light' : 1,1,0.5,0,0,0,
2. The Fuzzy set 'normal' : 0,0,0.5,1,0.5,0,
3. The Fuzzy set 'heavy' : 0,0,0,0.5,1,0.5,
4. The Fuzzy set 'very heavy' : 0,0,0,0,0.5,1,

Do you want to apply an existing fuzzy set (Y=Yes(default) or N=No)? N

Please input the value for each domain points :

Domain Point [1]    :0.1
Domain Point [2]    :0.2
Domain Point [3]    :0.3
Domain Point [4]    :0.4
Domain Point [5]    :0.5
Domain Point [6]    :0.6

The input fuzzy set is : 0.1,0.2,0.3,0.4,0.5,0.6,
Would you like change these values (Y=Yes, N=No(default))?
```

3.3 Once all the input Customer Attributes are defined, the system will proceed to carry out Rule Evaluation in order to obtain an output fuzzy set. This fuzzy set will then be defuzzified to give a crisp Target Value for the Product Attribute being considered. The screen will appear as follows:

```
RUN THE FUZZY INFERENCE PROGRAMME

Press [ENTER] to continue.

The membership function of the output fuzzy set for the Product Attribute, 'Engine
Output Power' is worked out to be: 0.1,0.2, 0.2,0 ,0, 0

    RESULT DISPLAY
The Defuzzified Output : Engine Output Power = 30 ( horsepower ).
Press [ENTER] to continue.
```

SECTION 4. -- DISPLAY DATA OF THE FUZZY MODEL

4. If option '4' is selected from the Main Menu, the following sub-menu will be shown.

```
DISPLAY DETAILS OF THE FUZZY MODEL


     1.   CUSTOMER ATTRIBUTES

     2.   PRODUCT ATTRIBUTES

     3.   FUZZY RULE BASES

     0.   EXIT


     PLEASE SELECT THE OPTION REQUIRED :
```

4.1. Depending on the option selected, the relevant data / parameters will be displayed. The following screen displays details of a fuzzy proposition / rule.

```
DISPLAY DETAILS OF THE FUZZY MODEL

PRODUCT ATTRIBUTE:  Engine Output Power

     FUZZY RULE 1

If

     Top Speed is slow
     Seating Capacity is small
     Weight is light

Then

     Engine Output Power is less

Press [Shift-Print Screen] to print the above model parameters .

Press [ENTER] to continue or Press [X] to exit.
```

SECTION 5. -- SAVE THE FUZZY MODEL

5. The data in an amended or newly created Fuzzy Model can be saved by selecting the Option '5' from the Main Menu as shown in the following screen:

```
UPDATE/SAVE THE CURRENT FUZZY MODEL


    Update/Save -- input the name of the Fuzzy Model:  (e.g. FUZZY2)


The current Fuzzy Model is saved.


Press [ENTER] to continue.
```

SECTION 6. -- AMEND THE FUZZY MODEL

6. To amend an existing Fuzzy Model, select Option '6' from the Main Menu, and the following screen will be displayed:

```
ATTRIBUTE DATA AMENDMENT

    Select the Attribute data to amend :

        1. General Data

        2. Customer Attributes

        3. Product Attributes

        4. Fuzzy Rule Base

        0. Exit

        Please Select the Option required :
```

6.1. If '1' is selected from the above sub-menu, the general parameters is activated for the necessary amendments as follows:

```
ATTRIBUTE DATA AMENDMENT

    Amend the Option of Customer Attribute (Y=Yes or N=No(default)?  Y

    Input the Option of Customer Attribute :  3

    Amend the Option of Production/Engineering Attribute
    (Y=Yes or N=No(default)?  Y

    Input the Option of Production/Engineering Attribute :  2

    Amend the Option of Fuzzy Rule (Y=Yes or N=No(default)?  Y

    Input the Option of Fuzzy Rule :  4

    Would you like to change the above data?(Y=Yes or N=No(default)
```

6.2 If '2' is selected, the current Customer Attributes will be listed, and the relevant attribute can thus be chosen for amendment.

```
ATTRIBUTE DATA AMENDMENT

    The Names of Customer Attributes :

    1. Top Speed

    2. Seating Capacity

    3. Weight

    0. Exit

    Please Select the Option required : 1
```

Then, the relevant screen will be displayed so that the items can be chosen for amendment as required:

```
ATTRIBUTE DATA AMENDMENT

    Select the Data of Top Speed to amend :

        1. Attribute Name

        2. Attribute Unit

        3. Attribute limit

        4. Fuzzy Set

        0. Exit

        Please select the Option required : 4
```

6.2.1. Depending on the selection in the above sub-menu, the appropriate screen will be brought up for data amendment.

If Option '1' is selected, the following screen will be displayed:

```
ATTRIBUTE DATA AMENDMENT


    The name of the attribute is Top Speed.

    Define the new name of attribute          :Top Speed

    Would you like to change the above data?(Y=Yes or N=No(default))
```

If Option '2' is selected, the following screen will be displayed:

```
ATTRIBUTE DATA AMENDMENT


    The unit of the Top Speed is km/h.

    Define the new unit of attribute          :m/s

    Would you like to change the above data?(Y=Yes or N=No(default))
```

If option '3' is selected, the following screen will be displayed:

```
ATTRIBUTE DATA AMENDMENT


    The minimum value of Top Speed is 0.

    Input the new minimum value of attribute      : 10

    The maximum value of Top Speed is 350.

    Input the new maximum value of attribute      : 150

    Would you like to change the above data?(Y=Yes or N=No(default))
```

If Option '4' is selected, the following screen will be displayed:

```
ATTRIBUTE DATA AMENDMENT


The membership function of Top Speed

0. The Fuzzy set 'unit' : 1,1,1,1,1,1,
1. The Fuzzy set 'slow' : 1,0.5,0,0,0,0,
2. The Fuzzy set 'normal' : 0,0,1,0,0,0,
3. The Fuzzy set 'fast' : 0,0,0,0.5,1,1,
4. The Fuzzy set 'extra fast' : 0,0,0,0,0.5,1,

Please input the option of  Fuzzy Set :  2
```

Then, the membership function for the chosen fuzzy set can be amended as follows.

```
ATTRIBUTE DATA AMENDMENT


Define the new label of the Fuzzy Set [2] of the Top Speed :average


Please input the value for each domain points :

Domain Point [1]      :1
Domain Point [2]      :0.8
Domain Point [3]      :0.6
Domain Point [4]      :0.4
Domain Point [5]      :0.2
Domain Point [6]      :0


The fuzzy set 'average' is : 1,0.8,0.6,0.4,0.2,0,

Would you like to change the above data?(Y=Yes or N=No(default)
```

6.3. The Product Attributes can be amended in similar fashion as with the Customer Attributes.

After the required amendments have been completed, the previous sub-menu will be display.

To return to the Main Menu, select '0'.

SECTION 7. -- TERMINATE FCRIS

7. While back in the Main Menu, select any option to perform further functions as shown:

Fuzzy Customer Requirements Inference System

1. CREATE A NEW FUZZY MODEL
2. ACTIVATE AN EXISTING FUZZY MODEL
3. RUN THE FUZZY INFERENCE PROGRAMME
4. DISPLAY DETAILS OF THE FUZZY MODEL
5. SAVE THE CURRENT FUZZY MODEL
6. AMEND THE CURRENT FUZZY MODEL
0. QUIT

PLEASE SELECT THE OPTION REQUIRED : 0

To quit the **FCRIS** programme, select Option '0'.

End of the programme

Press [ENTER]

The programme will then be terminated.

End of User Guide

APPENDIX III

SAMPLE QUESTIONNAIRES FOR CAPTURING CUSTOMER ATTRIBUTES ON MID-RANGE Hi-Fi EQUIPMENT

Appendix III (a):

Design Rationale of Questionnaire 1 for CD Players

INTRODUCTION

Questionnaire 1 was designed to study the customer requirements on multi-disc CD players. A copy of Questionnaire 1 is attached in Appendix III(b).

DESIGN OF QUESTIONNAIRE 1

1. Customer habit

Questions 1 to 6 address the habit of listening and the frequency of changing disc during listening. They are used to capture the customer attributes and the relevant product attributes on multi-disc CD players. The reasoning behind these questions are as follows:

Q No	*Question*	*Choice*	*Purpose*
1	Does the interviewee have a CD player	2 choices	To find out the percentage of the interviewees who have a CD player
2	Where is the CD player normally used	4 choices	To find where customers usually use their CD players
3	Duration of listening	4 ranges	To find out the normal duration of playing a CD player each time
4	Habit of listening	2 choices	To find out if customers normally listen a CD from start to end
5	Average time of listening one CD	5 choices	To find out how often customers change a CD
6	Average time to change a CD	5 choices	To find out how long to take to change a CD on average

2. Customer expectation

Questions 7 to 15 investigate customers' needs and wants on the design of a multi-disc design CD player, covering the design requirements, the internal mechanism, the reason for choosing a multi-disc drive, the speed for a disc change and the expected price range for such a combination. The reasoning behind these questions are given as follows:

Q No	*Question*	*Choice*	*Aim*
7	Type of CD drive	3 choices	To find out the preferable type of CD drive
8	Number of discs held	4 choices	To find out the expected number of discs that the CD player can hold
9	CD arrangement in disc drive	3 choices	To find out the expected disc arrangement in a disc drive
10	Method of disc loading	3 choices	To find out the expected disc loading method
11	Would the interviewees like to change CD while playing another one	2 choices	To find out the actual need for disc changing without disturbing the CD being played
12	Main inconvenience in disc changing	3 choices	To discover what annoys the users most when changing CD's
13	Expected waiting time for an automatic disc change	4 choices	To find out the expected waiting time for an automatic disc change
14	Longest acceptable waiting time for an automatic disc change	---	To get a feel for the longest acceptable time for an automatic disc change
15	Expected price	4 choices	To find out how much the customers are prepared to pay

3. Priority of factors considered when choosing a CD player

Question 16 covers eight factors which might affect customers' choice when buying a CD player. Interviewees are asked to rank the factors according to their importance. The eight factors include:

	Factor	*Areas affected on a CD player*
a	Sound Quality	Many parts of the CD player
b	Reputation of the brand name	Marketing and promotion of a certain brand name
c	Price	Price of the CD player
d	Size	Overall size of the CD player
e	Appearance	Exterior features, layout of the control panel and display functions, etc.
f	Ease and flexibility in disc loading	Disc tray design, loading mechanism, etc.
g	Ease of access to a large number of songs	Multi-disc drive, size of memory, etc.
h	Speed of access between songs	Laser head mechanism

4. Problems encounter when using CD players

Question 17 addresses the possible problems when using a CD player and finds out their frequency of occurrence. The factors include:

- high humidity
- high temperature
- impact
- unstable power supply

5. **Features requiring improvement on CD players**

Question 18 asks the interviewees to indicate which of the given six features they would like to see improvement on their own CD player.

- CD loading mechanism
- Speed of accessing songs
- Ease of changing CDs
- Sound quality
- Appearance
- Size

6. **Personnel data**

- Sex
- Age
- Occupation

DISCUSSIONS

As the Questionnaire 1 is designed to focus on the disc drive design of a multi-disc CD player, the results of the survey are arranged using Affinity Diagram into different categories, such as disc drive, loading mechanism, display features, etc. For instance, in the category of disc drive, 13 more essential features are established as follows :

1. Time for a disc change
2. Smoothness of the loading mechanism
3. Capability of holding more than 1 CD
4. Ease of inserting CD into the disc drive
5. Possibility of changing CD when playing another one
6. Protection of the CD from scratches when loading and playing
7. Secure positioning of the CD on the tray

8. Size of the disc drive

9. Appearance of the disc drive

10. Reliability of loading/unloading mechanism after using long period of time

11. Facility for programming the sequence of play

12. Display functions showing the programme information

13. Display functions showing the current information of the CD being played

A more specific questionnaire (Questionnaire 2) is prepared for a second survey in order to gain further insights into these essential areas relevant to the disc drive design.

APPENDIX III(b): Questionnaire 1 (For CD Players)

Part A

1. Do you have a CD (Compact Disc) player?

   a. Yes ______

   b. No ______

   (If NO, please give your own opinion and expectation on the following question assuming you are going to have a CD player.)

   ____

2. Where do you normally use your CD player? *(You can choose more than one answer.)*

   a. At home ______

   b. In the car ______

   c. In the office ______

   d. Others, please specify

   ____

3. How long do you usually listen to CDs?

   a. less than 1 hour ______

   b. less than 2 hours ______

   c. less than 4 hours ______

   d. more than 4 hours ______

   ____

4. Do you usually listen to a CD from the beginning to the end?

   a. Yes, then ***Go to Part B*** ______

   b. No ______

   ____

5. What is the average time you spend on a CD each time before changing to another one?

   a. less than 15 min. ______
   b. less than 30 min. ______
   c. less than 45 min. ______
   d. less than 60 min. ______
   e. more than 60 min. ______

____

6. How long does it take to change a CD in your CD player?

   a. less than 5 sec ______
   b. less than 10 sec ______
   c. less than 15 sec ______
   d. less than 20 sec ______
   e. more than 20 sec ______

____

Part B *(Please answer this part according to your expectation if you are going to buy a CD player.)*

7. Which type of CD drive would you prefer?

   a. Top-loading type ______
   b. Sliding-in type ______
   c. Others, please specify

____

8. How many discs do you want in your CD player to hold?

   a. less than 3 discs ______
   b. less than 5 discs ______
   c. less than 10 discs ______
   d. more than 10 discs ______

(If d, please specify number of discs expected and give the reasons for it.)

____

9. How would you like the CDs arranged in your CD drive?
   a. In layers ______
   b. In Circular flat tray ______
   c. Others, please specify (e.g. like an old-fashion juke-box ______

____

10. How are discs loaded into your disc drive?
    a. Inserted all discs laterally at the same time ______
    b. Loaded into the disc tray one by one ______
    c. Others, please specify

____

11. Would you like to be able to change some CDs when you are playing another one?
    a. Yes ______
    b. No ______

____

12. What is the major inconvenience in changing CD's?
    a. Take too long to change ______
    b. Having to change CD too frequently ______
    c. Others, please specify

____

13. How long would expect an automatic disc change to take?
    a. less than 2 seconds ______
    b. less than 4 seconds ______
    c. less than 6 seconds ______

d. more than 6 seconds ______

---

14. In your opinion, what is the longest acceptable time for an automatic disc change? ______

---

15. How much are you prepared to pay for the CD player that you specify above?
    a. Less than US$300 ______
    b. Less than US$400 ______
    c. Less than US$500 ______
    d. More than US$600 ______

---

16. Rank the relative importance of the following factors if you are going to buy a CD player? *(1 for the most important feature, 8 for least important feature)*
    a. Sound Quality ______
    b. Reputation of the brand ______
    c Price ______
    d. Size ______
    e. Appearance ______
    f. Ease and flexibility in disc loading ______
    g. Ease of access to a large number of songs (e.g. having more than one CD loaded at a time.) ______
    h. Speed of access between songs ______

Part C ***(Only applicable if you have a CD player at present)***

17. Did you experience problems with your CD player under the following conditions? *(Tick where appropriate)*

	Very frequently	Frequently	Sometimes	Never
a. High humidity	______	______	______	______
b. High temperature	______	______	______	______
c. Sensitive to vibrations	______	______	______	______
d. Unstable power supply	______	______	______	______
e. Others, please specify				

____

18. Which part(s) of your CD player do you think need improvement? *(Tick where appropriate)*

a. CD loading mechanism ______
b. Speed of accessing songs ______
c. Ease of changing CDs ______
d. Sound quality ______
e. Appearance ______
f. Size ______
g. Others, please specify

____

Part E *(Personal Data)*

19. Sex

    a. Male ______

    b. Female ______

20. Age Group

    a. <20 ______

    b. 21-30 ______

    c. 31-40 ______

    d. 41-50 ______

    e. >50 ______

21. Occupation

____

Appendix III(c):
Design Rationale of Questionnaire 2 for Disc Drives in CD Players

INTRODUCTION

The Questionnaire 2 was designed to further investigate the key attributes on disc drive extracted in Questionnaire 1. The survey would be conducted through telephone interviews. At the same time, competitive comparisons based on those attributes are carried out to ask the interviewees to comment on the performance of their own CD player. Contents of Questionnaire 2 can be shown in Appendix III(d).

DESIGN OF QUESTIONNAIRE 2

1. **Obtaining the priority rating**

   Questions 1 to 13 address the key features extracted from the findings of the first survey. Interviewees would be asked to prioritise according to their preferences on the features of disc drive design in multi-disc CD players. A scale of 1 to 10 is used with 1 representing "the most important" and 10 "the least important".

2. **Customer attitude towards price and quality**

   In Question 14, the interviewees are asked to express their expectations on price and quality of CD disc drives. They are to score price and quality in percentages which would sum up to 100% in order to determine the design emphasis to be deployed in these two critical attributes.

3. **Expected number of CD's to be held in the disc drive**

   Question 15 asks the interviewees to indicate how many CD's they would expect a multi-disc CD player to hold.

4. **Competitive comparisons**

   In Questions 16 to 29, interviewees are asked to indicate the make of their own CD player and rate its performance against the 13 attributes on a scale of 1 to 10, ranging from 1 being "the most satisfied" to 10 being "the least satisfied".

The findings from surveys similar to this for every category of product attributes would be used to complete the entries in the Planning Matrix in the corresponding basic HoQ.

APPENDIX III(d): Questionnaire 2 (For Disc Drives of CD Players)

Part A

This part concerns about the design of the **disc drive** of a **multi-disc CD player**. Please encircle the correct rating to the following factors.

1 for the most important, and 10 for the least important.

1. The time for a disc change	1 2 3 4 5 6 7 8 9 10
2. Smoothness of the loading mechanism	1 2 3 4 5 6 7 8 9 10
3. Capability of holding more than one CD	1 2 3 4 5 6 7 8 9 10
4. Ease of inserting CD into the CD drive	1 2 3 4 5 6 7 8 9 10
5. Changing CD when playing another one	1 2 3 4 5 6 7 8 9 10
6. Protection of the CD from scratches when loading and playing	1 2 3 4 5 6 7 8 9 10
7. Secure positioning of the CD on the tray	1 2 3 4 5 6 7 8 9 10
8. Size of the disc drive	1 2 3 4 5 6 7 8 9 10
9. Appearance of the disc drive	1 2 3 4 5 6 7 8 9 10
10. Reliability of loading/unloading mechanism	1 2 3 4 5 6 7 8 9 10
11. Facilities for programming the sequence of play	1 2 3 4 5 6 7 8 9 10
12. Display functions showing the program information	1 2 3 4 5 6 7 8 9 10
13. Display functions showing the current state of play	1 2 3 4 5 6 7 8 9 10

Part B

14. Express the % preference of (a) price and (b) quality, such that (a) + (b) = 100%

a. Price ___________

b. Quality ___________

---

15. How many discs would you expect the CD player to hold if you are going to buy a multi-disc CD player?

____

Part C

16. Please tick the brand of the CD player you have.

______	Aiwa	______	Akai
______	Hitachi	______	JVC
______	Kenwood	______	Marantz
______	Mitsubishi	______	Panasonic
______	Pioneer	______	Sansui
______	Sanyo	______	Sharp
______	Sony	______	Toshiba
______	Fisher	______	Philips

Others, please specify : ________________________________

Based on your current CD player, please encircle the correct rating according to the following factors.

"1" for the best, and "10" for the worst.

17. Time for a disc change 1 2 3 4 5 6 7 8 9 10

18. Smoothness of the loading mechanism	1 2 3 4 5 6 7 8 9 10
19. Capability of holding more than one CD	1 2 3 4 5 6 7 8 9 10
20. Ease of inserting CD into the CD drive	1 2 3 4 5 6 7 8 9 10
21. Changing CD's while playing another one	1 2 3 4 5 6 7 8 9 10
22. Protection of the CD from scratches when loading and playing	1 2 3 4 5 6 7 8 9 10
23. Secure positioning of the CD on the tray	1 2 3 4 5 6 7 8 9 10
24. Size of the disc drive	1 2 3 4 5 6 7 8 9 10
25. Appearance of the disc drive	1 2 3 4 5 6 7 8 9 10
26. Reliability of loading/unloading mechanism	1 2 3 4 5 6 7 8 9 10
27. Facilities for programming the sequence of play	1 2 3 4 5 6 7 8 9 10
28. Display functions showing the program information	1 2 3 4 5 6 7 8 9 10
29. Display functions showing the current state of play	1 2 3 4 5 6 7 8 9 10

Part D

Sex : ____________

Age : ____________

Occupation : ____________

End of Sample Questionnaires