A WEB-BASED COLLABORATIVE DECISION MAKING SYSTEM FOR CONSTRUCTION PROJECT TEAMS USING FUZZY LOGIC

HONGMEI YANG

A thesis submitted in partial fulfilment of the requirements
of Loughborough University
for the degree of Doctor of Philosophy

May 2001

ABSTRACT

In the construction industry, the adoption of concurrent engineering principles requires the development of effective enabling IT tools. Such tools need to address specific areas of need in the implementation of concurrent engineering in construction. Collaborative decision-making is an important area in this regard. A review of existing works has shown that none of the existing approaches to collaborative decision-making adequately addresses the needs of distributed construction project teams. The review also reveals that fuzzy logic offers great potential for application to collaborative decision-making.

This thesis describes a Web-based collaborative decision-making system for construction project teams using fuzzy logic. Fuzzy logic is applied to tackle uncertainties and imprecision during the decision-making process. The prototype system is designed as Web-based to cope with the difficulty in the case where project team members are geographically distributed and physical meetings are inconvenient/or expensive. The prototype was developed into a Web-based software using Java and allows a virtual meeting to be held within a construction project team via a client-server system. The prototype system also supports objectivity in group decision-making and the approach encapsulated in the prototype system can be used for generic decision-making scenarios.

The system implementation revealed that collaborative decision-making within a virtual construction project team can be significantly enhanced by the use of a fuzzy-based approach. A generic scenario and a construction scenario were used to evaluate the system and the evaluation confirmed that the system does proffer many benefits in facilitating collaborative decision-making in construction.

It is concluded that the prototype decision-making system represents a unique and innovative approach to collaborative decision-making in construction project teams. It not only contributes to the implementation of concurrent engineering in construction, but also it represents a substantial advance over existing approaches.

ACKNOWLEDGEMENTS

I wish to express my sincere appreciation to my supervisors, Professor Chimay Anumba and Ms. Patricia Carrillo, for providing guidance and information for the research. My special thanks go to Prof. Anumba, for his constant encouragement, support and friendship. I owe a deep debt of gratitude to him.

I am also deeply grateful to the following individuals who provided helpful advice at various stages of the research: Dr. John Kamara, Dr. Ashraf El-Hamalawi, Dr. Bing Yu, and other colleagues in the department who participated in the system evaluation. I also appreciate the participation of various organisations in the industry survey.

Financial support for this project was provided by the Department of Civil and Building Engineering, Loughborough University.

I am very much indebted to my husband, Yuen and son Alex, for their love, support and patience. The support of my parents, friends Mrs. Mabs Taylor, Ms. Liying Meng and Ms. Barbara Fowler is also deeply appreciated.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

List of Notations

μ	Membership function
$\rightarrow$	Mapping
$\underset{\sim}{A}$	Fuzzy set
U	Universe
A_{SUP}	Support of a fuzzy set
$\mathcal{I}$	Lattice
$\vee$	Supremum
$\wedge$	Infimum
L	Lattice measuring
$\subset$	Proper set inclusion
$\in$	An element belong to a set
$\subseteq$	Set inclusion
sup, Supp	Support
inf	Infimum
$\underset{\sim}{\subset}$	Fuzzy set inclusion
Ker	Kernel
$\times$	Binary relation
$\forall$	Random, any
N	Set of natural numbers
$\mathcal{T}$	A set of syntagms
CON	Concentration
DIL	Dilation
INT	Intensification
$\neg$	Negation
$\otimes$, $\cdot$	Product of fuzzy sets
$\oplus$	Addition of fuzzy sets
R	Set of real number
$\cup$	Union (also for fuzzy sets)
$\cap$	Intersection (also for fuzzy sets)

CHAPTER 1

INTRODUCTION

1.1 INTRODUCTION

This chapter introduces the research reported in this thesis. It describes the background, aims, objectives and methodology of the research, and provides a guide to the contents of the thesis.

1.2 BACKGROUND

In the construction industry, the adoption of concurrent engineering principles requires the development of effective enabling IT tools. Such tools need to address specific areas of need in the implementation of concurrent engineering in construction. Collaborative decision-making is an important area in this regard. However, existing decision-making tools cannot fulfil all the functions needed by a collaborative construction project team, especially when the team members are geographically distributed. This was the motivation for this research.

1.2.1 Collaborative Decision Making in Construction

In the general industry environment, a survey published in 1999 reported that 69% of British companies have adopted the philosophy of concurrent engineering (Balbontin et al, 1999). Concurrent engineering is a philosophy that enables a company to reduce the time in which they can design, develop and introduce a product to the market (Aniscough and Yazdani, 2000). Since construction can be considered as a manufacturing process, concepts that have been proven to be successful in the manufacturing industry should also be beneficial to construction. In the context of the construction industry, concurrent engineering is a methodology that can optimise the design of the project and its construction process to achieve reduced lead times, and improved quality and cost by the integration of design, fabrication, construction and erection activities and by maximizing concurrency and collaboration working practices (Evbuomwan and Anumba, 1998). A number of studies (Clausing, 1991, Jebb et al, 1992, Evbuomwan and Anumba, 1996, Kamara et al, 1999) have been undertaken in the past concerning the implementation and realisation of concurrent engineering. These studies show that of the key issues addressed in the implementation of concurrent engineering within the construction industry, two points are stressed:

- Use multifunctional teams for executing concurrent engineering;
- Use of modern information technologies.

Construction projects usually involve many professionals and disciplines, such as architects, structural engineers, contractors, quantity surveyors, mechanical/electrical service engineers, and erectors, to play active role at different stages. These professionals /disciplines conventionally intend to work independently but make decisions that inevitably affect each other. The implementation of concurrent engineering gathers them as a team within which collaborative decisions are made.

Team working can be defined as "a number of people with complementary skills who are committed to a common purpose, performance goals, and approach for which they hold themselves mutually accountable" (Katzenbach and Smith, 1993). Team working within a concurrent engineering environment requires the deployment of a multifunctional team as a means for enabling cross functional communication and quick decision making (Ainscough and Yazdani, 2000). Various studies (Phillips, 1994, Ngwenyama et al, 1996, Hague and Taleb-Bendiab, 1998, Dowling and Louis, 2000) concern decision-making issues within a team environment and provide applicable frameworks for different objectives. However, few appear to provide an optimum framework particularly for collaborative decision making in construction project teams. Furthermore, as IT is important for achieving concurrency, the IT software used in the existing approaches is not wholly appropriate for typical construction project teams (which are usually distributed); therefore, a novel software is imperative. Another weakness of the existing collaborative decision-making systems is their ability for dealing with uncertainties and imprecision during the decision making process.

1.2.2 Fuzzy Logic and Construction

In engineering and science, complex physical systems are usually described by mathematical models (Kruse et al, 1994). However, many real life problems are too complex for formulation as mathematical models. This might be one of the reasons that the rate of practical application of numerous technical and theoretical works on the use of computers and quantitative analysis to support managerial decision-making remains fairly low. One method to simplify complex systems is to tolerate a reasonable amount of imprecision, vagueness, and uncertainty during the modelling phase. Certainly the resulting systems are not perfect, but in many cases they are capable of solving the modelling problem in an appropriate way (Nguyen and Walker, 1997). This is the basis of fuzzy set concepts for mathematical modelling presented by Zadeh in 1965. His contention is that meaning in natural language is a matter of degree.

Membership is used to characterize fuzzy sets. Fuzzy logic refers to a fuzzy system or a mapping from input to output that depends on fuzzy rules; the rules in turn depend on fuzzy sets or vague concepts that depend on fuzzy membership (Kosko, 1997).

Fuzzy logic means reasoning with vague concepts. In practice it can mean computing with words. The use of fuzzy systems has yielded impressive success in recent years and covers many subject areas, such as economics, medicine, management science, psychology, sociology, and engineering (Maeda et al, 1987, Cohen and Hudson, 1992, Kartalopoulos, 1996, Pacini and Kosko, 1997, Hopgood et al, 1998). The examples of application of fuzzy systems in engineering are many, such as fuzzy control, robotics and situation analysis in power systems, but specific applications in the construction sector are few compared to other industry sectors. In many cases, these are limited to the structural engineering domain (Soh and Yang, 1996, Biondini et al, 2001). Recent efforts made in its application to the construction management domain (Chao and Skibniewski, 1998; Fayek and Sun, 2001; Boussabaine and Lewis, 2001; and Graneshan et al, 2001) do not appear to concern collaborative decision-making. Few of the previous fuzzy-based decision-making approaches (Tong and Bonissone, 1980, Vlacic et al, 1997, Lam et al, 2001) support group work. This leaves gaps for potential use of fuzzy logic in construction for collaborative decision-making.

In the conventional process, project team members often adopted an adversarial approach to decision making; they are required within a concurrent engineering framework to be effective team players, working together for the good of the project. In some cases, these project team members are geographically distributed making regular physical meetings inconvenient, time-consuming and expensive. In making decisions, project team members bring their own disciplinary or individual views to the decision making process. This often means that conflict arises based on how important an issue is to different disciplines. Perhaps what one discipline considers very important is of low importance to another. The disparate priorities are usually expressed in linguistic fuzzy terms (e.g. very important, important, low importance, and not important). There is often no formal or quantitative way of reconciling these. In physical meetings, the personalities of the individuals involved often have a great part to play and may result in sub-optimal solutions being adopted. This means that, in project team decision-making, the contributions from all participants are not always adequately considered or taken into account. Sometimes, decision alternatives are also expressed in linguistic fuzzy terms. Uncertainties and vagueness such as these need to be addressed since they have a significant impact on a project team's daily decisions.

In the light of the foregoing, there is the need for decision-making systems that are capable of providing an objective and rational framework within which collaborative decisions can be taken by virtual construction project teams. It is this need that this research project seeks to address.

1.3 AIM AND OBJECTIVES OF THE STUDY

The aim of the research project was to investigate the applicability of fuzzy logic principles to collaborative decision-making in construction project teams. The following specific objectives were defined:

1. To review concurrent engineering theory and collaborative decision-making models and theories;
2. To explore the potential for the use of fuzzy logic in the development of a decision-making system for construction project teams;
3. To develop a fuzzy logic-based collaborative decision-making system for virtual construction project teams;
4. To evaluate the system using hypothetical (or real-life) project team decision-making scenarios.

1.4 RESEARCH METHODOLOGY

This research focused on the development of a decision-making tool that facilitates collaboration within virtual construction project teams. The aim is that geographically distributed team members can make decision effectively. In order to achieve the preceding objectives of the research, various tasks and related strategies were adopted. These include a mixture of literature review, pilot industry survey, case studies, and rapid prototyping.

1. The extensive literature review mainly focused on three areas: conceptual theories and principles of concurrent engineering, its application in construction, decision making theories, current status of collaborative decision-making in construction, fundamental theories of decision support system and its existing approaches in construction and other sectors; key concepts and important operational principles of fuzzy sets and systems, and existing tools in construction and decision-making and other fields based on fuzzy logic. The investigation into the principles of collaborative decision-making and fundamentals of fuzzy theory established the

base and focus of this research. The information about current trends and technology for the application of fuzzy logic was obtained from the investigation into the existing tools. In reviewing such literature particular attention was given to any fuzzy logic theory and method that facilitate multidisciplinary multi-criteria decision-making. Other works that could provide relevant information, such as concurrent engineering applications in the manufacturing industry, knowledge-based decision support systems, fuzzy logic-based expert systems etc., were also studied.

2. A pilot industry survey was carried out with a group of industrial practitioners who were involved in construction project team for decision-making, using a pilot questionnaire. The investigation provided an insight into collaborative decision making in the construction industry. Its specific objectives were:
    1. to ascertain in what situations (or stages in the construction process) that collaborative decision making takes place between project team members;
    2. to establish the extent to which collaborative decision making takes place within each discipline, and whether it is managed differently from those situations involving other disciplines;
    3. to determine the procedure adopted in collaborative decision making, with a view to identifying elements of good practice, weaknesses in existing procedures, tools and techniques used, personnel / parties involved, the role of IT, etc.;
    4. to investigate how uncertainties are managed in the collaborative decision-making process.

3. A decision-making model of the proposed system was developed, based on the knowledge gained during the literature review phase and the information obtained from the industrial investigation. The development of the model followed an iterative process which involved the following:
    - Development of the system architecture and operational mechanisms;
    - Review and feedback by academic staff involved in the research;
    - Peer review from other researchers at conferences and workshops;
    - Discussion with some experts in the fuzzy logic domain

4. The proposed system was developed on a PC. The language utilised was Java as the system was designed to be Internet-based.

5. The system was evaluated to assess its benefits and limitations. The evaluation was designed for two group decision-making scenarios – a generic situation and a construction-specific scenario. Evaluators were drawn from researchers and construction professionals. At the end of each evaluation sessions, evaluators were requested to complete a questionnaire that summarizes the value of the system from various perspectives.

6. At the final stage, inferences were drawn and recommendations made for future extension of the prototype.

Details of the specific methods adopted at each of the stages of the research project are provided at appropriate points within the thesis.

1.5 THESIS STRUCTURE

This thesis is divided into 7 chapters as follows:

Chapter 1 introduces the research undertaken and describes the background, aim, objectives and methodology of the research and also states the problem to be solved in this study.

Chapter 2 reviews basic concepts and principles relating to concurrent engineering and collaborative decision-making in construction. It also explores the limitations of existing approaches in this area.

Chapter 3 starts with fundamental definitions and important principles of fuzzy set theory and then examines the major advantages of fuzzy systems. The applications of fuzzy set theory in construction and other industries are investigated in this chapter, followed by a discussion of gaps and opportunities for further development.

Chapter 4 describes the conceptual model of the prototype system after examining the suitability of three existing fuzzy logic-based approaches. This chapter also reports the six primary steps of the decision-making system. An example is used to show how the system would operate.

Chapter 5 describes the development and operation of the prototype system. It reports on the system development environment, program organization, user-interface design and code development, and then demonstrates the system operation using a computer-based example in which the key features of the system are highlighted.

Chapter 6 describes the system evaluation. It summarises the results of the system evaluation using two decision-making scenarios and discusses the system's merits and demerits.

Chapter 7 provides the summary and conclusions of this thesis. It discusses the extent to which the aims and the objectives of the research have been achieved and then concludes with the key findings of the research. Recommendations for further work are also provided.

CHAPTER 2

CONCURRENT ENGINEERING AND COLLABORATIVE DECISION MAKING IN CONSTRUCTION

2.1 INTRODUCTION

This chapter reviews the basic concepts and principles of Concurrent Engineering (CE) and Collaborative Decision-Making (CDM), and describes their implementation in construction. It further discusses the importance of group decision-making in CE and the limitations of existing CDM approaches in the construction sector.

2.2 CONCURRENT ENGINEERING

2.2.1 Introduction and Definition

Concurrent Engineering was initially proposed as a means to minimise product development time (Prasad, 1996). This was necessitated by changes in manufacturing techniques and methods, management of quality, market structure, the increasing complexity of products, and demands for high quality and accelerated deliveries at reduced costs. These changes resulted in a shift in corporate emphasis with the result that, the ability to rapidly react to changing market needs and time-to-market became critical measures of business performance (Constable, 1994, Thamhain, 1994). With its growing use in industry, many definitions and some interpretations of CE have emerged. Below are some definitions or explanations of what CE is:

- Winner et al (1988): CE is a systematic approach to the integrated, concurrent design of products and their related processes, including manufacture and support. This approach is intended to cause developers, from the outset, to consider all elements of the product lifecycle from concept through to disposal, including quality, cost, schedule and user requirements;

- Monroy (1992): CE is the earliest possible integration of the company's overall knowledge, resources, and experience in development, marketing, manufacturing, and sales into creating successful new products with high quality and low cost, while meeting customer expectations.

- Koskela (1992): CE is a term that refers to an improved design process characterised by rigorous up-front requirements analysis, incorporating the constraints of subsequent phases into the conceptual phase and tightening of change control towards the end of the design process.

- Barkley (1993): CE is used to convey a philosophy of multiple processes occurring simultaneously. It does not represent a single idea but a combination of methodologies, which include multi-disciplinary teams, integrated tools, lessons learned, databases and quality function deployment.

- Madan (1993): the key ingredient of CE is multi-functional teamwork where teams work together from the outset to anticipate problems and bottlenecks and to eliminate them early in the product development cycle.

- Carter (1994): CE means teamwork and it enables individuals from different disciplines to communicate and collaborate to solve problems and develop manufacture and support products.

- Ranky (1994): CE is a logical and systematic framework that represents an opportunity for working together in teams, sharing and integrating data and information using appropriate engineering data management tools and systems.

- Prasad (1995): CE refers to the re-engineering of the product process so that tasks are organised concurrently. CE systems stem from Computer Integrated Manufacturing (CIM) systems or Engineering Information Systems (EIS).

- Harding and Popplewell (1996): CE is a holistic methodology for the co-ordination of distributed, heterogeneous expertise to achieve cost-effective, market-driven products in minimum time scales.

- Ainscough & Yazdani (2000): CE encompasses philosophies that enable a company to execute each phase of product development process in parallel so as to reduce the time in which they can design, develop and introduce a product to the market.

To sum up the foregoing definitions and explanations, CE is therefore:

1. a methodology that contains other methodologies, such as multi-disciplinary teams, integrated tools, databases and quality function deployment etc;
2. a logical and structured framework that facilitates integration of

- different aspects of product development process, such as design, manufacturing, marketing etc;
- techniques, tools, knowledge, and information;
- people

3. a concept that is aimed at reducing product development time and cost, increasing quality and value, and satisfying the customer.

2.2.2 Principles of Concurrent Engineering

Many researchers have described the principles of CE (Madan, 1993, Nicholas, 1994, Carter, 1994, Ranky, 1994, Prasad, 1995, Evbuomwan and Anumba, 1996). Ranky (1994) suggested that the most important CE principles and necessary techniques for its implementation include the following:

1. Improving communication with the current and potential customers and users. Translate customers' needs into specific product specifications, quality requirements, process, function and aesthetic requirements;
2. Employing multi-disciplinary product design teams;
3. Designing the manufacturing and required processes simultaneously;
4. Involving suppliers & sub-contractors at an early stage of the design;
5. Creating a three dimensional/solid (CAD) model of the design at an early stage;
6. Integrating CAD/CAM and analysis tools;
7. Simulating product performance and the manufacturing processes as early as possible in the design stage in order to avoid production line problems;
8. Using structured techniques to enhance product quality and reliability;
9. Using quality techniques to understand the role and integration of product & process parameters;

10. Incorporating the lessons learned from previous products in a new design;

11. Eliminating the non-value-adding activities in your design and manufacturing processes.

Key goals and principles of CE summarised by Evbuomwan and Anumba (1996) include:

- proper analysis and establishment of customer requirements and specifications;
- development of conceptual solutions that are modular, easy to manufacture and assemble;
- integration of the manufacturing process and product design that best matches needs and requirements;
- designing the interface between subsystems within a project to take account of tolerances as well as designing the product to be robust;
- adopting a systems approach to product development and taking into account the entire product lifecycle;
- continually focusing on improvement of the product and manufacturing process;
- location of multifunctional teams together, when possible, to facilitate better communication;
- reduction of product lead times and product costs;
- paralleling the design process.

Other views on the principles of CE, from various sources are as follows:

a. CE involves two fundamental principles: doing up-front work carefully to avoid later changes, and the use of parallel processing wherever feasible (Madan, 1993).
b. The team is responsible for conceptualising the project correctly at the initial stage. This involves doing the up-front work thoroughly, even at the price of lengthening that phase (Madan, 1993). High-level teamwork is essential to successfully implement CE (Nicholas, 1994).
c. Support for CE should occur at multiple levels within the enterprise and should include:
   - The support by top management to enforce organisational changes which are required to implement CE;
   - Changes in the communication infrastructure;
   - Trace-ability and correlation of customer requirements throughout the product development cycle (Carter, 1994);

The broad principles of CE provide guidelines for its implementation, which directly address the problems in the construction industry.

2.2.3 Concurrent Engineering in Construction

The success of concurrent engineering in the manufacturing industry is a motivation for the construction industry to adopt CE. In the context of the construction industry, the definitions provided in the earlier section can be modified thus: "Concurrent Engineering attempts to optimise the design of the project and its construction process to achieve reduced lead times, and improved quality and cost by the integration of design, fabrication, construction and erection activities and by maximizing concurrency and collaboration in working practices" (Evbuomwan and Anumba, 1998).

There is an increasing need for the integration of all key players in any construction project into a multi-disciplinary team. It is imperative that the industry will have to change its *modus operandi* by adopting new business processes that overcome the problems posed by the fragmentation of the various functional disciplines involved in construction projects. These problems include (Anumba and Evbuomwan, 1997):

a) Elimination of viable design alternatives due to pressure of time;
b) Prevalence of costly engineering changes and design iterations;
c) The lack of adequate communication between each of the disciplines involved in the construction process;
d) Characterisation of the design process with rigid sequence of activities;
e) Produce-ability and supportability issues are considered late in the process;
f) Fragmentation of design data and difficulty in maintaining data consistency;
g) Loss of information about design intent;
h) Inappropriate estimation of construction costs.

The adoption of concurrent engineering within the construction industry enables the above problems to be solved. The benefits of CE and collaborative working in construction are now being recognised (de la Garza et al., 1994, Evbuomwan and Anumba, 1996, Love and Gunasekaran, 1997, Hannus et al., 1997, Anumba and Newnham, 2000) and can be realised by establishing procedures and processes, developing resources, tools, techniques and systems to support its concepts and principles. The integration of these features will lead to the development of successful projects by bringing together all the key functional disciplines in design, fabrication and construction as early as possible. In the implementation of CE within the construction industry, the following key issues should be addressed (Evbuomwan and Anumba, 1998):

1. the need to focus on the customer/owner/client;
2. the need to integrate the activities of the various functional disciplines involved in the project;
3. carrying out competitive benchmarking of design and construction practice and processes;
4. focusing on the quality, cost and delivery of projects;
5. concurrently developing the design of the project along with the fabrication, construction and erection processes;
6. establishing strategic relationships with materials and component suppliers and sub-contractors;
7. integration of CAD and other design tools for CE;
8. use of modern project management techniques to enable paralleling and overlapping of the design and construction activities;
9. integration and commonalization of design knowledge, data and information;
10. the use of new materials and technologies;
11. the effective use of computer hardware and software.

To address the above issues, the implications for the implementation of CE in construction arise from the nature of the industry. The implementation of CE in construction refers to established practices and traditions which characterise the industry and which may bear upon the implementation of CE. They include the following (Kamara, et al, 1997):

a. The position of the professions. One of the key factors for implementation of CE is multi-functional teams and high levels of co-operation and information sharing. In the case of construction, this involves breaking down professional and organisational barriers.

b. The practice of competitive tendering. This implies that the effective inclusion of contractors and suppliers in the design team becomes unlikely. However, procurement by design and build provides a more appropriate framework for the inclusion of downstream project participants early on in the construction process.

c. The nature of project organisations. A narrow view of CE is 'integrating product and process design' (Prasad, 1996). A wider view is 'integrating over the product life', which involves 'integrating over the enterprise'. In construction, project organisations are temporary multi-organisations and such 'enterprise' integration may not be easily achieved. The change in the mix of project team members for different projects would also make it difficult to establish the necessary organisational procedures and processes that provide a suitable framework for CE implementation. However, the growing practice whereby construction companies form consortia (e.g. Bennett et al, 1988) predicts the way forward for the industry and to some extent, provides a basis for the adoption of CE.

d. The use of standard forms of contract. Successful implementation of a CE method of procurement should either be accompanied with a standard form of contract, or the current practices and attitudes in regard to the use of these forms, must change.

Efforts to develop the methodologies and tools for the implementation of CE in construction are varied and have been made by a number of researchers, such as Sanvido and Medeiros (1990), Fiksel and Hayes-Roth (1993), Perkinson et al (1994), Sivaloganathan and Evbuomwan (1997), Morris et al. (1998), Kamara et al. (1999) Anumba et al. (2000), Chen and Li, (2000), and Ganeshan et al, (2001).

Kamara et al (1999) described an approach to the improved processing of clients' requirements in construction. The approach was designed to address the deficiencies in current briefing practices, as well as satisfy the requirements for requirements processing in concurrent life-cycle design and construction. CE was implemented in the methodology presented by Anumba et al (2000) in a steelwork construction project while Chen and Li (2000) developed a satisfaction-driven and multifunctional approach with applications to concurrent product design. Collaborative technology was applied by Ganeshan et al (2001) to infrastructure management that involved an interdisciplinary team. Some of the other researchers tend to focus on communication and information management tools to enable collaborative and concurrent working between construction professionals, as information management is an important aspect of CE implementation in construction. However, very few tools have been developed to facilitate group decision-making in construction, especially to tackle conflicts between different professionals and the uncertainties existing in the process of group decision-making.

2.2.4 Group Decision-Making in Concurrent Engineering

Concurrent Engineering is usually considered to be synonymous with simultaneous engineering and collaborative engineering (Huovila et al, 1997). The importance of group decision-making in CE is reflected in two CE definitions that stress teamwork (Prasad, 1996):

1. CE is a logical and structured framework that facilitates early integration of the entire product development process (processes, tools, technologies, and people)
2. CE is a philosophy which contains several other methodologies, and involves: paralleling of life-cycle functions, teamwork, consensus and co-operation, cost-effective robust design from conception through disposal, simultaneous design of all downstream processes during upstream phases, minimisation of total product development time, and reduction of lead time, and lower costs.

Since a multi-disciplinary team and integration over the entire enterprise are key factors in the effective implementation of CE in construction and the fact that an enterprise in construction is a temporary multi-organisation, the barriers between different professionals must be broken down. The combination and coordination of the talents and energies of many members of a project team are needed. Groupwork is imperative to meet the requirements of a CE working environment and support the implementation of CE principles.

Group decision-making is also of importance in CE in terms of facilitating collaborative working. In this regard, information management is important and should help to (Prasad et al, 1993):

1. Capture design intent, knowledge, rationale, heuristics and decision processes;
2. Test responsiveness (sensitivities) relative to different events (e. g. input of changes, how they propagate, and who is affected);
3. Enforce strategies;

4. Trigger events and actions automatically (e. g. execute a design verification, algorithm or allow automatically execution of an analysis program).

Therefore, to develop adequate enabling technologies for CE, computer-aided decision support applications that enable groups and teams to interact, collaborate and make decisions during product realisation are essential; also, open and distributed computer-based information architectures are expected to provide different services for the achievements of high levels of integration and communication (Molina et al, 1995). These have been realised and some studies have explored the aspect of group decision making or team work in the implementation of CE (Hague and Taleb-Bendiab, 1998, Cointe and Matta, 1998).

Clearly, group decision-making is necessary for CE and there is the need for effective tools to facilitate this between both collocated and distributed group members.

2.3 COLLABORATIVE DECISION-MAKING

2.3.1 General Nature of Decision-Making

The decision-making process may be considered by anyone outside it as simply the product of a single event, in which an instruction is handed down from some powerful persons. This is a typical ill-defined concept. Decision making, defined quite broadly, is perhaps best regarded as a bundle of interconnected activities that include gathering, interpreting, and exchanging information; creating and identifying alternative courses of action; choosing among alternatives by integrating the often-differing perspectives and opinions of team members; and implementing a choice and monitoring its consequences (Guzza, 1994). A general case of decision-making is considered as an end decision that is the product of a whole series of subsidiary decisions and the interaction of many interested parties (Chicken, 1994). Fig. 2.1 illustrates the various parties that are likely to be involved in decision-making related to major projects.

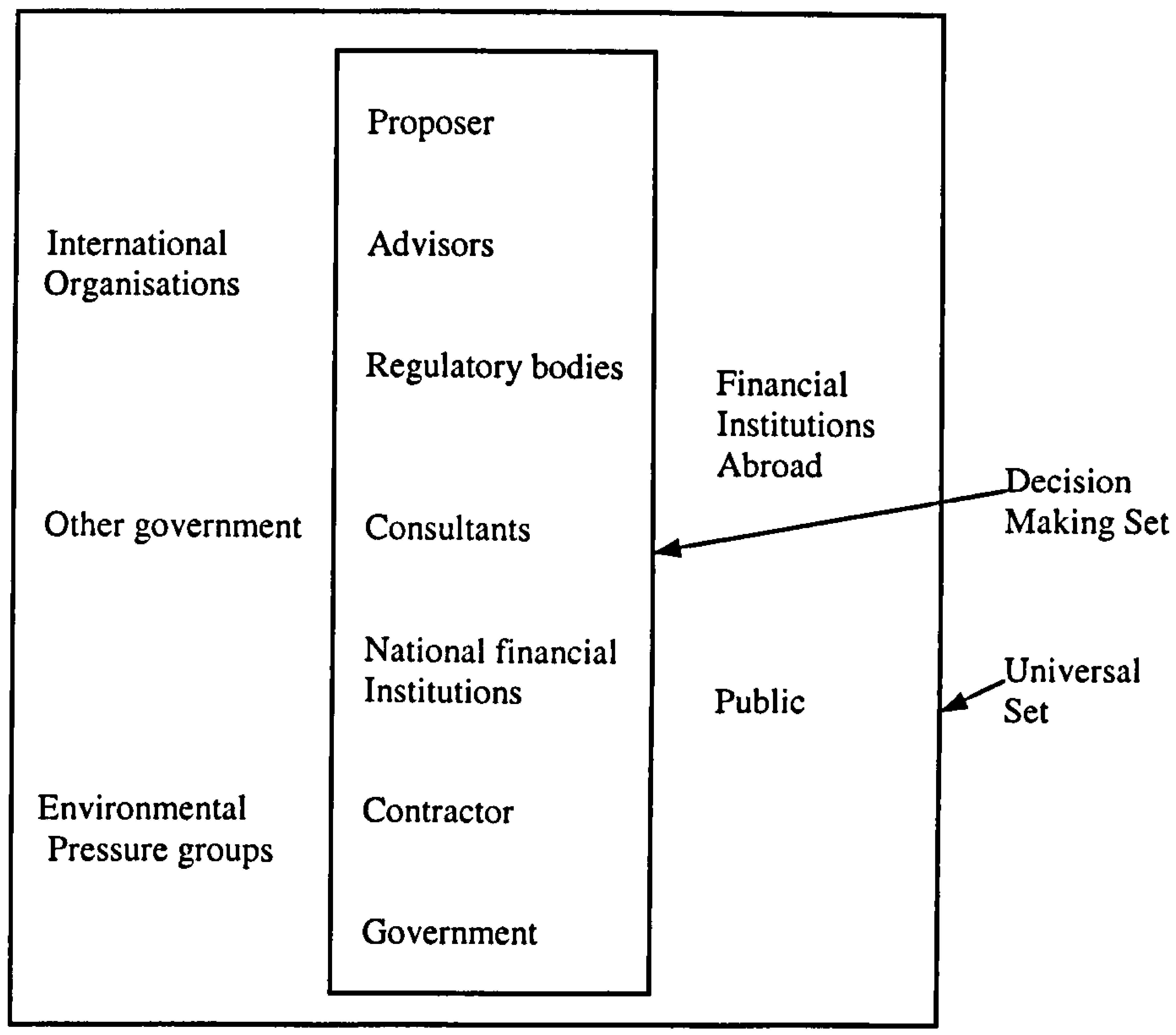


Fig. 2.1 Composition of a Decision Making Set (Chicken, 1994)

Differences in decision-making can be classified by organisational level. Anthony (1965) grouped decision-making in an organisation into three categories: strategic, management control, and operational control. Laudon and Laudon (2000) added one more – knowledge-level decision-making. These are described below:

- Strategic decision-making determines the objectives, resources, and policies of the organisation. A major problem at this level of decision-making is predicting the future of the organisation and its environment and matching the characteristics of the organisation to the environment.

- Decision-making for management control is principally concerned with how efficiently and effectively resources are utilized and how well operational units are performing.

- Knowledge-level decision-making deals with evaluating new ideas for products and services; ways to communicate new knowledge; and ways to distribute information throughout the organisation.

- Decision-making for operational control determines how to carry out the specific tasks set forth by strategic and middle management decision makers.

Within each of these levels of decision-making, Simon (1960) classified decisions as being programmed or non-programmed, which are also referred to as structured decisions and unstructured decisions. Unstructured decisions are those in which the decision maker must provide judgement, evaluation, and insights into the problem definition. Structured decisions are repetitive, routine, and involve a definite procedure for handling so that they do not have to be treated each time as if they were new. Some decisions are semi-structured, which means that only part of the problem has a clear-cut answer provided by an accepted procedure (Laudon and Laudon, 2000).

A decision making process consists of different activities that take place at different times, which are described as four different stages (Simon, 1960):

- Intelligence consists of identifying the problems occurring in the organisation;
- Design allows the individuals to design possible solutions to the problem;
- Choice consists of choosing among alternatives;
- Implementation allows managers to use a reporting system that delivers routine reports on the progress of a specific solution.

In terms of the people involved, decision-making can be categorised into individual decision-making and group decision-making, which is the focus of this study.

2.3.2 Group Decision-Making

2.3.2.1 Decision-making groups

Wilson and Rosenfeld (1990) defined small groups as two or more individuals who interact with one another and where there is a psychological interrelationship between them. No matter how small or big a group is, there must be a significant level of interdependence between group members. A group (or team) is defined by Morgan et al. (1986) as "a distinguishable set of two or more individuals who interact interdependently and adaptively to achieve specified, shared, and valued objectives". There are two types of groups/teams to be examined in light of this definition (McIntyre and Salas, 1995):

- Tactical decision-making group/team, which concerns the making of decisions under time pressure and threat;
- Slow paced, non-emergency decision-making group/team, which often involves long-term consequences and perhaps economic threat to the organization.

Groups/teams can also be categorized into: formal groups and informal groups (Wilson and Rosenfeld, 1990):

- Formal Groups are designed and created around specific tasks. Individuals assigned same membership in an organisation but different tasks may serve the group for a specified length of time. Formal groups would usually show up on the organisational chart and they are mostly specified by functional differentiation.
- Informal Groups These groups often evolve from the interaction of people within an organisation. Informal groups can cross functional and hierarchical boundaries.

Teamwork is critical to the performance of the team/group. Within the group/team, members play different roles and take on specific tasks. Collaboration between formal groups is normally achieved through 'linking pins' created by multiple group membership. Informal groups usually focus on information sharing, allow the testing out of new ideas and schemes, act as sounding boards for all kinds of information. The coherence and psychological solidarity that characterise informal groups can be a great asset to the organisation and help the goals be achieved quicker than most formal routes (Wilson and Rosenfeld, 1990).

According to Murnighan (1982), Game Theory has been the dominant theoretical framework for analysis of the intricacies of situations (games) involving conflicting preferences among individuals (players). The game of group decision-making consists of a set of individuals, each of whom holds a set of preferences for a set of possible decisions, and a decision process that determines how those preferences will be combined to yield a decision. Thus group decision-making is regarded as a game that is co-operative. In the case of non-co-operative games, individuals focus on obtaining benefits, concentrating solely on self-preservation and protection.

2.3.2.2 Group decision processes

Although the formal rules of different groups make the decision processes very different, in practice, the informal processes used by groups may not vary much. Below are characteristics of group decision making processes summarised on the basis that the issue in need of a decision has been identified (Murnighan, 1982).

- Unanimity: The unanimous decision process does not specify how a group decides between alternatives; it merely indicates that all must agree with at least one alternative.
- The consensus: Besides unanimity, compromise is appropriate. All group members must agree with the final solution, but there is usually at least an implicit norm that the group should seek a solution that satisfies everyone.
- Majority rule: It takes many forms, such as,
  (1) individuals can all vote for their most preferred alternative, and the alternative which receives the most votes wins;

(2) individuals vote on pairs of alternatives, with the winner in each pairing included in the subsequent pairing, and the last remaining alternative is chosen;

(3) voters rank order the alternatives in line with their preferences, the group choice is determined by differentially weighting each voter's first second, third, etc. choices, adding up the weights, and choosing the alternative with the largest sum.

- Hierarchical: Decision procedures can also have many forms. Most involve a discussion of the alternatives by group members, with a single individual being responsible for the group's final decision.

Since the decision makers in a group tend to be reactive to demands and seek solutions to their current problems by seeing what the group did in the past, the organisation in which the group exists develops slowly and in piecemeal fashion rather than through radical steps (Wilson and Rosenfield, 1990). This view is at the centre of *Incrementalism*, or the science of muddling through (Lindblom, 1995). In addition to *Incrementalism*, there are two other theories describing the decision process: Garbage Can Theory (March and Olsen, 1976) and Process Typology (Hickson et al, 1986). These three theories are described below:

- Incrementalism is the way most decisions are handled in organisations most of the time. Current and future decisions are dominated by the history of actions in the past. Even when problems arise and cannot be tackled piecemeal, managers still attempt to muddle through by taking bits at a time and by relying on history for guidance.

- Garbage Can Theory argued that organisations were really collections of solutions. Solutions represent an individual's or group's view of what ought to be done in a given set of circumstances. These solutions were the outcomes of previous decision processes and a product of organisational culture. One of these pre-existing solutions would be picked up and attached to the fresh problem faced by decision-makers.

- Process Typology It is found that there appears to be an attempt by decision-makers at achieving some linear sequences. They are usually characterised by many interruptions and many recycles, especially at the stage when alternatives are being considered and the nature of the problem came in for some redefinition. So, while processes are complicated, decision-makers attempt to achieve some linear sequences.

Managing the decision process is complex but not impossible. It is just one phase of group decision making, while managing the decision making group is another.

2.3.2.3 Making groups work

Decision making is not the only activity of relevance to teams, but it is a key activity contributing to team effectiveness (Guzzo, 1995). Decision-making in a team/group is quite distinct from individual decision making and groups are more effective and offer more advantages than individuals (Wilson and Rosenfeld, 1990). There have been a number of techniques introduced to make groups work although all have had limited success:

Groupthink: is a distractive shortcoming of group work. It is described as "a deterioration of mental efficiency, reality testing and moral judgement that is the result of in-group pressures. (Janis, 1972) ". The symptoms of groupthink are (Wilson and Rosenfield, 1990):

1. The group feels invulnerable. There is excessive optimism and risk-taking;
2. Warnings are discounted by the group members in the name of rationality;
3. There is an unquestioned belief in the group's morality. The group will ignore questionable stances on moral or ethical issues;
4. Those who dare to oppose the group are called evil, weak, or stupid;
5. There is direct pressure on anyone who opposes the prevailing mood of the group;
6. There is an illusion of unanimity. Silence is interpreted as consent;
7. There are often self-appointed people in the group who protect it from adverse information. These people are referred to as "mindguards".

All of the above can commonly occur in committees or board meetings. Organisations can very quickly become helpless. Simultaneously, managerial decisions drifting towards goals are either inappropriate or are left unquestioned.

Brainstorming was initially used by Osborn (1963). Fundamental to this method is the 'principle of suspended judgement', which means that evaluation is postponed during the period of idea generation. Group members' efforts are concentrated on developing a roster of possible solutions before their evaluation. Before many alternatives have been proposed and described, no solution can acquire enough positive comments to pass the adoption threshold or enough negative comments to drop below the rejection threshold. The aim of brainstorming is to break through conventional thinking and come up with a comparatively superior solution. Unfortunately, the bulk of empirical research does not support claims of any superior creative performance from brainstorming groups (Van de Ven & Delbecq, 1974, Wilson and Rosenfeld, 1990).

Delphi Technique was designed primarily for non-interacting groups. It avoids face-to-face contact, but uses multiple ideas and inputs from individuals. In its simplest form, the method asks each member of the group to make an independent and anonymous judgement on a predefined problem. The judgements are then averaged, giving each person's judgement equal weight. The members are then told what the average and the distribution of judgements were and asked to vote again. The reasons for different votes may be included in the report. The process is repeated until a consensus is reached. This method has the following advantages:

- it caters for groups whose members are geographically distributed;
- it can minimise the effects of status differences on the decision-making process;
- it aims to try and obtain all the benefits of a group decision (multiple ideas, suggestions, more expertise, and greater amounts of information);
- it aims to avoid the disadvantages of group processes (groupthink, interpersonal conflict etc.).

However, the Delphi Technique also has disadvantages:

- it is time-consuming;
- it can feel artificial or forced to managers;
- it lacks understanding of the problem and of the final decision;

- it lacks members' commitment to the decision gained from expressing one's personal support for the decision (Wilson and Rosenfeld, 1990).

There is another technique, called the Nominal Group Technique (NGT), which is similar to the Delphi Technique. The difference is that in the Nominal Group Technique individuals rank the ideas of others in the 'group'. The decision is then made on the basis of the highest-ranking idea.

Quality Circles are groups of employees who meet together regularly in company time to generate solutions to problems they face. This method is designed to enable people to talk over problems (such as poor quality of manufactured goods, or suggestions for improving production processes) and to discuss difficulties that come up in everyday work. It is originally designed to improve the quality of manufactured products. Now it is extensively used to achieve participative decision-making throughout the whole organisation. The results of this technique are mixed. Many quality circles end up with plenty of talk but little action on their ideas (Lawler & Moreman, 1985).

Decision Conferencing has its genesis in high-technology decisions, starting in the 1980s. It is usually a two- or three-day decision-making session. The participants of the meeting are all 'owners' of a problem or set of problems. The participants' different viewpoints are combined into a computer model that is generated on the spot by the group. The model then allows experimentation to test the consequences of preferred courses of action.

Three specialist staff are required in the Decision Conferencing technique:

a) A facilitator that looks after the group processes that occur;

b) An analyst that looks after the computer modelling;

c) A recorder that uses a projected word processor to highlight to the group the words it is using and to determine the central issues.

Decision Conferencing is likely to be employable in all kinds of decision activity. It is designed to handle complex decisions. It suits the cases in which there are different points of view already known and the objective is to reach consensus. The decision process is intensive but expensive.

Overcoming Groupthink Some specific techniques have been developed to overcome 'groupthink' (Furtado, 1988). The early attempt made by Furtado (1988) stated how to overcome the phenomenon of groupthink: 'clearly defining a vision, getting the organisation behind it, encouraging risk taking and participative involvement of all the workforce are not incompatible with the basic management skills'.

Belbin (1981) suggested that the following 8 roles should be represented:

1) chairman: the co-ordinator
2) team leader: the shaper, gives the process direction
3) innovator: creative thinker
4) monitor: the critical thinker
5) company worker: getting the task done for the firm
6) team worker: manages the interpersonal interaction in the group
7) the completer: keeps the team on its toes by always making reference to the end goal of the decision

8) resource investigator: keeps the team in touch with others in the organisation

All the roles above are necessary. Individuals in a small group may adopt two or more roles. Collaboration between these roles keeps groups well balanced and allows full discussion and avoids any pitfalls of groupthink.

2.3.3 Collaborative Decision Making in Construction

While the construction industry forges rapidly ahead to a more competitive world, collaborative working involving different disciplines, different locations and different IT methods is becoming more and more important in project management. Over the past few years, construction companies have benefited much by successful collaborative decision-making. It facilitates completion of the project both in time and with high quality in some cases. Many researchers such as Pena-Mora et al (1995), Rezgui et al (1998), Anumba and Newnham (2000) and Marir et al (2000) have investigated aspects of collaborative decision-making in construction.

The development of large-scale engineering systems requires the collaboration of numerous specialists. Their decisions reflect their different perspectives of a project, and may lead to conflicts. The study presented by Pena-Mora et al (1995) addresses the representation, use, and communication of design rationale for conflict mitigation in a collaborative environment. Rezgui et al (1998) defined mechanisms to handle a number of issues relating to the management of information to support decision-making in collaborative projects. It is essential that enabling information and communication technologies are available for effective collaborative working between the parties in a construction project team. The model developed by Anumba and Newnham (2000) provides an agent-based system for the automated design of light industrial buildings, involving the use of distributed artificial intelligence. Marir et al (2000) also investigated providing information management and decision support in the context of distributed collaborative construction engineering, focusing on process specification based on case based reasoning techniques.

In general, no construction project is free from group decision-making, whether it is a building, road or bridges, dams or offshore structures. The decisions often need close collaborative working between members of the project group/team. A single manager would usually lack sufficient information or technical skill to make decisions alone even if he is creative and energetic as an individual decision-maker. Thus, most managers find themselves most of the time involved with other managers discussing a wide range of problems. Sometimes, a manager represents the collective feeling or viewpoint of his or her department on a topic in the decision group while at other times, he or she might be called into a group because what is to be decided will affect his or her area (Wilson and Rosenfeld, 1990).

Therefore, decision-making in a group is characterised by a number of aspects that are specific to group rather than individual processes. The act of trying to make a decision will also result in specific kinds of behaviour from group members. Every profession or discipline in the project team, such as the architect, structural engineer, contractor, quantity surveyor, mechanical/electrical service engineer, works independently of one another but makes decisions that inevitably affect the others. Hence, there is an increasing need for effective collaborative working between all the key participants in any construction project.

There will always be some friction in a collaborative venture. The following commandments for collaboration proposed by Ritchie (1995) will help construction project teams to cope with it:

1) There has to be a moral commitment.
2) There should be no preconceived idea and collaborators should be open to almost anything.
3) Learn to really listen and to interrupt, and be ready to be interrupted.
4) Ideas are shared - no one can claim them afterwards.
5) Be altruistic, not competitive.
6) Respect the minds of your collaborators; their individual skills will become valuable later.
7) There is time together - synthetic time, and time alone - reflective time.
8) All participants are equal; there are no bosses.
9) You have to respect the common concept as being more important than one you could have conceived by yourself.
10) Be prepared to improvise.

In practice, there are several combinations of the above principles and diverse environments of project cases. As such, established methods and systems are used to handle the conflicts between participants of a project team and to support the decision makers throughout all the phases of a decision making process.

2.3.4 Decision Support Systems

2.3.4.1 DSS fundamentals

Decision support systems (DSS) can support decision making in a number of ways. They can automate certain decision procedures (e.g. determining the highest price that can be charged for a product to maintain market share). They can provide information about different aspects of the decision situation and the decision process, such as what opportunities or problems triggered the decision process. They can stimulate innovation in decision making by helping managers question existing decision procedures or explore different solution designs (Dutta et al, 1997).

Since recent advances in computer processing and database technology have extended the definition of a DSS to include systems that can support decision making by analysing vast quantities of data, today there are two basic types of DSS – model driven and data driven (Dhar and Stein, 1997). The difference between the two types is (Laudon and Laudon, 2000):

- Model-driven DSS were primarily standalone systems isolated from major organizational information systems that used some type of model to perform "what-if" and other kinds of analyses.
- Data-driven DSS support decision making by allowing users to extract useful information that was previously buried in large quantities of data.

There is another type of DSS called 'datamining', which provides technology for finding hidden patterns and relationships in large databases and inferring rules from them to predict future behaviour. It is more discovery driven.

The components of a DSS may include a database and a software system. A database is a collection of current or historical data from a number of applications or groups; while a software system can be collection of software tools that are used for data analysis (Laudon and Laudon, 2000). Fig. 2.2 describes what probably came to be a more customarily used model of the decision-making process in a DSS environment.

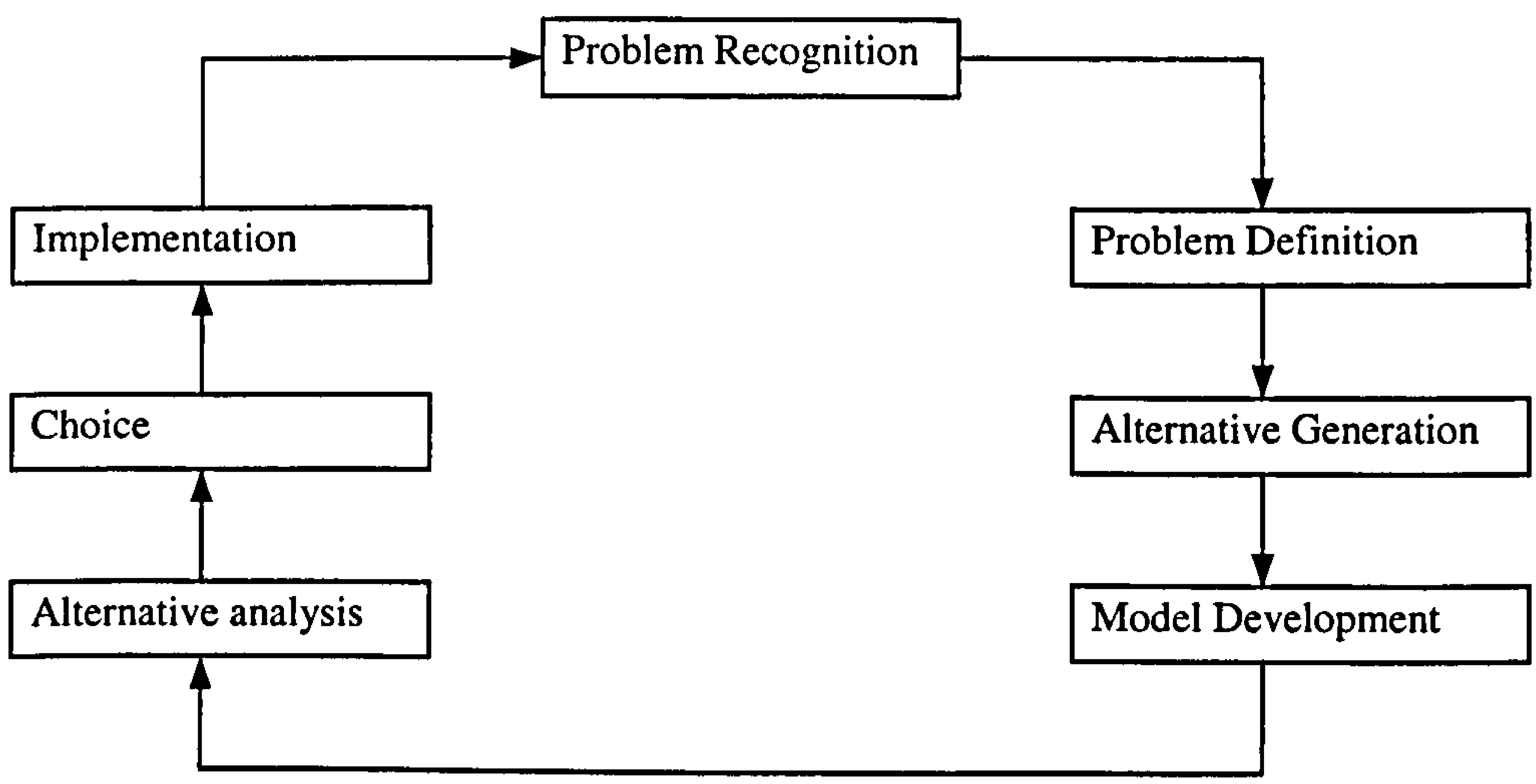


Fig. 2.2 The Conventional DSS Decision Making Process (Courtney, 2001)

2.3.4.2 Group DSS

A group decision support system (GDSS) is an interactive computer-based system to facilitate the solution of unstructured problems by a set of decision makers working together as a group (DeSanctis and Gallupe, 1987). GDSS are still relatively new. However, after being studied, GDSS are now being used widely and have shown benefits. Below are some aspects of how GDSS can enhance group decision-making (Laudon and Laudon, 2000):

- Improved preplanning. Electronic questionnaires, outlining software and other PC software can structure planning, thereby improving it;
- Increased participation. Using GDSS software, studies show the optimal meeting size can increase while productivity also increases;
- Open, collaborative meeting atmosphere;
- Criticism-free idea generation. Anonymity ensures that attendees can contribute without fear of personally being criticized or of having their ideas rejected because of the identity of the contributor;
- Evaluation objectivity. Evaluation in an anonymous atmosphere increases the free flow of critical feedback and even stimulates the generation of new ideas during the evaluation process;
- Idea organization and evaluation. Structured GDSS allow individuals each to organize and then submit their results to the group, the group then iteratively modifies and develops the organized ideas until a document is completed;
- Setting priorities and making decisions. Anonymity helps lower-level participants have their positions taken into consideration along with the higher-level attendees;
- Documentation of meetings. GDSS allow post-meeting use of the data. Attendees can continue their dialogues after the meeting and discuss the ideas with those who did not attend;
- Access to external information;
- Presentation of "organizational memory". Some GDSS facilitate access to the data generated during a GDSS meeting, allowing non-attendees to locate needed information after the meeting.

There have been many decision support or group decision support systems developed to support decision making in various sectors. Some examples are discussed below.

2.3.4.3 DSS and GDSS in practice

Specific techniques are used in DSS and GDSS to facilitate functions in economic decision making (Poh, 2000), in military decision making (Hill, 1991), or general information systems (Ngwenyama et al, 1996; Jeusfeld and Bui, 1997; Romano et al, 1998; Dowling and Louis, 2000).

Ngwenyama et al (1996) presented a set of techniques and an approach to support the facilitator in building consensus during group decision-making in computer supported group work. The data about each participant's expressed preferences for a set of alternatives, in their approach, are analysed to provide the facilitator with information about the level of group consensus, coalescing of sub-groups, and areas of strong disagreement.

The Internet has been grabbing most of the attention of information systems researchers and practitioners. Jeusfeld and Bui (1997) proposed a script language to make use of the vast resource of the Internet as a means to better make DSS known to potential users; and to allow construction of DSS components stored on various Internet sites. The script language was intended to ensure effective search of DSS components and rapid development and deployment of application-specific DSS. The group decision support system developed by Romano et al. (1998) is Web-based and has the functionality that group participants express their opinions and cast their votes electronically. It is designed for a general manufacturing environment and does not concern any issues of uncertainties and imprecision during decision-making processes.

The techniques making groups work have been updated with the application of their computer-assisted implementations. Nominal Group Technique (NGT) is one of the most successful processes for structuring meetings. Dowling and Louis (2000) provide a computer-assisted asynchronous implementation for the teams especially with non-standard work schedules.

There have been a lot of knowledge-based DSS that can be applied in a construction CE environment; examples include Shen and Grivas (1996), Attoh-Okine (1997), Ghasemzadeh and Archer (2000), Marir et al, (2000) Harrison et al (2001), Lam et al, (2001); or general manufacturing CE environment (Eden and Ackermann, 1994, Grabot et al, 1996, Bhargava et al, 1997, Poh, 1998, Hague et al, 2000, Rees and Koehler, 2000). Below are brief descriptions of some of the DSS or GDSS above.

The DSS developed by Shen and Grivas (1996) is for the preservation of civil infrastructure and it aims at providing assistance for decisions concerned with the three main tasks of infrastructure maintenance and rehabilitation: symptom observation, condition diagnosis, and treatment identification. Two methodologies – knowledge graphs and damage assessment – were incorporated into the system, with a uniform representation scheme to organize the knowledge and data.

A DSS was also developed for project portfolio selection with the implementation of an organized framework (Ghasemzadeh and Archer, 2000). Harrison et al (2001) presented a computer-based DSS for life-cycle-based solid waste management while Grabot et al (1996) developed a DSS for product activity control to cope with the increasing flexibility of manufacturing system. The research of Lam et al (2001) illustrated a mathematical approach to the solution of decision-making problems that combine qualitative and quantitative objectives. The mathematical model can be applied to construction project problems by suggesting an optimal path of corporate cash flow that results in the minimum use of resources. The information provided by the mathematical model allows the planner to eliminate excess use, or idleness, of resources during the construction of a project.

In Attoh-Okine's approach to rough set theory in pavement rehabilitation and maintenance DSS, the rough set concept is an effective tool for the analysis of information systems in a pavement management system database gained by both objective and subjective method. Poh (1998) presented an implementation of an intelligent system that provides an integrated environment for multiple attribute decision-making. The knowledge-based system intends to guide users in the selection of the most appropriate multiple attribute decision-making methods after being given information about the problem characteristics by the users.

The study of Rees and Koehler (2000) concerned groups using GDSS for addressing organizational problems and developed an analytical model that is based on a genetic algorithm (GA) and can be used to estimate GA parameter values from experimental data. The study examined possible relationships between the GA crossover and mutation parameters and the group context variables of leadership.

Although the literature has documented many decision support systems and group support systems that have been developed to facilitate decision making with different knowledge-based functions, for the construction sector, most of existing approaches have limited use in practice. The limitations of the existing approaches are now discussed.

2.4 LIMITATIONS OF EXISTING APPROACHES

The benefits of collaborative decision-making in concurrent engineering environment have been realised and understood both by researchers and industrial practitioners over the last few years. While existing approaches in concurrent engineering and decision-making areas help people address their problems, notable limitations do exist. A survey reported that less than a fifth of British industry had taken up the CE philosophy and this was partly attributed to a lack of understanding with respect to its implementation (Ainscough & Yazdani, 2000). In terms of collaborative decision-making tools in construction, the following limitations are evident:

1. Some DSS can be applied in a construction or general manufacturing CE environment but provide support only for a certain phase or aspect of product development process (e.g. Shen and Grivas, 1996, Grabot et al, 1996, Attoh-Okine, 1997, Hague & Taleb-Bendiab, 1998, Ghasemzadeh and Archer, 2000, Marir et al, 2000, Haque et al, 2000, Harrison et al, 2001);
2. Some decision-making systems contribute to individual decision-making effectively but do not support group collaboration (e.g. Grabot et al, 1996, Jeusfeld and Bui, 1997, Poh, 1998, Ghasemzadeh and Archer, 2000, Marir et al, 2000, Lam et al, 2001);

3. Some approaches are designed to facilitate group decision making or concern the issues of group decision making (Eden and Ackermann, 1994; Ngwenyama et al, 1996; Romano et al., 1998; Dowling and Louis, 2000; Rees and Koehler, 2000) but few decision-making systems are capable of dealing with the uncertainties and imprecision during a practical decision-making process. Also, few existing systems are designed particularly to encourage objectivity and eliminate unhealthy and antisocial behaviour in group decision-making.
4. Of the multiple ways in which organisations can facilitate group collaboration and coordination, the Internet (with its capabilities for e-mail and discussion groups) and intranets (for corporate information sharing) are prime options (Laudon and Laudon, 2000). For a given construction project, its organisation is a temporary multi-disciplinary team and its members are usually geographically distributed. Thus, Internet-based decision-making systems can best enhance group collaboration between members of a construction project team. Very few existing approaches (Romano et al., 1998) are Web-based and so do not adequately meet the needs and work practices of a distributed construction project team.

As there is a lack of effective collaborative decision-making systems to overcome the limitations of the existing approaches, the research project presented in this thesis is intended to develop a new Internet-based collaborative decision making system to facilitate construction project team decision-making by geographically distributed members.

2.5 SUMMARY

This chapter has reviewed the fundamental concepts and principles of concurrent engineering and group decision-making. It has also investigated the application of CE and collaborative decision-making in the construction industry. The importance of group decision-making in CE was stressed. It was established that group collaboration technologies could strongly enhance the work of a group, if the applications are properly designed. This was done by exploring the limitations of existing approaches to collaborative decision-making in construction. Another important aspect of the prototype system presented in this thesis - fuzzy set theory - is discussed in the next chapter.

CHAPTER 3

FUZZY SET THEORY AND APPLICATIONS

3.1 INTRODUCTION

This chapter reviews the fundamental concepts and principles of fuzzy set theory and highlights the theories employed in the development of the prototype system. Some key advantages of fuzzy systems are explored in this chapter, followed by a discussion of the application of fuzzy set theory in various industry sectors.

3.2 FUNDAMENTALS OF FUZZY SET THEORY

Real-world objectives are often classified into different categories (Chak et al., 1998). Categories such as young man, good quality, and cold weather all convey linguistic hazy information. The concept of membership of an object in such categories is not obvious and not precise. Classic logic and set theory are weak and limited in application to such cases. Thus the idea of fuzzy sets proposed by Zadeh (1965) aims to deal with such information.

Fuzzy sets involve capturing, representing, and working with linguistic notions – objects with unclear boundaries (Pedrycz & Goide, 1998). Fuzzy set theory is an extension of classical set theory. In classical set theory, an element either belongs to a set or does not belong to a set. In fuzzy set theory, an element may partially belong to a set. The mathematical definition of fuzzy set and other fundamentals of the theory are introduced below.

3.2.1 Key Concepts

The important concepts include the definition of a fuzzy set and fuzzy binary relations, on which the Fuzzy Structural Modelling method that is adopted in the system is based.

3.2.1.1 Definition of a Fuzzy Set

Since a fuzzy set deals with uncertainties which arise when the boundaries of a class of objectives are not sharply defined, it can be defined mathematically by assigning to each possible element in the universe of discourse a value representing its grade of membership in the fuzzy set. This grade corresponds to the degree to which that element is similar or compatible with the concept represented by the fuzzy set (Klir and Folger, 1988). The following example from Kaufmann (1975) illustrates the above ideas:

Consider a finite set with six elements:

$E=\{x_1, x_2, x_3, x_4, x_5, x_6\}$ and let

$A=\{x_2, x_3, x_5\}$

and let $\mu_A(x_1)=0$, $\mu_A(x_2)=1$, $\mu_A(x_3)=1$, $\mu_A(x_4)=0$, $\mu_A(x_5)=1$, $\mu_A(x_6)=0$ to represent A by accompanying the elements of E with their characteristic function values:

$A=\{(x_1, 0), (x_2, 1), (x_3, 1), (x_4, 0), (x_5, 1), (x_6, 0)\}$

Now if this characteristic function may take any value in the interval [0,1], an element x_i of E may not be a member of A ($\mu_A=0$), could be a member of A a little (μ_A near 0), may more or less be a member of A (μ_A neither too near 0 nor too near 1), could be strongly a member of A (μ_A near 1), or finally might be a member of A ($\mu_A=1$). In this manner the notion of membership leads to the concept of a fuzzy set. Its mathematical expression is:

$$\underset{\sim}{A}=\{(x_1|0.3), (x_2|0), (x_3|0.5), (x_4|1), (x_5|0.8), (x_6|0)\}$$

where x_i is an element of the reference set E and where the number placed after the bar is the value of the characteristic function for the element.

A formal presentation of the fuzzy set theory is as follows (Chak et al., 1998):

Let $x \in U$ and let S be a subset of U, then

- $\mu(x)$: $U \rightarrow [0, 1]$ is called the membership function which represents the degree of x belonging to the subset S;
- U is called the universe of discourse;
- The fuzzy set A is defined to be a set of ordered pairs A = $\{(x, \mu(x)) \mid x \in S, S \subset U\}$;
- The membership function is denoted by $\mu_A(x)$ for the fuzzy set A;
- The support of a fuzzy set A denoted as A_{SUP} is the crisp set of all points x in U such that $\mu_A(x) > 0$. A fuzzy set A whose support A_{SUP} contains a single point x in U with $\mu_A(x)=1$ is referred to a fuzzy singleton. A fuzzy set A whose support A_{SUP} is the universe of discourse U with $\mu(x)=1$ is referred to as a fuzzy universe.

In Novak's (1989) definition, fuzzy set is a function:

Let U be a class called the *universe*. It can be the universal class of all sets. Let $\mathcal{L}$ = $\langle L, \vee, \wedge, 1, 0\rangle$ be a lattice where 1 is the greatest and 0 the smallest element. This lattice represents the scale of membership grades in a fuzzy set. In most applications it is supposed that $L = \langle 1, 0 \rangle$. Then the *fuzzy set* A in the universe U is a function:

$$A : U \rightarrow L.$$

The function A is usually called the *membership function* of the fuzzy set A. To each element $x \in U$ is adjoined an element $Ax \in L$ called the *membership grade* of x in the fuzzy set A. If $Ax=0$ then x does not belong to A. If $Ax=1$ then x belongs to A. If $Ax \neq 0,1$ then x partly belongs to the fuzzy set A.

The relevant notations of the above definition are:

1. Structure: A structure is a set together with a collection of operations and relations (in general, n-ary). A pair $\langle A, \leq \rangle$ is called a *partially ordered* set, where A denotes the set.

2. The smallest element in a partially ordered set A is an element $o \in A$ such that $o \leq x$ holds for every $x \in A$. The set A is *well ordered* if every non-empty subset has a smallest element.

3. Let set $B \subseteq A$. Then an *upper bound* of B is an element $m \in A$ such that $y \leq m$ holds for every $y \in B$. A *lower bound* of B is an element $o \in A$ such that $o \leq y$ holds for every $y \in B$. The *least upper bound* is called the *supremum*

   $$\sup_A (B) = \bigvee_{x \in B} x$$

   And the *greatest lower bound* is called the *infimum*

   $$\inf_A (B) = \bigwedge_{x \in B} x$$

4. A *lattice* is a structure $\langle A, \vee, \wedge \rangle$ where $\vee$, $\wedge$ are two binary operations in the set A which are called *join* (supremum) and *meet* (infimum) respectively. A lattice is *complete* if each of its non-empty subsets has a supremum as well as infimum. The greatest (smallest) element of the lattice (provided it exists) is called the *unit* (*zero*) and is denoted by 1 (0). The lattice $\langle A, \vee, \wedge, 1, 0 \rangle$ is *complementary* if to every $x \in A$ there is an element $x' \in A$ such that $x \wedge x' = 0$, $x \vee x' = 1$ hold true.

Let $A \underset{\sim}{\subseteq} U$ be a fuzzy set, then we have some definitions as following:

- The *support* of fuzzy set A is a classical set

  Supp $(A) = \{x: Ax \neq 0\}$,

  which is utilised in the calculation of 'Maximizing Set' (see Section 3.2.3.2).

- The *α-cut* of the fuzzy set A for the given $\alpha \in L$ is a classical set

  $A_\alpha = \{x; Ax \wedge \alpha = \alpha\} = \{x; \alpha \leq Ax\}$.

  In the operation of fuzzy numbers addition and multiplication, the method of *α-cuts* form connected intervals of membership function and transforming the corresponding operation to manipulation with edges of the intervals (see Section 4.5.5).

- The *kernel* of the fuzzy set A is a classical set

  Ker $(A) = \{x; Ax = 1\}$,

  which is an important concept for the definition of linguistic modifiers (see Section 3.2.2.2).

3.2.1.2 Fuzzy Binary Relations

An ordinary binary relation on a set U is a subset of U×U.

Let R be a relation on U, then R: $U \times U \rightarrow \{0,1\}$ and the relation R on U is (Nguyen & Walker, 1997):

- Reflexive if $R(x, x)=1$;
- Symmetric if $R(x, y)=1$ implies $R(y,x)=1$;
- Transitive if $R(x, y)=R(y, z)=1$ implies $R(x, z)=1$;
- Antisymmetric if $R(x, y)=R(y, x)=1$ implies $x=y$.

Many other properties of a relation are defined in terms of these. For example, R is an equivalence relation if it is reflexive, symmetric, and transitive. To generalise relations to fuzzy relations is just that of going from subsets to fuzzy subsets. If R is a fuzzy relation on a set U, then R: $U \times U \rightarrow [0,1]$, and the relation R is:

- Reflexive if $R(u, u)=1$; for $\forall (u, u) \in U \times U$;
- Symmetric if $R(u, v)=R(v, u)$ for $\forall (u, v) \in U \times U$;
- Transitive if $R(u, w) \geq R(u, v) \wedge R(v, w)$ for $\forall$ u, v, w $\in U$, $u \neq v \neq w$;
- Anti-symmetric if $R(u, v)>0$ and $R(v, u)>0$ imply $u = v$,

  for $\forall (u, v) \in U \times U$, $u \neq v$.

There is another definition that relaxes the restrictions above by introducing a threshold parameter p (Tazaki & Amagasa, 1979):

Let p be a real number given on the semi-open interval (0, 1], then the relation R is called:

- fuzzy reflexive, if $R(u, u) \geq p$, for $\forall (u, u) \in U \times U$;
- fuzzy irreflexive, if $R(u, u) < p$, for $\forall (u, u) \in U \times U$;
- fuzzy symmetric, if $R(u, v) \geq p$, and $R(v, u) \geq p$, for $\forall u, v \in U$, $(u \neq v)$;

- fuzzy asymmetric, if either $R(u, v)$ or $R(v, u) < p$, for $\forall u, v \in U$, $(u \neq v)$;
- fuzzy transitive, if $R(u, w) > \vee_v[R(u, v) \wedge R(v, w)]$, for $\forall(u, v), (v, w) (u, w), u, v, w \in U, u \neq v \neq w$;
- fuzzy semi-transitive, if $R(u, w) \geq \vee_v[R(u, v) \wedge R(v, w)] \geq p$, for $\forall(u, w), (u, v), (v, w) \in U \times U, u \neq v \neq w$.

If a system object is $S=\{s_1, s_2, \ldots, s_n\}$, a fuzzy subordination matrix A can be constructed to represent a fuzzy subordination relation among the elements of S on the basis of a certain contextual relation:

$$A = [\, a_{ij} \,], i = 1, 2, \ldots, n$$

where A is a square n×n matrix and the element a_{ij} of A is given by the fuzzy binary relation f_R as follows:

$$a_{ij} = f_R(s_i, s_j), 0 \leq a_{ij} \leq 1, \quad i, j = 1, 2, \ldots, n$$

This shows the extent of s_i is subordinated to s_j. A parameter p is introduced as a threshold to show that the extent of subordination is greater than a certain grade. The value of p must be on the semi-open interval (0, 1]. This idea forms the basis of the Fuzzy Structural Modelling (FSM) method employed in the prototype decision-making system.

3.2.2 Fuzzy Linguistic Expressions

The concepts related to linguistic expression include linguistic variables, linguistic hedges (linguistic modifiers), linguistic approximation, linguistic quantifiers etc. Only linguistic variables and linguistic modifiers are discussed below as they are employed in the development of the prototype decision-making system.

3.2.2.1 Linguistic Variables (Zadeh, 1975)

In general, a linguistic variable is a variable whose values are words or word expressions called *terms*. Their meanings are fuzzy sets in some universe. For example, age, height, truth, temperature are linguistic variables, whose values (terms) can be young, tall, false, or low respectively.

Any variable is determined by a triple $\langle X, U, R(X)\rangle$ where X is the name of the variable, U is a universe and $R(X)$ is the range(boundary) of the variable X which is a subset of U, $R(X)\subseteq U$. For example, IQ is a variable attaining values in the universe U=N and R(IQ)={1, 2, ..., 100}. N represents the set of natural numbers here.

If the boundary $R(X)$ of the variable X is a fuzzy set in U, i.e. $R(X)\underset{\sim}{\subset} U$, then X is a fuzzy variable. This boundary is characterised by the property that every $x\in U$ is a value of X only to some degree. A linguistic variable is a special type of variable. Zadeh (1975) introduced the concept of linguistic variables as follows:

A linguistic variable is characterised by a quintuple denoted by $\langle \mathcal{X}, \mathcal{T}(\mathcal{X}), U, G, \mathcal{M}\rangle$, where $\mathcal{X}$ is the name of the variable, $\mathcal{T}(\mathcal{X})$ is the term set of $\mathcal{X}$ whose elements are labels of linguistic values of $\mathcal{X}$. U is an universe, G is generally a grammar for generating the names of $\mathcal{X}$. $\mathcal{M}$ is a semantic rule for associating each term $\mathcal{A}\in \mathcal{T}(\mathcal{X})$ with its meaning $\mathcal{M}(\mathcal{A})\underset{\sim}{\subset} U$.

In general terms, the semantics of a linguistic variable yield a mapping,

$$\mathcal{M}: \mathcal{T}(\mathcal{X}) \rightarrow \mathcal{F}(U),$$

that assigns to each term of $\mathcal{T}(\mathcal{X})$ a corresponding fuzzy set in U; $\mathcal{F}(U)$ denotes a family of fuzzy sets defined in U.

3.2.2.2 Linguistic Modifiers (Novak, 1989)

The adverbs such as *very, more or less, roughly, slightly* etc. are very often used in natural language because using them we can specify the meaning more closely. For example, 'very good result', 'rather complicated operation' specify what is referred to in more detail. The meaning of a linguistic modifier m is a pair of functions:

$$M(m)=<\zeta_m,\nu_m>,$$

Where $\zeta_m : U \rightarrow U$ (universe) and $\nu_m : L \rightarrow L$ is a function fitting a lattice $\mathcal{L}$.

Let term $\mathcal{A} \in \mathcal{T}$ be a syntagm whose meaning induces an ordering in the universe U, let $M(\mathcal{A}) = A \subseteq U$ and let m be a linguistic modifier with $M(m)=<\zeta_m,\nu_m>$, then the meaning of the expression $m\mathcal{A}$ is a fuzzy set in U given by:

$$M(m\mathcal{A}) = \nu_m \cdot A \cdot \zeta_m$$

where '·' denotes the composition of functions.

In membership degrees,

$$M(m\mathcal{A})\,x = \nu_m(a\zeta_m(x)) \quad \text{for every } x \in U$$

where $a\zeta_m(x)$ is the membership degree of the element $\zeta_m(x) \in$ U in the fuzzy set $A=M(\mathcal{A})$. The function ν_m is usually defined by means of several special functions fitting $\mathcal{L}$:

Concentration: $\mathrm{CON}(\alpha)=\alpha\cdot\alpha$, $\alpha \in <0,1>$

Dilation: $\mathrm{DIL}(\alpha)=\neg\mathrm{CON}(\alpha)$, $\alpha \in \mathrm{L}$, "$\neg$"denotes negation

Intensification: $\mathrm{INT}(\alpha)=((\neg\mathrm{CON}(\alpha)\rightarrow\mathrm{CON}(\alpha))\wedge\alpha)\vee(\neg\mathrm{CON}(\neg\alpha)\otimes\neg\mathrm{CON}(\neg\alpha))$, $\alpha \in L$.

The linguistic modifiers employed in the development of the system can be introduced by extending the above definition, which assumes that $\mathcal{A}\in\mathcal{T}$ is a syntagm with the meaning $M(\mathcal{A}) = A \subseteq U$, denoted by:

$$s_{\mathcal{A}} = \begin{cases} \inf\limits_{x\in U}(Ker(A)) & \text{for } \mathcal{A} \text{ positive} \\ \text{Approximate centre of Ker}(A) & \text{for } \mathcal{A} \text{ zero} \\ \sup\limits_{x\in U}(Ker(A)) & \text{for } \mathcal{A} \text{ negative} \end{cases}$$

- <u>The modifier *very*:</u>

  This is the most often used modifier whose meaning is defined as 'Concentration':

  $\nu_{very}(\alpha)=\text{CON}(\alpha), \quad \alpha\in L$

  $\zeta_{very}(x)=\begin{cases} y,\ y\le x, \text{ if } \mathcal{A} \text{ is positive, or } \mathcal{A} \text{ is zero and } x\le s_{\mathcal{A}} \\ y,\ y\ge x, \text{ if } \mathcal{A} \text{ is negative, or } \mathcal{A} \text{ is zero and } x\ge s_{\mathcal{A}} \end{cases}$

  $y=\zeta_{very}(x)$ is determined by the kernel of A.

  When $U\subseteq \mathrm{R}$ (real number), A is convex,

  $\zeta_{very}(x)=x+(-1)^k d.||\text{Ker}(A)||,$

  k=1 for $\mathcal{A}$ positive/zero and $x\le s_{\mathcal{A}}$

  k=2 for $\mathcal{A}$ negative/zero and $x\ge s_{\mathcal{A}}$

  $||\text{Ker}(A)||$ is the length of the interval $\langle\inf(\text{Ker}(A)), \sup(\text{Ker}(A))\rangle$ and d is a parameter, experimentally estimated as $0<d\le 0.5$.

  The membership function curves of the modifier *very* are depicted in Fig. 3.1, in which dotted lines represent the membership function curves of the linguistic variable with *very*. It is shown that the membership degrees are concentrated and the membership function curve is shifted to right or left when $\mathcal{A}$ is a positive or negative syntagm respectively in figure (a). Figure (b) shows that if $\mathcal{A}$ is a zero syntagm then its kernel is made narrower.

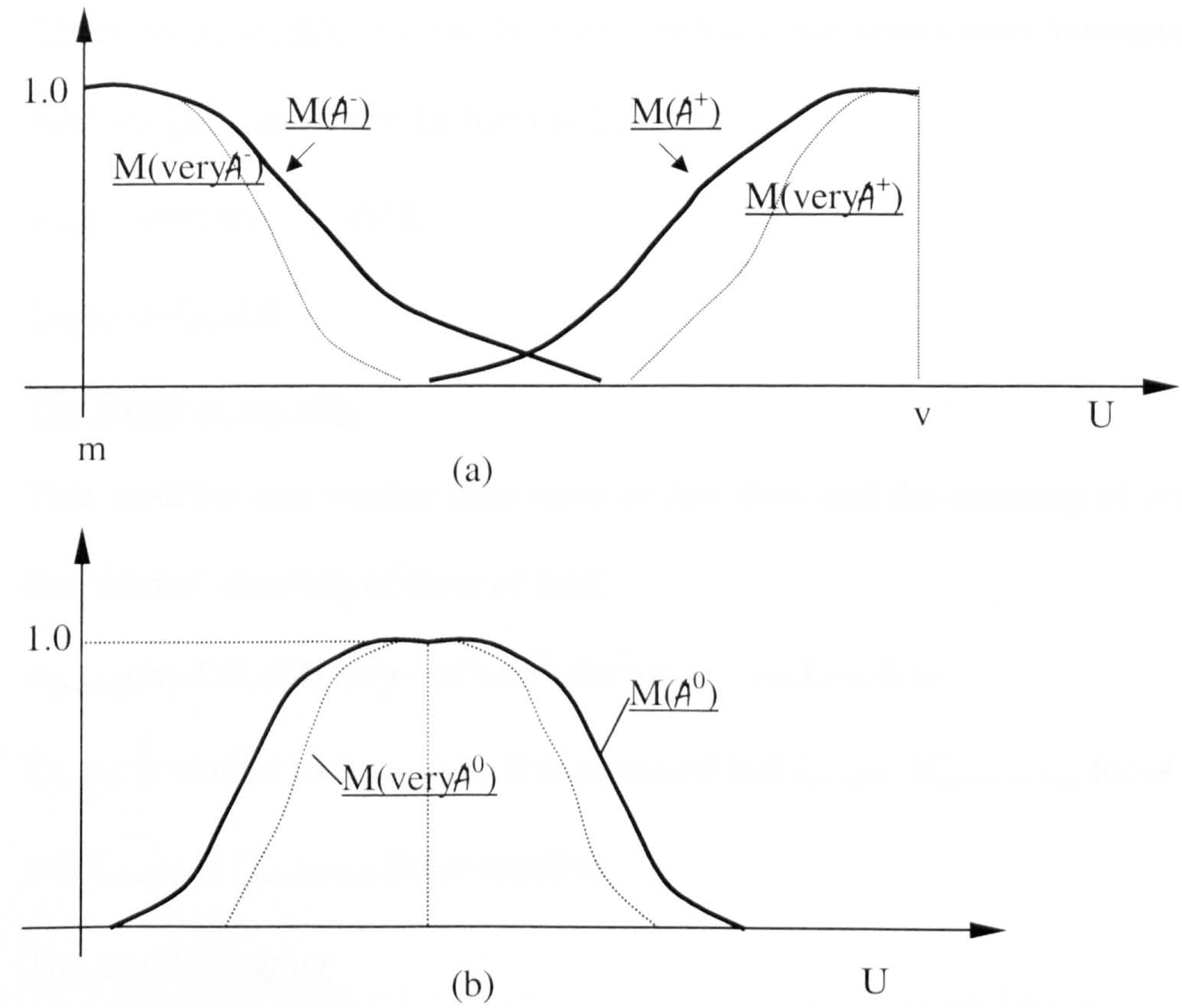


Fig. 3.1 Membership Function Curves of the Linguistic Modifier *very* (Novak, 1989)

- The modifier *more or less*

  This modifier is regarded as the inverse to the modifier *very*. Its meaning is given below:

  $\nu_{more\ or\ less}(\alpha)=DIL(\alpha)=2\alpha-\alpha^2 \quad \alpha\in L=<0,1>$

$$\zeta_{more\ or\ less}(x)= \begin{cases} y\geq x & \text{if } \mathcal{A} \text{ is positive, or } \mathcal{A} \text{ is zero and } x\leq s_{\mathcal{A}} \\ y\leq x & \text{if } \mathcal{A} \text{ is negative, or } \mathcal{A} \text{ is zero and } x\geq s_{\mathcal{A}} \end{cases}$$

When $U\subseteq \mathbb{R}$ (real number),

$\zeta_{very}(x)= x+(-1)^k d.\|Ker(A)\|$,

k=1 for $\mathcal{A}$ negative/zero and $x\geq s_{\mathcal{A}}$

k=2 for $\mathcal{A}$ positive/zero and $x\leq s_{\mathcal{A}}$

- The modifier *highly* acts similarly to *very* but concentrates more intensively. The function ζ_{highly} has a similar form to ζ_{very}.

  $\nu_{highly}(\alpha)=\alpha\cdot\alpha\cdot\alpha \qquad \alpha\in L$

  $\zeta_{highly}(x)=\zeta_{very}(x)$

- The modifier *roughly*

  This modifier acts weaker than *more or less* does and the meaning of *roughly* is the 'dilated' meaning of *more or less*:

  $\nu_{roughly}(\alpha)=\mathrm{DIL}(\mathrm{DIL}(\alpha))=-\alpha^4+4\alpha^3-6\alpha^2+4\alpha \qquad \alpha\in L=<0,1>$

  $\zeta_{roughly}$ is similar to $\zeta_{more\ or\ less}$. It is supposed that $\zeta_{roughly}\geq\zeta_{more\ or\ less}$ for $\mathcal{A}$ positive and $\zeta_{roughly}\leq\zeta_{more\ or\ less}$ for $\mathcal{A}$ negative.

- The modifier *rather*

  This modifier is considered in an intensive sense and its meaning is given as an intensified concentrated membership function:

  $\nu_{rather}(\alpha)=\mathrm{INT}(\mathrm{CON}(\alpha))=(2\alpha^4\wedge\alpha^2)\vee(-2\alpha^4+4\alpha^2-1) \quad \alpha\in<0,1>$

  $\zeta_{rather}=1_U$

- The modifier *not*

  This modifier is regarded as negation:

  $\nu_{not}(\alpha)=\neg(\alpha) \qquad \alpha\in<0,1>$

  $\zeta_{not}=1_U$

The membership function curves of modifiers *more or less*, *highly*, *roughly*, *rather* for a zero syntagm $\mathcal{A}$ are depicted as (a), (b), (c), and (d) respectively in Fig. 3.2. It is evident that the kernel of $\mathcal{A}$ becomes narrower in (b) (highly), wider in (a) (more or less) and (d) (roughly), and mainly narrower in (c) (rather).

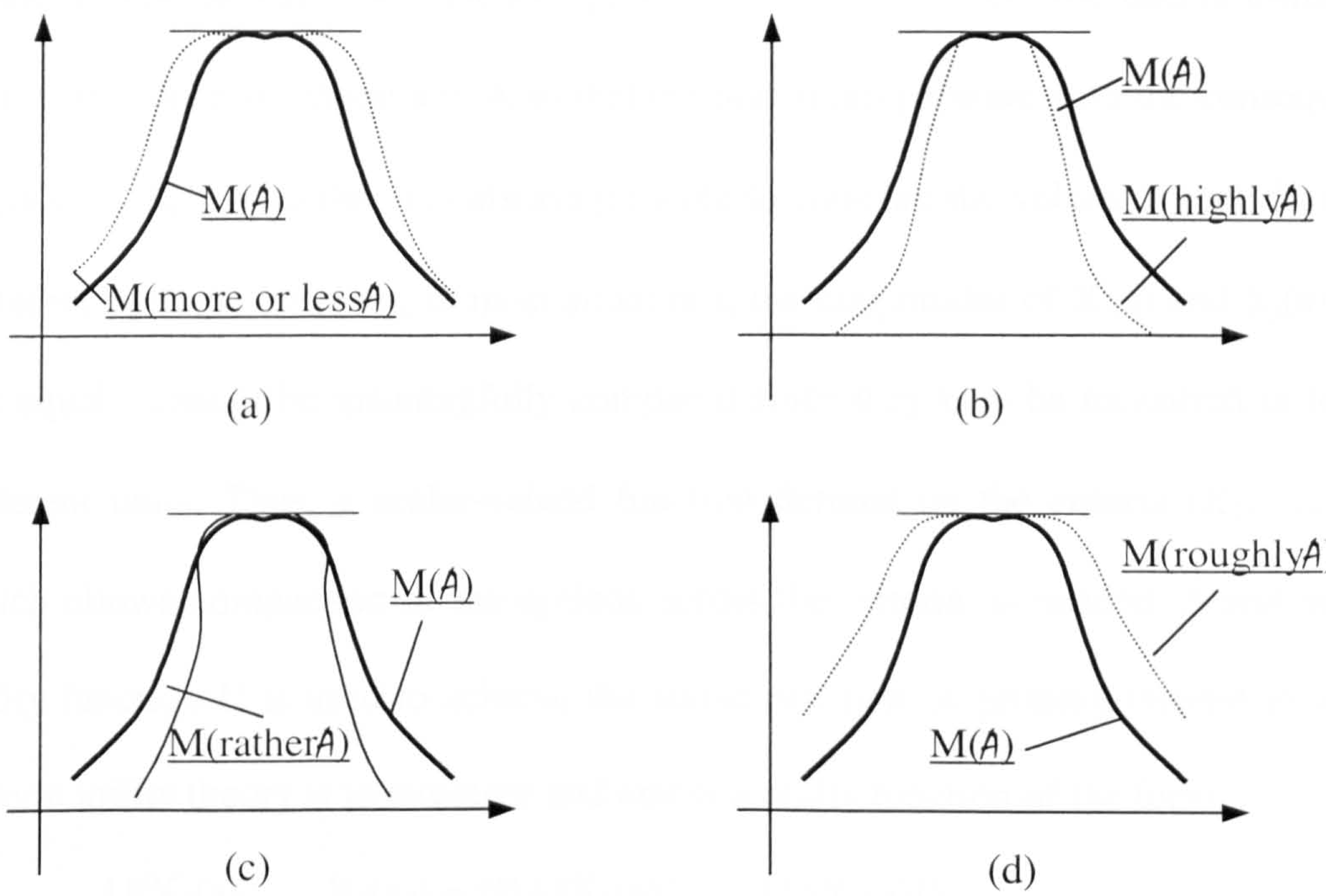


Fig. 3.2: Membership Function Curves of Modifiers *more or less*, *highly*, *rather*, and *roughly* for a Zero Syntagm (Novak, 1989)

3.2.3 Important Operational Principles

The operational principles discussed below are adopted for the operation on fuzzy sets in the development of the prototype decision-making model.

3.2.3.1 Utility

The general concept of utility in the standard decision analysis paradigm can be presented as the following (Sage, 1992):

It is assumed that a set of feasible options $A=(a_1, \ldots, a_m)$ and a set $(X_1, \ldots, X_n)$ of criteria or evaluators of the options can be identified. Associated with each option or course of action a in A, there is a corresponding consequence $X_1(a), X_2(a), \ldots, X_n(a)$

in the n-dimensional consequence space $X = X_1, X_2, \ldots, X_n$. The decision-makers' aim is to choose an option a in A so that the maximum pleasure with the consequence $(X_1(a), \ldots, X_n(a))$ results. It is always possible to compare the values of each $X_i(a)$ for different options; however, in most situations, the magnitudes of $X_i(a)$ and $X_j(a)$ for i not equal j cannot be meaningfully compared since they may be measured in totally different units. Thus, a scalar-valued function defined on the criteria $(X_1, \ldots, X_n)$, which allows comparison of the options across the criteria, is needed. A real-valued utility function U is used to achieve the above function. A primary interest in multi-criteria utility theory is to structure and assess a utility function of the form:

$$U[X_1(a), \ldots, X_n(a)] = f\{U_1[X_1(a)], \ldots, U_n[X_n(a)]\}$$

where U_i is a utility function over the single criterion X_i and f aggregates the values of the single criterion utility functions so that the scalar utility of the options can be computed.

The utility function can be defined in many ways. The definition of utility adopted in the development of the prototype system, which is based on Novak's (1989) approach, takes into account various degrees of importance of criteria and grades of options by the criteria.

Let $C_1, \ldots, C_m$ be criteria with weights $w_1, \ldots, w_m$ respectively, let the scores of each alternative $a_i \in A$ (i=1, 2, ..., n) be judged by a number $r_{ij} \in$ R(real number) from each criterion C_j, j=1, 2, ..., m, then the total utility of the alternative a_i from all the criteria C_j, j=1, 2, ..., m is:

$$u_i = \sum_{j=1}^{m} w_j \cdot r_{ij}$$

In the case that r_{ij} and the weights w_j are expressed in natural language, the utility value u_i is a fuzzy set. The aim of the method adopted in this research is to construct a fuzzy set of the best alternatives for a decision-making group.

Given the linguistic variables $\langle Score, \mathcal{T}(Score), \langle 0,1\rangle, G, M_G\rangle$, $\langle Importance, \mathcal{T}(Importance), \langle 0, 1\rangle, G, M_G\rangle$, the set of alternatives $A=\{a_i;\ i=1, 2, \ldots, n\}$and criteria $C_1,\ldots,C_m$. The score of an alternative a_i from the criterion C_j is judged using a linguistic expression $\mathcal{S}_{ij} \in \mathcal{T}(Score)$ with the meaning $M(\mathcal{S}_{ij}) \subseteq \langle 0, 1\rangle$. The weight of the criterion C_j is judged using a linguistic expression $\mathcal{W}_j^{\circ} \in \mathcal{T}(Importance)$ with the meaning $M(\mathcal{W}_j^{\circ}) \subseteq \langle 0, 1\rangle$. Then the total utility is a fuzzy set

$$Z_i = \sum_{j=1}^{m} M(\mathcal{W}_j^{\circ}) . M(\mathcal{S}_{ij})$$

where the sum and the product of fuzzy sets are computed using the extension principle, which is described in Section 3.2.3.3. In addition, the fuzzy set of the best alternatives can be constructed using a maximising set, which is adopted in this research.

3.2.3.2 Maximizing Set (Novak, 1989)

The maximizing fuzzy set is a simple tool to compare all the alternatives and establish the fuzzy set of the best alternatives. It is constructed by finding maximal element x_{max} in the universe such that its membership to some of the considered fuzzy sets B_i is non-zero. The detailed definitions are as follows:

Let $B_1, \ldots, B_n \subseteq R$ be fuzzy sets and let $x>0$ hold at least for one element $x \in Supp(\bigcup_{i=1}^{n} B_i)$. Then the fuzzy set $M \subseteq R$ given by the membership function

$$Mx = \begin{cases} \left(\frac{x}{x_{\max}}\right)^k & \text{If } x \in \text{Supp}(\bigcup_{i=1}^{n} B_i) \\ 0 & \text{otherwise} \end{cases}$$

where $x_{\max} = \vee\{x;\ x \in \text{Supp}(\bigcup_{i=1}^{n} B_i)\}$ and $k \in \mathrm{N}$ is the *maximising set* on the fuzzy sets $B_1, \ldots, B_n$.

Let M be a maxising fuzzy set on the utility fuzzy sets Z_i of all the alternatives $a_i \in A$. Then the fuzzy set $A_i = Z_i \cap M$ takes into account all the alternatives. The fuzzy set of the best alternatives is $A \underset{\sim}{\subseteq} A$ and is given by the membership function:

$$Aa_i = \text{Hgt}\ (A_i)$$

for each $a_i \in A$ and Z_i, where Hgt stands for 'Highest'.

3.2.3.3 Extension Principle

The extension principle is fundamental for translating set-based concepts into their fuzzy-set counterparts and, essentially, is used to transform fuzzy sets via functions (Pedrycz and Gomide, 1998). The definition below is based on Klir and Folger (1988):

The extension principle provides the means for any function f that maps points x_1, x_2, ..., x_n in the crisp set X to the crisp set Y to be generalized such that it maps fuzzy subsets of X to Y. Formally, given a function f mapping points in set X to points in set Y and any fuzzy set $A \in P(X)$, where

$A = \mu_1/x_1 + \mu_2/x_2 + \ldots + \mu_n/x_n$, and P stands for the extension principle,

The extension principle states that

$$f(A) = f(\mu_1/x_1 + \mu_2/x_2 + \ldots + \mu_n/x_n)$$
$$= \mu_1/f(x_1) + \mu_2/f(x_2) + \ldots + \mu_n/f(x_n).$$

If more than one element of X is mapped by f to the same element $y \in Y$, then the maximum of the membership grades of these elements in the fuzzy set A are chosen as the membership grade for y in $f(A)$. If no element $x \in X$ is mapped to y, then the membership grade of y in $f(A)$ is zero.

Novak (1989) expands the principle for transforming a classical addition and product operation into their counterparts on fuzzy set:

Let $*: U \times U \rightarrow U$ be a binary operation on U and $A, B \underset{\sim}{\subseteq} U$. Then the extension of '*' on the fuzzy sets A, B is the fuzzy set $C = A * B$ with the membership function

$$C_Z = \begin{cases} \vee \{ Ax \wedge By; x, y \in U \text{ and } z = x * y \} & \text{for every } z \in U \\ \mathbf{0} & \text{otherwise} \end{cases}$$

Where '*' can be the operation of product '·' or addition '⊕'. This definition is used in the computation in Section 4.5.5.

3.3 Principles and Advantages of Fuzzy Systems

3.3.1 Principles

Fuzzy systems, based on fuzzy sets and fuzzy logic, can be used for different kinds of purpose such as modelling, prediction, classification, and control in the field of systems science (Chak, 1999). In terms of the dependency between fuzzy systems, fuzzy logic, and fuzzy sets, Kosko (1997) describes as follows: fuzzy logic refers to a fuzzy system or a mapping from input to output that depends on fuzzy rules; the rules in turn depend on fuzzy sets or vague concepts that depend on fuzzy degrees of truth or set membership. The fuzzy system is a function or mapping.

To describe a system, there are basically two approaches – *structural* and *behavioural*. The first method describes the system from the viewpoint of its inner structure and aims to find principles leading to the emergence of new properties of the system as a whole, while the latter describes the system by means of its outer tokens, i.e. using some measurable parameters whose values change in time (dynamic). The parameters are usually divided into *inputs*, *outputs* and *states* (Novak, 1989). Accordingly, a fuzzy system is a dynamic system using fuzzy sets and based on the following principles:

1. It contains sets of inputs
2. It has sets of outputs
3. The states of the system can be represented
4. It possesses a *transition function* (system dynamics) to derive every new state of the system affected by the new input parameter
5. It possesses an *output function* to derive every new output generated by every new state of the system.
6. An initial state should be given in the system.

3.3.2 Advantages

In the above principles, the input, output and the state as well as the transition function and output function must be determined exactly and unambiguously. If, however, the real system is full of uncertainties or too complex then it might be not possible. Thus generally, there are four situations that lead to fuzzy sets (Klir & Folger, 1988, Dubois & Prade, 1988, Novak, 1989):

1. The real system is described only verbally.

2. The equations describing the system behaviour are there but the parameters cannot be exactly defined.
3. The equations describing the system are too complex to be cleared up and it is more reasonable to formulate a verbal description based on them.
4. The real system is uncertain or imprecise and one can only estimate linguistic rules for the description of its behaviour.

In these situations, fuzzy systems are able to cope with the difficulties and have the following advantages:

1. Fuzzy systems have natural language semantics and linguistic variables.
2. Measures of fuzziness have been established in various aspects, such as measures of dissonance/consensus, measures of confusion and measures of non-specificity. The development of membership functions has enhanced the successful application of different measuring methods of fuzziness in practice.
3. In fuzzy algorithms, ambiguous and vague instructions can be interpreted and executed freely.
4. The evaluation and ranking of objects can be done by the use of fuzzy set theory. This particularly leads to the development of the decision-making theory.
5. Heuristic searches can be conducted in an imprecise environment, such as imprecise evaluations and fuzzy values.

With so many advantages, fuzzy systems have been widely applied in practice while exploratory researches are still going on.

3.3.3 Disadvantages

Fuzzy set theory has been developed from several points of view, of which the studies on the general algebraic structure of fuzzy sets are mostly based on the notion of *t*-norm (Pedrycz and Gomide, 1999, Novak, 1989). However, in the studies, there has been a lack of a unifying framework and the approaches do not present a lucid understanding of the subject. Similar situations are found in fuzzy logic especially where various kinds of implication-like operations are studied (Nguyen and Walker, 1997). Fuzzy set theory and fuzzy logic need a well-founded theory with powerful results.

3.4 Fuzzy Set Applications

Since Zadeh coined the concept of fuzzy sets in 1965, there have been a number of applications of fuzzy sets and fuzzy logic to a variety of fields including psychology, engineering, economics, medicine, sociology, genetics, artificial intelligence, meteorology and decision-making.

3.4.1 Applications in Other Industries

As the purpose of the application of fuzzy set theory is to reduce complexity and deal with uncertainty, fuzzy set theory is applicable in any field in which issues of complexity arise. The successful research applications of fuzzy set theory are diverse and widespread. It is only intended to refer to some practical examples in other industries here, which are no means exhaustive, including medicine, social science, engineering and management/decision making.

3.4.1.1 Medicine

Imprecision and uncertainty play a large role in the field of medicine, which has become one of the most active areas of application for the theory of fuzzy sets. Within this field, it is the uncertainty found in the process of diagnosis of disease that has most frequently been the focus of these applications. Applications in medicine go back to the early 80s:examples include the applications presented by Adlassnig (1982, 1986), by Gupta et al. (1984), by Asse et al. (1987), and by Maeda et al (1987).

A type of approach to modelling the medical diagnostic process utilizes fuzzy cluster analysis (Esogbue and Elder, 1983). The technique of clustering examines the elements of some universal set and groups them according to similarity. Thus, elements grouped in one cluster are similar to each other and dissimilar to the members of other clusters. Since the boundaries of these clusters are not precisely defined, each cluster is a fuzzy set in which the grade of membership of any element indicates the similarity of that element to other members of that cluster. Any particular element can belong with varying degrees to several different clusters.

In another approach presented by Cohen and Hudson (1992), fuzzy set theory is applied to develop a pattern recognition system, which is useful to classify diverse types of medical data. The experimental application of the system, including the diagnosis of bacterial infection, detection of liver and spleen disorders etc., showed that the fuzzy-based approach produced more accurate results than conventional methods.

3.4.1.2 Social Science

The various social sciences have been active areas for the application of the mathematics of uncertainty and information. The applications of fuzzy set theory include explorations within psychology and cognitive science of concept formation and manipulation, memory and learning, as well as studies in the fields of sociology, economics, ecology, meteorology, biology, and others (Klir and Folger, 1988).

In the fuzzy associate memory systems developed by Kosko (1992), fuzzy set theory is used to provide an alternative to traditional AI expert-system knowledge representation and inferencing. Fuzzy set theory is also utilised to facilitate reliable and efficient communication, e.g., in COMEX- an autonomous fuzzy expert system for tactical communication networks (Schneider et al. 1992). Fuzzy set theory and fuzzy logic are increasingly applied in various areas in social life; examples include recognition of faces, speech reproduction from text, onboard satellite navigation systems, validation of written signatures and checks, real-time process visualisation, servo control, prediction of lightning strikes, loan eligibility prediction, credit-card fraud detection, stock market prediction, and domestic appliances, among many others (Kartalopoulos, 1996).

3.4.1.3 Engineering

A wide spectrum of applications is contained in the literature, ranging from civil engineering and architecture to automatic control and robotics. In a broad sense, engineering applications involve goals to be achieved under technical, economical, and social constraints. Steps must be taken to develop solutions in situations where the criteria for choice are not always as certain as they are wished to be (Pedrycz, 1998).

Fuzzy control is the most developed area of application of fuzzy set theory in engineering; and fuzzy controllers commonly control engineering artefacts that take advantage of fuzzy sets and rule-based systems in particular. Industrial processes have made use of automatic control in lieu of or in addition to a human operator since the 1980s, such as the fuzzy logic traffic controller developed in Japan by Nakatsuyama et al. (1984), and the fuzzy autopilot controller designed and implemented by Larkin (1985), which demonstrated good results when tested on a flight simulator. Research on practical applications of fuzzy theory has been active. Take recent approaches for example; the study conducted by Hopgood et al (1998) is in the electronic engineering field, and focuses on Plasma processing units, which are used for depositing coatings on the surface of electronic or mechanical components and are controlled by a blackboard system employing fuzzy logic (Algorithmic and Rule-based Blackboard System, ARBS). In the mean-value-based functional reasoning scheme presented by Watanabe and Tzafestas (1998), conclusions consist of a function of mean values on each membership function in the antecedent; and some fuzzy-based controllers are developed by using the scheme.

Various models and methods have been developed for use in different engineering fields. The novel image sensor presented by Sarkodie-Gyan et al. (1997) is for continuous conditioned monitoring of high-precision tolerances of a complex automotive product. In the approach, a novel mechanic-optical arrangement was designed and validated to capture the images/silhouettes of the components based on an approximate reasoning architecture. In the additive fuzzy system developed by Pacini and Kosko (1997), fuzzy IF-THEN rules are adopted to detect noisy signals in an uncoded digital communication system.

Another area of application of fuzzy set theory is computer science, which may also be classified as engineering. It has been developed quite extensively, particularly in those endeavours concerned with the storage and manipulation of knowledge in a manner compatible with human thinking. This includes the construction of database and information storage and retrieval systems as well as the design of computer-based expert systems (Klir & Floger, 1988). Many studies focusing on this field have taken place in recent years and the outcomes are fruitful. In the electronic market for decision technologies proposed by Bhargava et al. (1997), modern information networks offer a solution to the problems that restrict the use of decision technologies. Cappetti and Santoro (1998) presented a computer visualisation application for fuzzy evaluation of windscreen wiper systems that must satisfy several requirements. Some requirements were modelled using fuzzy sets in the application. In the KBS (Knowledge-Based System) based on the hierarchical knowledge model designed by Murlidharan (1999), it is shown that knowledge modelling facilitates the acquisition of knowledge that is vague and uncertain. The KBS has the flexibility to handle the uncertainties using probabilistic and fuzzy set approaches depending on the nature of uncertainty. In the optimum design method for large-scale structural systems developed by Ohkubo and Dissanayake, (1998), fuzzy membership function technique is used to deal with relative evaluation of all objective functions. This example addresses dealing with fuzziness during a decision-making process, which is another application area discussed in the next section.

3.4.1.4 Management and Decision-Making

Decision-making process is of key importance in the area of management for functions such as inventory control, investments, personnel actions, new product development, allocation of resources, and many others. Applications of fuzzy sets within the field of decision-making have consisted of extensions or 'fuzzifications' of the classical theories of decision-making. Fuzzy decision-making theory attempts to deal with the vagueness or fuzziness inherent in subjective or imprecise determinations of preferences, constraints, and goals (Klir & Folger, 1988).

Research has been conducted on the measures of the degree of consensus in group decision-making since the 1980s (Spillman and Spillman, 1987, Kacprzyk, 1987). It was shown that the theory of fuzzy sets could also effectively incorporate professional judgement in the decision-making process; where a fuzzy exponent was required because the assessment of the relative perceptiveness of individuals is non-crisp (Chameau et al., 1987). Considerable progress has been made in the application of fuzzy sets to this field in recent years. For instance, the study focusing on the steel materials selection problem by Chen (1997) developed a new method for solving the problem under fuzzy environment, where the importance weights of different criteria and the ratings of various alternatives under different criteria are assessed in linguistic terms represented by fuzzy numbers. In the non-numeric method for pair-wise fuzzy group decision analysis proposed by Marimin et al. (1997), the preference relations are expressed and processed non-numerically. The proposed method is suitable for group decision-making cases in which a full consensus is the most important role in selecting the alternative.

Decision support systems have interested many researchers and have been developed for use in business or different industry divisions, such as the decision support system developed by Kuo & Xue (1998) for sales forecasting through fuzzy neural networks with asymmetric fuzzy weights. For practising industrial engineers, Vlacic et al. (1997) proposed an algorithm that can support the process of group decision-making relating to industry automation, especially involving the selection of control and instrumentation equipment.

Several decision support systems have also been developed for the construction industry (Moore et al, 1997, Wanous et al., 2001). However, there are very few applications that address the use of fuzzy set theory in decision-making. The next section introduces general applications of fuzzy set theory in construction.

3.4.2 Applications in Construction

The use of fuzzy set theory in construction has been developed to treat many complex and uncertain problems. Ross (1988) made an effort of particular relevance to structural engineering. It is a difficult process to assess what the damage to a structure from any disturbance is like, as the information needed to make a damage assessment with high confidence is often incomplete and involves uncertainty, particularly when the uncertainties encountered include both random and non-random data. Ross (1988) summarised the damage assessment process for protective structures by discussing all the kinds of information available for the problem and the inherent uncertainty. He particularly addressed the use of information and its associated uncertainty to reach conclusions about damage through an approximate reasoning approach.

Fuzzy set theory is used in the assessment of the probability of failure of a protective structure and in dealing with subjective information in another application in structures (Wong et al., 1987). It was proved that fuzzy set theory could represent those non-crisp and judgmental data existing in the description of damage to a structure more realistically than using classical methods. Studies on the application of fuzzy set theory have been making progress in more recent years. Examples include applications in constructing reliability measures for the cases when both load and resistance are fuzzy (Shrestha and Duckstein, 1998) and an application dealing with the reliability assessment of reinforced and prestressed concrete framed structures (Biondini et al., 2001).

Expert, or so-called knowledge-based, systems have been increasingly developed in recent research projects in construction. Many of these now include approaches based on fuzzy set theory. Examples in this respect include the fuzzy controlled genetic-based search technique for structural shape optimisation investigated by Soh and Yang (1995), the network scheduling method based on fuzzy set theory presented by Lorterapong and Moselhi (1996), the linguistic approach to 2D geometric modelling of hierarchical systems developed by Lakmazaheri and Edwards (1997), and the fuzzy logic-based, risk-incorporating approach to evaluating new construction technology presented by Chao and Skibniewski (1998).

In the work of Soh and Yang (1995), an automated optimal procedure based on the proposed approach was developed and used in the least-weight design of truss structures, which included their geometry as a design variable to be optimised. To increase the performance of the genetic-based approach for shape optimisation problems, the design constraints relating to member stress, joint displacement, and member buckling were designed using fuzzy set theory. A fuzzy rule-based system representing expert knowledge and experience is incorporated in the approach to control the optimal search process.

The method developed by Lorterapong & Moselhi (1996) aims to provide schedules that can appropriately account for the nature as well as the type of uncertainties normally encountered in construction projects. The method incorporates a number of techniques to facilitate

- the representation of imprecise activity durations;
- the calculation of scheduling parameters;
- the interpretation of the fuzzy results generated.

The approach of Lakmazaheri and Edwards involves defining geometry linguistically and then generating the geometry from its linguistic definition via logical deduction in a logic-based CAD system. The evaluation method of Chao and Skibniewski (1998) intends to produce consistent evaluation of available options, according to a set of user-defined linguistic rules that state the priorities in a given project scenario. This approach actually is designed to tackle the uncertainties existing in the process of evaluating construction technology alternatives.

Explorations of the application of fuzzy set theory on construction management issues have also been made, for instance, studies concerning risk in construction. Jablonowski and Standard (1998) suggested a framework for the conceptual analysis of risk using fuzzy set theory, and described a potential application to the safety monitoring of civil engineering to demonstrate the benefits of the fuzzy risk analysis. The membership function of fuzzy set theory is also effectively applied in the fuzzy approach developed by Lin (1998), which solves non-structured problems, such as risky investment problems for engineering projects. However, fuzzy set theory has also been applied in studies concerning other management issues. Examples include the framework for evaluating design project performance described by Fayek and Sun (2001), the hierarchy fuzzy method for studying rapid transit system contracting model developed by Shieh and Ku (2001).

From the foregoing, it can be seen that the application of fuzzy set theory in construction is still relatively new. This leaves the uncertainties and imprecision existing in many practical aspects during construction process unresolved and there are gaps that need to be filled, which also represent new opportunities for the development of fuzzy set theory.

3.4.3 Application Gaps and Opportunities

Through the above review of previous work, it is evident that fuzzy set theory has proved to be very useful in the engineering field. Some successful applications in construction also abound with the approach being used to address practical problems. There are also some applications in the decision-making field. However, particularly in the construction area, there exist many decision-making situations but very few effective decision-making tools. In a project team, there are usually several members all of whom need to be effective team players within a concurrent engineering framework. In making decisions, project team members have different perspectives, or biases, on the same issue and their opinions can conflict with one another. In other words, the personalities and professional or cultural background of the individuals involved often have a great part to play and may result in sub-optimal decisions being made. Thus a decision-making system that is able to provide an objective and rational framework is needed when collaborative decisions are being taken by virtual construction project teams. This is what this research aims to address. In particular, it is intended to develop a collaborative decision-making tool that:

- is generic and applicable to a wide range of group decision making scenarios;
- is Web-based and able to facilitate decision-making by members of a geographically distributed project team;
- does not require the knowledge about the decision-making issue to be encapsulated within it (as is the case with most conventional knowledge-based or decision support systems).

None of the existing tools incorporates these three features.

3.5 Summary

The original concepts and key principles associated with fuzzy set theory have been reviewed in this chapter. It is proposed that fuzzy set theory has undoubted advantages for tackling the uncertainties and imprecision that occur in many environments that conventional systems cannot handle. Fuzzy systems are increasingly being applied to the solution of a variety of problems, including engineering and non-engineering applications. Engineering applications are many but specific applications in the construction sector are few compared to other industry sectors. In many cases, these are limited to the structural engineering domain. There is much potential for the application of fuzzy systems in construction, and there are opportunities particularly in collaborative decision-making. The next chapter explores the potential for the application of fuzzy systems to collaborative decision-making in construction.

CHAPTER 4

CONCEPTUAL MODEL OF THE PROTOTYPE SYSTEM

4.1 INTRODUCTION

The focus of this chapter is the underlying conceptual model behind the development of a prototype decision-making system for collaborative project teams. This is presented after a discussion of the reason for the use of fuzzy set theory in collaborative decision-making. Different current approaches are also introduced briefly and analysed. The fundamental principles of concurrent engineering and group decision-making are taken into account as the basis of the system while fuzzy sets theory is applied to address the uncertainties and imprecision during the decision-making process discussed in the earlier chapters. The representation of the model is done using a paper-based example.

4.2 FUZZY SET THEORY IN COLLABORATIVE DECISION MAKING

4.2.1 Why Use Fuzzy Set Theory in Collaborative Decision Making?

As stated previously, more and more decisions in construction project teams are made in a collaborative environment, based on an integration of all team members' views. The diversity of the team members' views, which often have independent and conflicting objectives with inherent technical, political, or budgetary constraints, introduces a high level of complexity to the decision-making process. The disparate priorities of different disciplines are usually expressed in fuzzy linguistic terms, which cannot be quantified with traditional methods. Most of the existing group decision-making methods are based on crisp concepts that are weak in handling imprecise and vague information. This was confirmed by the pilot survey undertaken at the early stages of this research project, which showed that:

- There exist many conflicts between different professionals during collaborative decision-making process in the construction industry;
- Most of the survey respondents are often involved in group decision-making and collaborate with other disciplines at the various stages of a construction project;
- Few of the survey respondents use any tools/techniques to support the decision-making process. The vast majority do not use IT in their decision-making processes;
- In project decision-making, the contributions from all disciplines are not equally weighted. There is a lack of appropriate mechanisms for aggregating the views of decision makers, taking adequate account of the relative importance of the decision makers in relation to the specific decision issue being addressed.
- There is a lack of effective techniques to cope with the disharmony and uncertainties in the views of the project team participants. In particular, there is inadequate support for distributed team members and for the use of linguistic variables to express preferences;
- The sometimes unhealthy influence of the personalities of the particular individuals contributing to a decision;
- Decision-making in situations where the decision alternatives and the associated decision criteria and considerations are ill-defined;

A blank questionnaire for the pilot industry survey is attached in Appendix 2.

According to Pena-Mora et al (1996), fuzziness is a measure of how well an instance (value) conforms to a semantic ideal or concept. Fuzzy sets are actually functions that map a value that might be a member of the set to a number between zero (value is not in the set) and one (value completely representative of the set) indicating its actual degree of membership. Accordingly fuzzy set theory can be applied, in a decision-making tool that is applicable to a variety of decision-making scenarios, to handle fuzziness and imprecision in the evaluation of decision alternatives.

4.2.2 Existing Approaches

Table 4.1 lists the key features of 3 representatives of the major trends in applying fuzzy set theory (FST) to collaborative decision-making (CDM).

Table 4.1 Approaches using FST in CDM

Characteristics	Aspiration & Reservation Level Method	Non-Numeric Method	Linguistic Quantifier Method
Propose	Vlacic et al (1997), to support group decision-making relating to industrial automation	Yager (1993), for multi-criteria group decision-making	Kacprzyk et al (1992), to show how linguistic quantified propositions can be used in group decision-making
Core Features	• Assume that decision makers are accustomed to thinking in terms of desirable or acceptable values of various performance measures • Rationalise criteria using FSM (see 4.5.3.2) • Decision makers specify their aspiration levels and reservation levels for each criterion • 'Dominant weighting factors' are defined to score criteria • Use a parameter to express the achievement of the object value of an option for a certain criterion • Combine rankings using 'the fuzzy Choquet Integral' method	• Each decision maker evaluates each option on each criterion and assign importance measure to each criterion in linguistic scales • The scales are essentially a linear ordering • Taking the negation on the linear scales • The method to find the unit score of each option only involves max, min, and negation • In the technique for combining the whole group's evaluation, it is assumed that each decision maker has the same importance • The technique is based on ordered weighted averaging (OWA) (Yager, 1988)	• The fuzzy linguistic quantifiers represent a fuzzy majority • The linguistic quantified proposition is used to state a truth • The fuzzy set 'Property' is used to represent the degree of a truth, especially for each member in whole group • The fuzzy preference relation between team members are given by membership function • 'The core' method is used to find the options that not defeated in pair-wise comparisons by a required majority
Advantages	Suitable for decision environment where there are commonly a number of objectives that have 'objective values'. This method can trade off the values of the objective functions.	Allows for the requisite aggregations and avoids numeric operations	Relatively natural at presenting the degrees of consensus within a group by the use of fuzzy majority
Disadvantages	• The assumption is not always practical. • Too much numeric parameters, definitions, and input operations • It often happens that the 'objective value' s are unknown.	• Relations between the linguistic scales that human beings reasonably manage are more complex than simple linear order • Only involving max, min, and negation operation would ignore the effect of intermediate values • In practice, decision team members are not always equally weighted	• This method does not concern any multi-criteria issues in group decision-making • No efforts made to deal with the different importance of decision team members

The proposed model that is presented below intends to overcome the disadvantages of the existing approaches listed above. It has made a particular effort to tackle the different weightings of decision team member issue and aims to deal with multiple criteria. The model also utilises linguistic variables, and linguistic modifiers to make the ranking scores closer to reality. The membership function operation in the model attempts to avoid too complex numeric calculations but maintains reasonable precision in characterising and aggregating results. The Fuzzy numeric addition and multiplication operation conducted in the model employs α-cut, extension principle etc fuzzy set theory fundamentals, rather than pure linear comparison.

To rationalise the raw criteria generated by the decision team members, the FSM method employed in the 'Aspiration & Reservation Level Method' in Table 4.1 is adopted. The model has also adapted and developed some ideas from the application of fuzzy sets theory explored by Novak (1989), which is described in more detail in Section 4.5.4 and Section 4.5.5.

4.3 ASSUMPTIONS IN DEVELOPING THE MODEL

In the development of the collaborative decision-making model, it was assumed that:

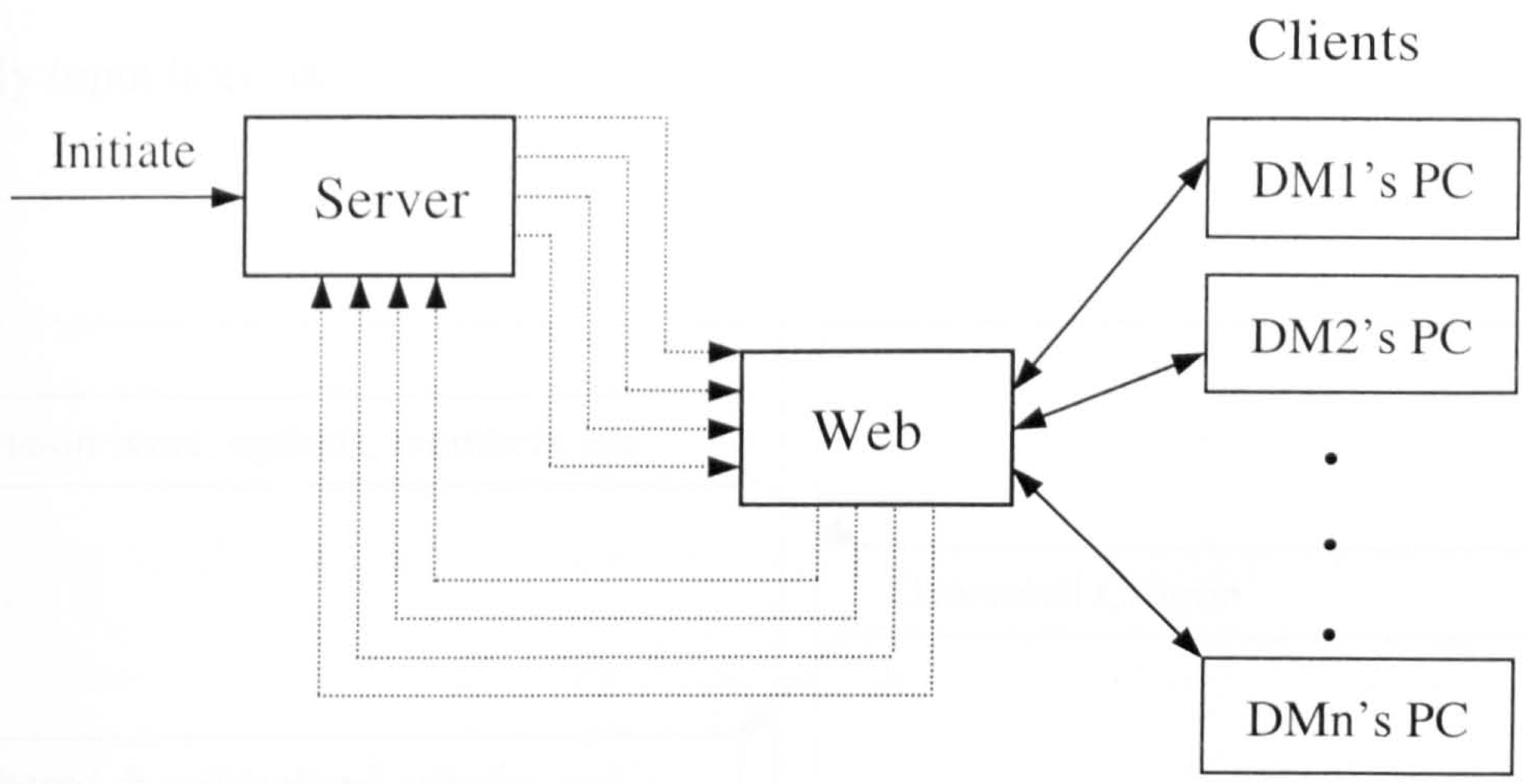
1. There is a chairman, who is in charge of organising the decision-making process, in a collaborative project team. This person is probably the project manager and he/she himself/herself does not participate the decision-making. In the context in this chapter, 'chairman' is used to refer to this person.
2. Before decision-making starts, the decision options have been defined and the team members have had full details of these options.
3. The chairman knows who is supposed to take part in the decision-making.

The overall architecture of the prototype system is presented below. This is the final version, which builds on the two earlier versions described in Yang and Anumba (1999); and Yang and Anumba (2000).

4.4 OVERALL ARCHITECTURE OF THE SYSTEM

Fig. 4.1 shows the general structure of the proposed collaborative decision-making system, which is composed of two major parts: project server part and project client part. The project server is run on the computer of the chairman assumed earlier and it is developed as Java application system later on. The client part is operated on project team members' PCs or wherever the Internet is available. The Web links the two parts together. The whole decision-making process is initiated on the server side by the chairman, who has the initiating form to complete. The data saved in the server after the initiating form has been completed then starts the client system. The project team members can access the client system via the Web, get the necessary information, and then submit their inputs to the server via the Web. The data transportation from the server to the client system takes place four times during the whole decision-making process. But the data transportation from the client system to the server happens $4 \times n$ times if there are n members in the decision-making team.

In terms of what sorts of data are transported, Fig. 4.2 gives a flowchart, in which 'decision issue, options, members, etc' is identified in the 'initiating form' mentioned above. To generate and transport other data in the flowchart, a number of steps need to be followed. These are described in detail below.



Note: DM=Decision Maker

Fig. 4.1 The Architecture of the Proposed Model

4.5 COLLABORATIVE DECISION MAKING STEPS

To demonstrate the proposed system's working process, a practical decision-making scenario could be like this: m decision makers need to determine a preferred one out of n alternatives that are rated in the light of r criteria. Let

Decision makers $d_i \in D$ (i=1, 2, …, m)

Alternatives $s_k \in S$ (k=1, 2, …, n)

Criteria $t_j \in T$ (j=1, 2, …, r)

Where D, S, T is the sets of decision makers, alternatives, and criteria respectively.

4.5.1 Identify Decision Options

Besides the decision issue and decision options, the user of the server part of the system (the chairman) also needs to provide other information such as project title, project location, decision-making start date and a list of potential decision makers' roles in the project team. The individual participants will confirm this when they supply input later on.

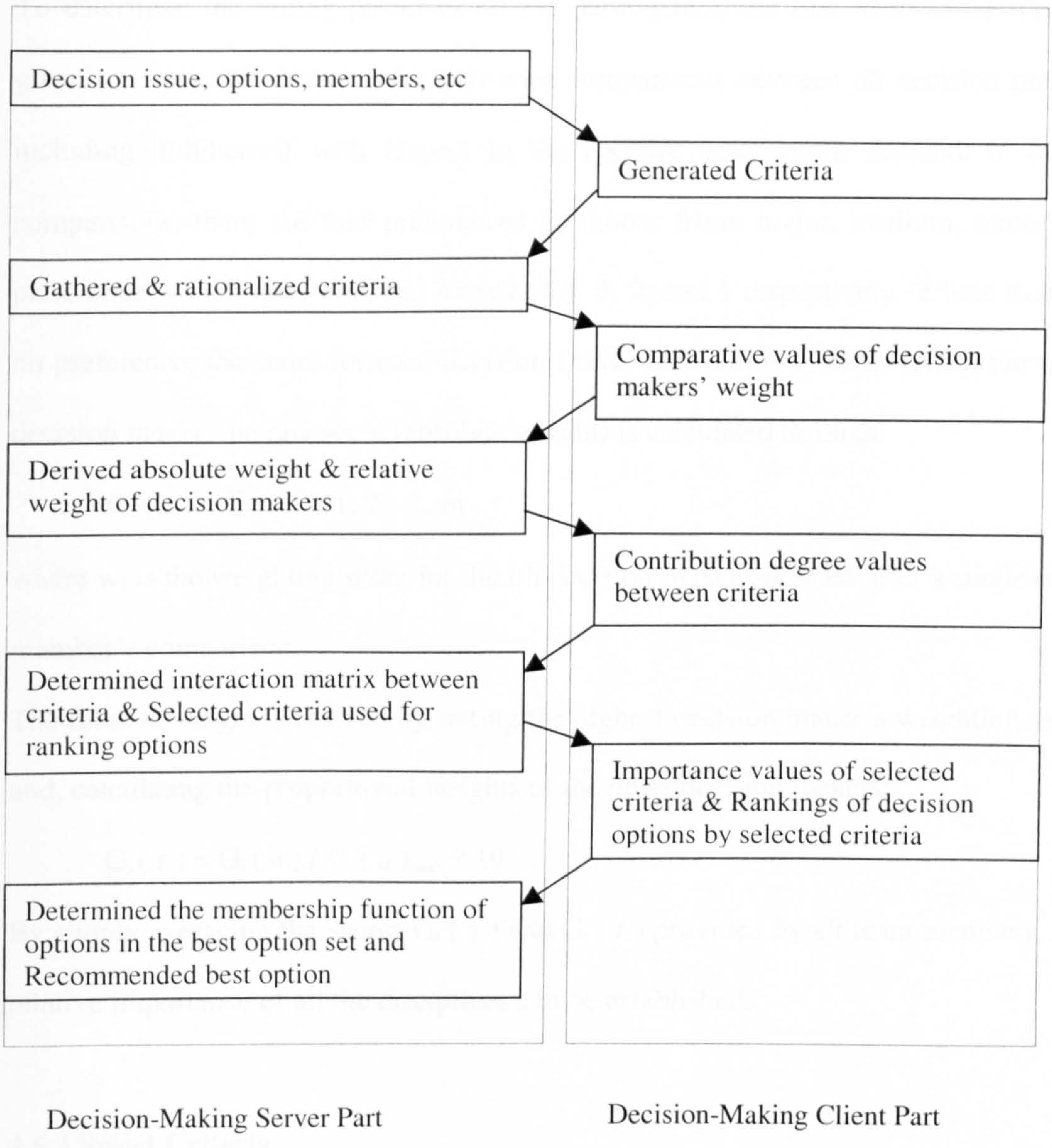


Fig. 4.2 The Data Transportation between the Server and Client System

4.5.2 Assign Weights to Decision Makers

The members of a project team are usually from various disciplines with either equal or different weightings, which depend on status, and relevance of the decision issue to each member's discipline/work. 'Weights' G_i (where i=1, 2,..., m) are used to specify the weightings of team members.

To determine the voting power of all the participants, the first Web-based form is given to every member to make pair-wise comparisons between all decision makers including him/herself with respect to the specific issue being decided. In rating comparisons, there are four preferences to choose from: major, medium, minor, no preference, which have assigned scores of 4, 3, 2, and 1 respectively. Where there is no preference, the score for each decision maker is taken as 1 (ICE, 1996). For each decision maker, the raw score (absolute weight) is calculated through:

$$G_i(a) = \sum w_i \quad i=1, 2, \ldots, m$$

where w_i is the weighting score for the *i*th decision maker obtained after a single team member's comparison.

The relative weight is derived by setting the highest decision maker's weighting as 10 and, calculating the proportional weights of the other decision makers:

$$G_i(r) = G_i(a) / G_i(a)_{max} * 10$$

By simply averaging the scores $G_i(a)$ and $G_i(r)$ provided by all team members, the relative importance of all the disciplines can be established.

4.5.3 Select Criteria

4.5.3.1 Generate and Gather Criteria

Decision makers give three top criteria that they consider necessary from their own perspective. After all the team members have submitted the Web-based form for specifying criteria, the server system collects all the inputs. Some criteria may have the same meaning but expressed differently. Thus the chairman needs to rationalise the list of criteria to avoid duplication. The number of raw criteria will vary depending on the specific situation. In order to reduce the complexity of criteria and find which ones to use in evaluating the alternatives, the system rationalises the criteria using a part of the Fuzzy Structural Modelling (FSM) method (Amagasa & Vlacic, 1993). This is described below.

4.5.3.2 Rationalise Criteria

Two groups of data shown in Fig. 4.2 are obtained through 'rationalise criteria': 'Contribution degree values between criteria' and 'determined interaction matrix between criteria & selected criteria used for ranking options'.

Step 1: In order to facilitate the construction of the hierarchical structure of criteria, a matrix F_i (i=1, 2, ..., m) is formulated by describing the relationships between criteria using fuzzy binary relations as follows:

$$F_i=\begin{bmatrix} f_{11} & f_{12} & \cdots & f_{1j} & \cdots & f_{1n} \\ f_{21} & f_{22} & \cdots & f_{2j} & \cdots & f_{2n} \\ \vdots & \vdots & & \vdots & & \vdots \\ f_{i1} & f_{i2} & \cdots & f_{ij} & \cdots & f_{in} \\ \vdots & \vdots & & \vdots & & \vdots \\ f_{n1} & f_{n2} & \cdots & f_{nl} & \cdots & f_{nn} \end{bmatrix}$$

Where the f_{ij} shows to what degree the criterion t_j contributes to criterion t_i, and $0 \leq f_{ij} \leq 1$. For describing the degree to which one criterion contributes to another, four linguistic scores are given to the team members: 'completely contributes', 'contributes very much', 'contributes a little', and 'no contribution'. The corresponding numeric gradings are 1, 0.7, 0.4, and 0 respectively. Some intermediate marks between the four grades can also be used according to the decision makers' judgements. Since the team meeting is 'virtual', the matrix elements are determined by weighted averaging of all the members' contribution:

$$f_{ij} = \frac{\sum_{(i)=1}^{m} f_{ij(i)} \cdot G_{(i)}(a)}{\sum_{(i)=1}^{m} G_{(i)}(a)}$$

Where $f_{ij(i)}$ represents the value of the element f_{ij} given by the ith decision maker, and $G_{(i)}(a)$ is the absolute weight of the ith decision maker.

Step 2: Modify F_i so as to satisfy the fuzzy irreflexive law, the fuzzy asymmetric law and the fuzzy semi-transitive laws. A threshold parameter p is introduced to determine the relationship 'whether or not the criterion contributes to another one'. This is called the structure parameter, which assures the flexibility of the system structure. The p must be a real number and be given on the semi-open interval (0, 1]. The complexity of the system structure depends on the value of p. If p increases, the number of relationships between criteria will decrease, until the system structure becomes a simple one. It is suggested to give the value $p \in [0.3, 0.5]$ after practical applications of the algorithm (Tazaki & Amagasa, 1979, Amagasa & Vlacic, 1993, Vlacic et al, 1997). In this system, the value of p is determined to be 0.4. The p determines if a criterion is qualified to be one of the major factors used to evaluate the decision options. The criteria contributing more than p to others, and to which others contribute less than p will qualify. Also, the criteria contributing less than p to others and to which others contribute less than p will be selected. The reason is explained in Step 3.

Step 3: Determine the group level of the criteria. The criteria are grouped under 4 level sets: the top level set L_t, the intermediate level set L_i, the bottom level set L_b and the isolated level set L_{is}. These level sets are respectively defined as follows:

$$L_t=\{t_i \mid \bigvee_{j=1}^{n} f_{ji} < p \leq \bigvee_{j=1}^{n} f_{ij}\}$$

$$L_b=\{t_i \mid \bigvee_{j=1}^{n} f_{ij} < p \leq \bigvee_{j=1}^{n} f_{ji}\}$$

$$L_i=\{t_i \mid \bigvee_{j=1}^{n} f_{ij} \geq p,\ \bigvee_{j=1}^{n} f_{ji} \geq p\}$$

$$L_{is}=\{t_i \mid \bigvee_{j=1}^{n} f_{ij} < p,\ \bigvee_{j=1}^{n} f_{ji} < p\}$$

Where $\vee$ represents 'maximum'. Each element of the top level set is not subordinate to anyone but has someone subordinated to itself. Each element of the intermediate level set is subordinate to anyone and has someone subordinated to itself. Each element of the bottom level set is subordinate to someone but has nothing subordinated to itself. Each element of the isolation level set is not subordinate to anyone, and has nothing subordinated to itself. If a criterion were subordinate to another, it would also be considered/included to a certain degree when another is used to rank decision options. This degree is determined by the p value. Thus the criteria classified in the intermediate level set and the bottom level set would not be grouped with the major factors in evaluating the decision options. However, the criteria in L_t and L_{is} are not subordinate to anyone and they should be considered to be the major factors.

4.5.4 Assign Importance to Selected Criteria and Rank Options by Them

The criteria selected through the last step are given importance values and the decision options are ranked in terms of each of these criteria, both in fuzzy linguistic expressions.

4.5.4.1 Assign a Measure of Importance to Each of the Criteria.

Decision makers are required to rate the importance of the criteria that are used in evaluating the alternatives using natural linguistic expressions. Five linguistic scores are given for the ranking: 'highly important', 'very important', 'important', 'not very important', and 'low importance'. With the linguistic variable definitions stated in Section 3.2, if

M(important)= $\bigcup_{x=0}^{1} x/x$, then

M(highly important)= $\bigcup_{x=0}^{1} x^3/x$

M(very important)= $\bigcup_{x=0}^{1} x^2/x$,

M(not very important) = M(less importance)= $\bigcup_{x=0}^{1}(2x-x^2)/x$

M(low importance) = M(roughly unimportant)

$$= \bigcup_{x=0}^{1}(-x^4+4x^3-6x^2+4x)/x$$

This step allows decision makers to minimise the influence of criteria that they did not consider important, by assigning them a low weighting.

4.5.4.2 Rank Options by Selected Criteria

This step is included in the last Web-based form for team members. The form is intended to enable each selected criterion to be used in evaluating each decision option, in effect answering the question "how good is the option on this criterion?" — An answer may be selected from the following linguistic rankings: Excellent (E), Very Good (VG), Good (G), Neutral (N), Poor (P), Very Poor (VP), and Unacceptable (U). Based on the fundamental theories reviewed in Chapter 3, if

M(good) = $\bigcup_{x=0.5}^{1}(2x-1)/x$, then

$$M(\text{very good}) = \bigcup_{x=0.5}^{1} (2x-1)^2 / x$$

$$M(\text{excellent}) = M(\text{very very good}) = \bigcup_{x=0.5}^{1} (2x-1)^3 / x$$

$$M(\text{neutral}) = M(\text{less good})$$

$$= \bigcup_{x=0.5}^{1} (2(2x-1)-(2x-1)^2)/x = \bigcup_{x=0.5}^{1} (-4x^2+8x-3)/x$$

$$M(\text{poor}) = M(\text{not good}) = \bigcup_{x=0.5}^{1} (1-(2x-1))/x = \bigcup_{x=0.5}^{1} (2-2x)/x$$

$$M(\text{very poor}) = M(\text{roughly poor}) = \bigcup_{x=0.5}^{1} (2-2x)^2 / x$$

$$M(\text{unacceptable}) = M(\text{rather poor}) = \bigcup_{x=0.5}^{1} (2-2x)^4 / x$$

4.5.5 Determine the Fuzzy Set of the Best Options by Each Decision Maker

This involves the calculation of utility function and the multiplication and addition of fuzzy numbers, using the method of α-cut and extension principle.

As defined earlier, a linguistic variable is characterised by a quintuple (see Section 3.2.2.1). Given

- Linguistic variable $\langle$ *score*, $\mathcal{T}$(*score*), $\langle 0, 1 \rangle$, G, M_G $\rangle$,
- Linguistic variable $\langle$*importance*, $\mathcal{T}$(*importance*), $\langle 0, 1 \rangle$, G, $M_G$$\rangle$,
- The set of alternatives $S = \{s_k; k=1, 2, \ldots, n\}$ and
- Criteria $t_1, \ldots, t_r$.

the scores of an alternative s_k from the criterion t_j ($j=1, \ldots, r$) is judged using a linguistic expression $R_{kj} \in \mathcal{T}(score)$ with the meaning $M(R_{kj}) \subseteq \langle 0, 1 \rangle$. The weight of the criterion t_j is judged using a linguistic expression $w_j \in \mathcal{T}(importance)$ with the meaning $M(w_j) \subset \langle 0, 1 \rangle$. Then the total utility is a fuzzy set

$$Z_k = \sum_{j=1}^{r} M(w_j) \cdot M(R_{kj})$$

Where the sum and the product of fuzzy sets are computed using the extension principle mentioned in the earlier chapter (Section 3.2.3.3),

$$A \cdot B = \bigcup_{\alpha=0}^{1} \alpha.(A \cdot B)_\alpha = \bigcup_{\alpha=0}^{1} \alpha.(A_\alpha \cdot B_\alpha)$$

$$A+B = \bigcup_{\alpha=0}^{1} \alpha.(A + B)_\alpha = \bigcup_{\alpha=0}^{1} \alpha.(A_\alpha + B_\alpha)$$

To complete the computation, there are four steps to be carried out:

- Divide A and B into increasing parts A_L, B_L, constant parts A_C, B_C (if they exist), and decreasing parts A_R, B_R.
- Choose 6 points $\omega_0 = 0, \omega_1, \ldots, \omega_5 = 1$ in the interval $\langle 0, 1 \rangle$ and construct a discrete representation for each part of A and B, e.g.

  $A_L = \{\omega_1/x_1^L, \ldots, 1/x_n^L\}$,

  $A_R = \{1/x_1^R, \ldots, 0/x_n^R\}$
- Compute $C_L = A_L * B_L$, $C_C = A_C * B_C$, $C_R = A_R * B_R$,

  $C_{LC} = A_L * B_C$, $C_{CL} = A_C * B_L$, $C_{RC} = A_R * B_C$, and $C_{CR} = A_C * B_R$ as follows:

  $C_L = \{\omega_1 / (x_1^L * y_1^L), \omega_2 / (x_2^L * y_2^L), \ldots, 1 / (x_n^L * y_n^L)\}$

  Where $x_i^L \in$ Supp (A_L) and $y_i^L \in$ Supp (B) and so on, '$*$' denotes the operations of addition or multiplication.
- Compute $C = C_L \cup C_C \cup C_R \cup C_{LC} \cup C_{CL} \cup C_{RC} \cup C_{CR}$

The operation method introduced in Section 3.2.3.3 is applied for the third step. There is a need for an extended explanation of the procedure for addition operation since it is more complex to add up non-decreasing set and non-increasing set, which were introduced by Prade & Dubois (1979). They further stated that the constant 'part' between two non-decreasing ones belongs to the non-decreasing set. The constant 'part', which is between 'parts' of different kinds, belongs to both. An example is given here to illustrate how to unionise the two parts.

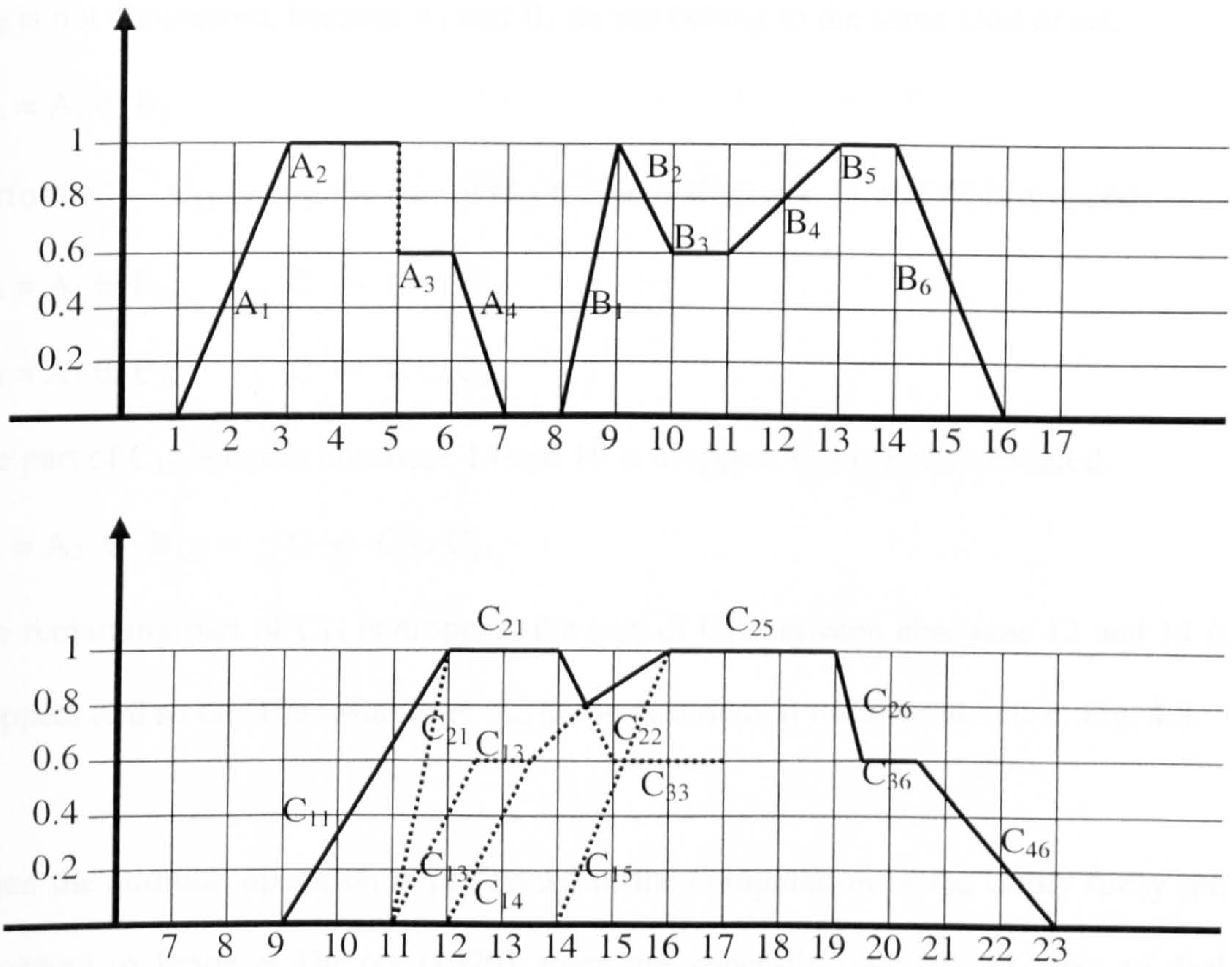


Fig. 4.3 Addition Operation Procedure of Two Fuzzy Numbers (Prade & Dubois, 1979)

Consider the two fuzzy numbers A and B pictured on Fig. 4.3, the calculation of C = A ⊕ B, where ⊕ denotes the extended sum, is described as follow:

First of all, defining non-decreasing set and non-increasing set.

A: non-decreasing set $\{A_1, A_2, A_3\}$

non-increasing set $\{A_2, A_3, A_4\}$

B: non-decreasing set $\{B_1, B_3, B_4, B_5\}$

non-increasing set $\{B_2, B_3, B_5, B_6\}$

C_{ij} denotes $A_i \oplus B_i$, the C_{ij}'s will be calculated in lexicographic order:

$C_{11} = A_1 \oplus B_1$; $C \leftarrow C_{11}$

C_{12} is not considered, because A_1 and B_2 do not belong to the same kind of set.

$C_{13} = A_1 \oplus B_3$

Perform $C \leftarrow C_{11} \cup C_{13}$, the part of C_{13} between abscissae 11 and 12 is dropped.

$C_{14} = A_1 \oplus B_4$; $C \leftarrow C \cup C_{14}$

$C_{15} = A_1 \oplus B_5$; $C \leftarrow C \cup C_{15}$

The part of C_{15} between abscissae 14 and 16 is dropped. C_{16} is not considered.

$C_{21} = A_2 \oplus B_1$; $C \leftarrow C \cup C_{21}$.

The remaining part of C_{13} is dropped, the part of C_{14} between abscissae 12 and 14 is dropped, and so on. The result after the union is shown in the second half in Fig. 4.3.

When the addition operation is performed in the computation of the utility fuzzy set, according to Prade & Dubois (1979), there are generally four typical cases to deal with. The other cases can usually be converted to these four. Transform the fuzzy set

$Z_k = \sum_{j=1}^{r} M(w_j) \cdot M(R_{kj})$ into

$Z_{k.1} = M(w_1) \cdot M(R_{k1}), Z_{k.2} = M(w_2) \cdot M(R_{k2}), \ldots,$

$Z_{k.(j-1)} = M(w_{j-1}) \cdot M(R_{k(j-1)}), Z_{k.j} = M(w_j) \cdot M(R_{kj}), \ldots, Z_{k.r} = M(w_r) \cdot M(R_{kr}),$

Then the four cases are:

1. When both $Z_{k.(j-1)}$ and $Z_{k.j}$ are single 'non-decreasing part's (or vice versa), their addition result looks like Fig.4.4 (the values on abscissae are assumed, same below)

2. When $Z_{k.(j-1)}$ is single increasing and $Z_{k.j}$ is non-increasing, their addition result looks like Fig.4.5.
3. When $Z_{k.(j-1)}$ has all the three parts – increasing, flat, decreasing, $Z_{k.j}$ is single increasing, their addition result looks like Fig. 4.6.
4. When $Z_{k.(j-1)}$ has all the three parts – increasing, flat, decreasing, $Z_{k.j}$ is non-increasing, their addition result looks like Fig. 4.7.

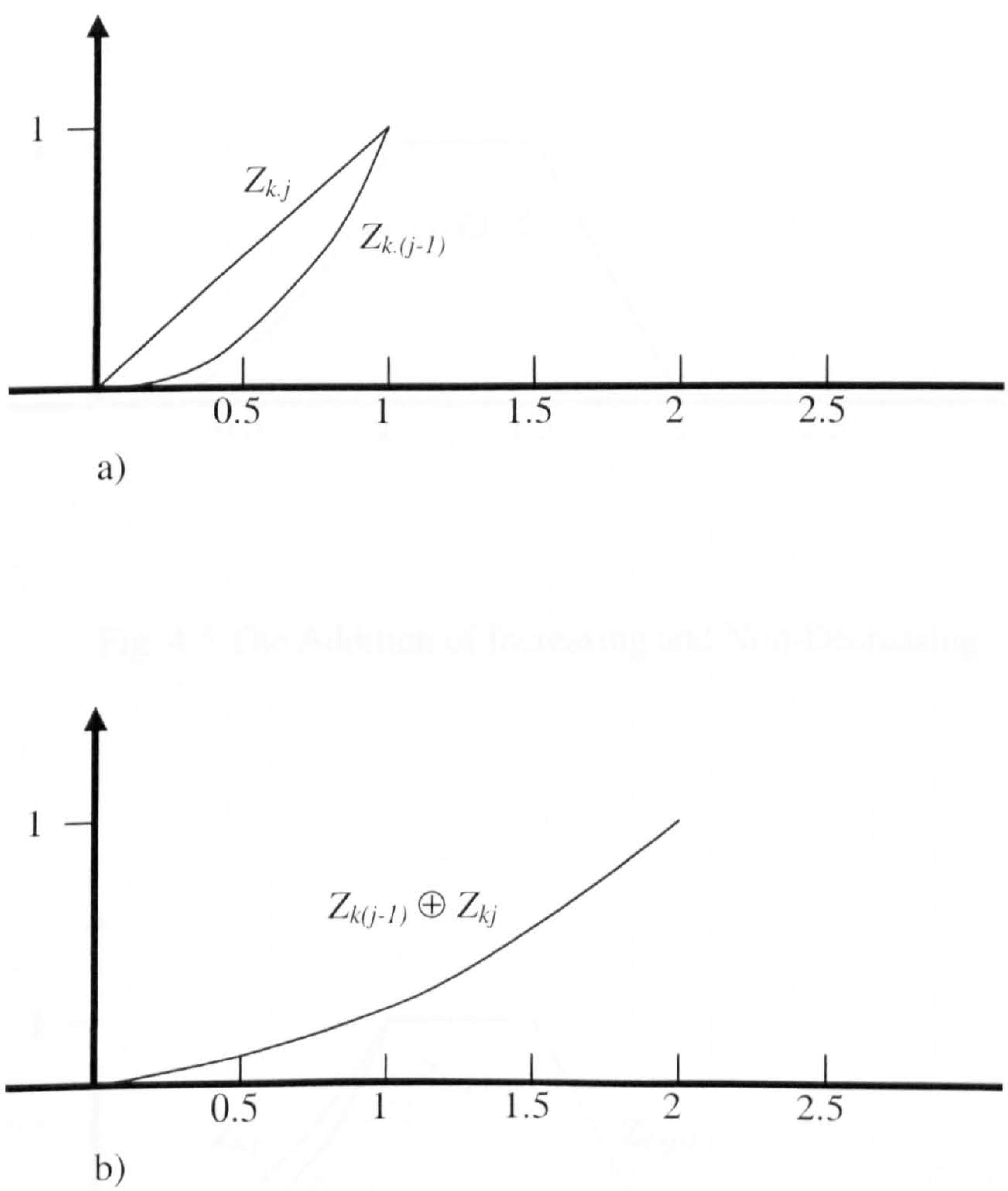
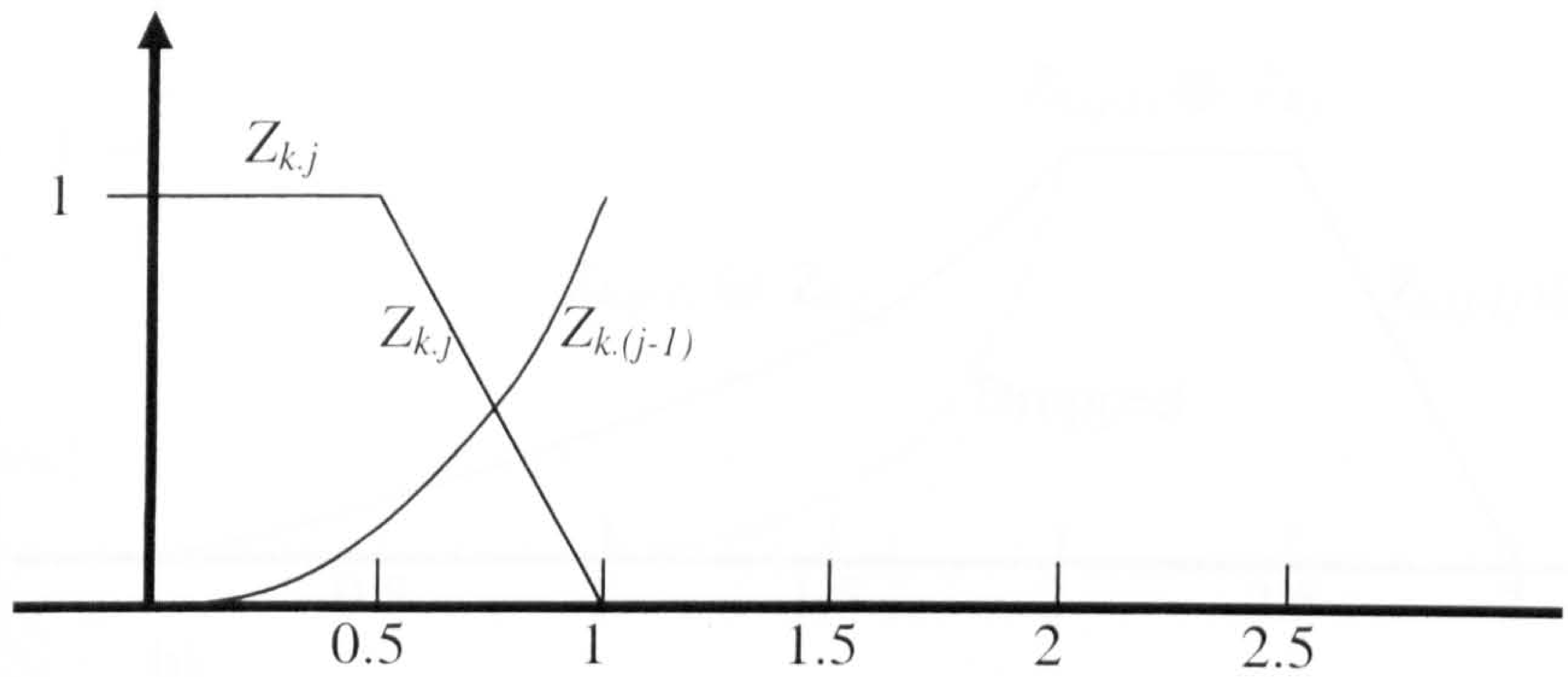
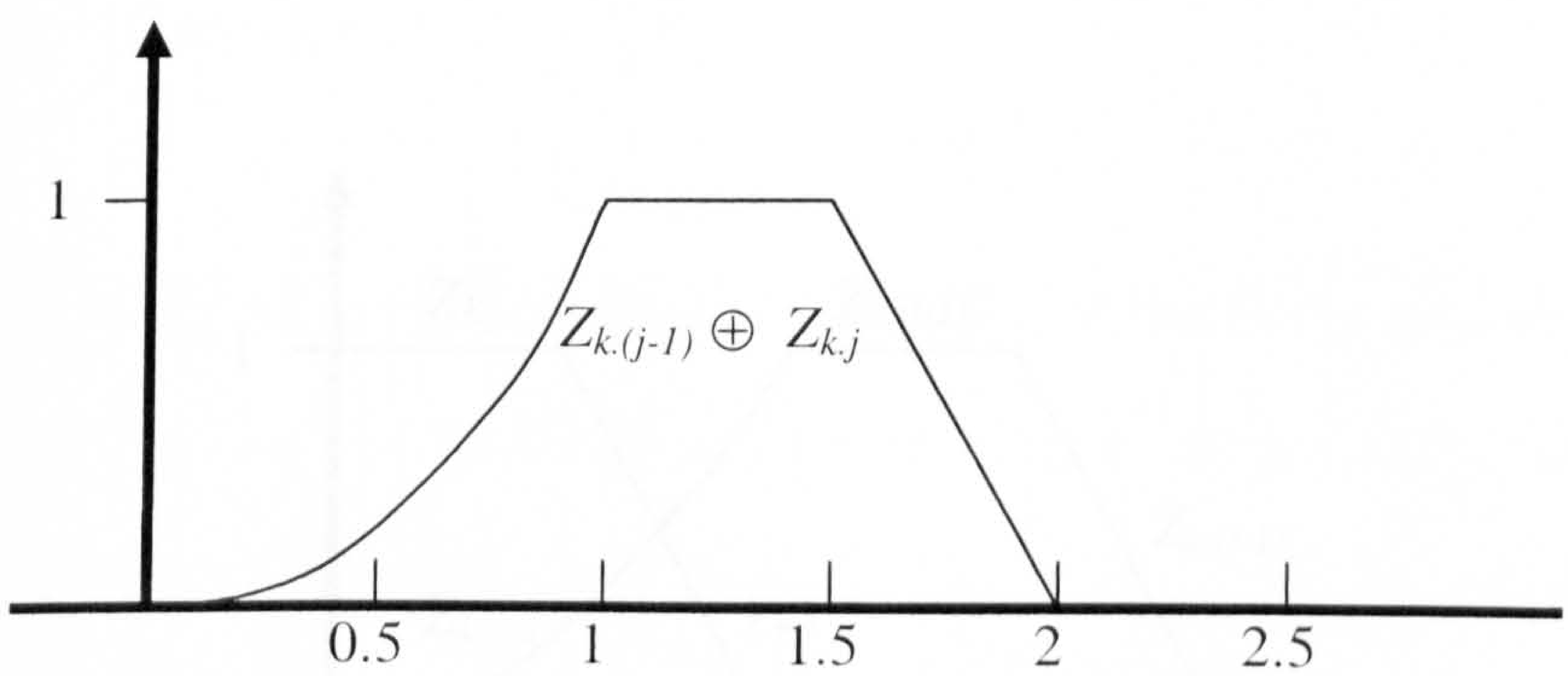


Fig.4.4 The Addition of Two Single Non-Decreasing Parts

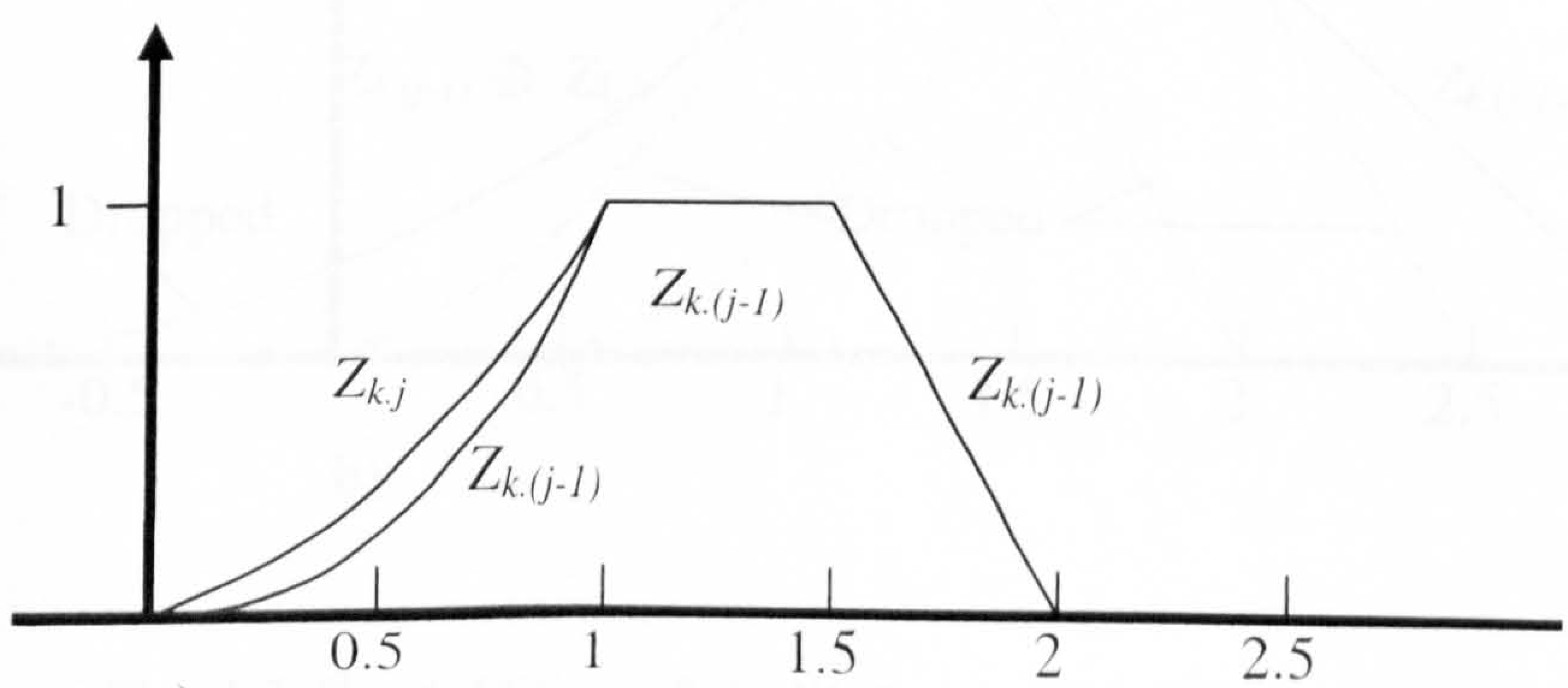


a)



b)

Fig. 4.5 The Addition of Increasing and Non-Decreasing



a)

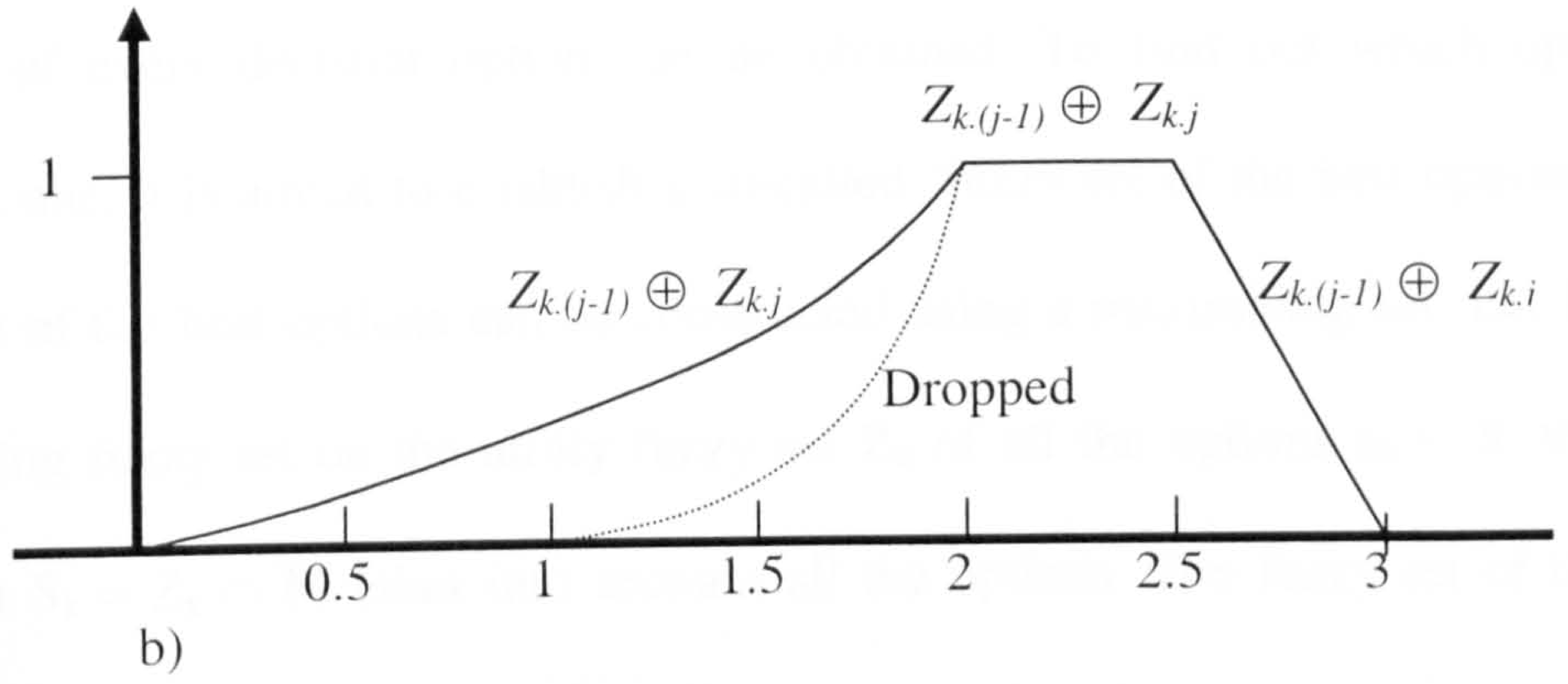


Fig. 4.6 the Addition of 'Full' Part and Increasing Part

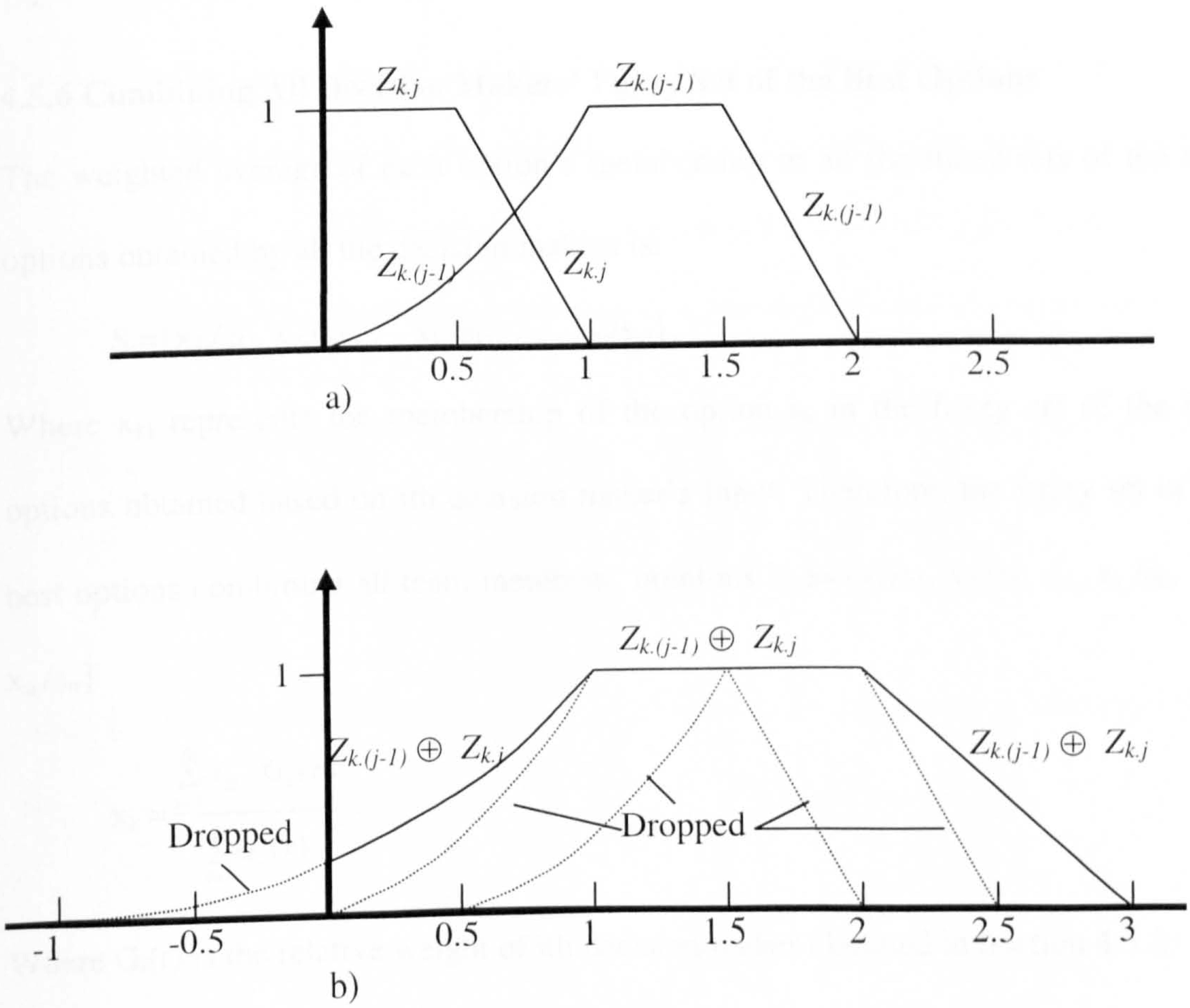


Fig. 4.7 The Addition of 'Full' Part and Non-Increasing Part

After the above calculation on extended product and sum, the fuzzy set of the utility function of every decision option can be obtained. To find out which option is preferred one, it is aimed to establish a so-called 'fuzzy set of the best options'. The fuzzy set of the best options can be constructed using a maximising set. Let M be a maximising fuzzy set on the utility fuzzy set Z_k of all the options $s_k \in S$, then the fuzzy set $S_k = Z_k \cap M$ takes into account all the options. The fuzzy set of the best option is given by the membership function

$$Ss_k = Hgt\,(S_k)$$

for each $s_k \in S$ and Z_k.

4.5.6 Combining All Decision Makers' Fuzzy Set of the Best Options

The weighted average of each option's membership in all the fuzzy sets of the best options obtained by all the decision makers is:

$$S_i = \{x_{1i}/s_{1i}, x_{2i}/s_{2i}, \ldots x_{ki}/s_{ki}, \ldots, x_{ni}/s_{ni}\},$$

Where x_{ki} represents the membership of the option s_k in the fuzzy set of the best options obtained based on ith decision maker's input. Therefore, the fuzzy set of the best options combining all team members' opinions is $S=\{x_i/s_1, x_2/s_2, \ldots, x_k/s_k, \ldots, x_n/s_n\}$

$$x_k = \frac{\sum_{i=1}^{m} x_{ki} \cdot G_i(r)}{\sum_{i=1}^{m} G_i(r)}$$

Where $G_i(r)$ is the relative weight of ith decision maker obtained in Section 4.5.2.

Thus far, the collaborative decision making system has obtained a comparative evaluation of all the decision options and is now in a position to recommend the preferred decision option.

4.6 Example of How the Model Works

An example of how the model can be used in practice is now presented. The decision-making issue is to select a suitable window for a wall. The scenario is that there are four decision makers (Client, Architect, Building Services Engineer, Structural Engineer) who need to determine a preferred option out of 3 alternatives.

Tables 4.2 - 4.5 give the weights of decision makers assigned by every team member using pair-wise comparisons. Take Table 4.2 as an example, decision maker A is considered to be of minor preference to decision maker B, the comparison between A and B is given as A-2 in column B. Where there is no preference the score is written down in a letter-letter format (e.g. A-D in column D), and each letter is allocated a score of 1. Table 4.6 shows the weighting scores of the decision makers, including their raw scores and relative scores. The decision makers: client, architect, building service engineer, and structural engineer are denoted A, B, C, and D respectively.

Table 4.2 Weights comparison (by A)

	B	C	D
A	A-2	A-3	A-D
	B	B-C	B-D
		C	C-D

Table 4.3 Weights comparison (by B)

	B	C	D
A	B-2	A-C	A-D
	B	B-3	B-2
		C	C-D

Table 4.4 Weights comparison (by C)

	B	C	D
A	A-2	A-C	A-D
	B	C-2	B-D
		C	C-D

Table 4.5 Weights comparison (by D)

	B	C	D
A	A-B	A-2	D-2
	B	B-C	D-2
		C	D-2

Table 4.6 The weighted scores of the decision makers

	Weighting Scores			
Decision Makers	Client	Architect	BS Engineer	Str. Engineer
Client	6	2	2	3
Architect	2	7	2	2
BS Engineer	4	1	4	3
Str. Engineer	3	2	1	6
Total or $G_i(a)$	15	12	9	14
Relative weight $G_i(r)$	10	8	6	9.3

By collecting the four decision makers' submissions, the following 12 criteria for selecting the best window alternative are identified:

t_1: Energy conservation

t_2: Appearance

t_3: Entry of light

t_4: Easy to open and close

t_5: Can withstand vandalism

t_6: Initial cost

t_7: Maintenance cost

t_8: Easy to obtain material for window

t_9: Fire resistant

t_{10}: Effect on structural stability of wall

t_{11}: Effect on neighbours-reflection of light away from the house

t_{12}: Maintaining privacy of occupants

For rationalising these criteria, the matrix shown in Table 4.7 is constructed to express the degree to which one criterion contributes to another. Considering the general case of the decision-making in the construction industry, the threshold parameter 'p' is assigned a value of 0.4, which is the middle value of the suggested in Section 4.5.3.2, then the level sets are determined as follows:

$L_t=\{t_1, t_2, t_4, t_6, t_{10}\}$,

$L_b=\{t_3, t_8\}$,

$L_i=\{t_5, t_7, t_9, t_{11}, t_{12}\}$,

$L_{is}=\phi$

Tables 4.8 - 4.11 are the selected criteria's importance and the ranking scores of the 3 alternatives on the selected criteria, both in linguistic terms. The abbreviations in the forms are as follows:

E: Excellent; VG: Very Good; G: Good; N: Neutral; P: Poor; VP: Very poor; U: Unacceptable.

Table 4.7 Matrix F_i describing the relationship between criteria

	t_1	t_2	t_3	t_4	t_5	t_6	t_7	t_8	t_9	t_{10}	t_{11}	t_{12}
t_1	0	0.2	0.6	0	0	0	0.6	0	0	0	0	0
t_2	0	0	0.4	0	0	0.3	0.6	0	0	0	0.5	0.5
t_3	0	0	0	0	0	0	0	0	0	0	0	0
t_4	0	0	0	0	0	0	0.5	0	0	0	0	0
t_5	0	0	0	0	0	0	0.8	0	0	0	0	0
t_6	0	0	0	0	0.6	0	0	0.7	0.3	0	0	0
t_7	0.3	0	0	0	0.5	0	0	0.4	0.4	0	0	0
t_8	0	0	0	0	0	0	0	0	0	0	0	0
t_9	0	0	0	0	0	0	0.4	0.4	0	0	0	0
t_{10}	0	0	0	0.3	0.3	0	0.4	0	0	0	0	0
t_{11}	0	0	0.5	0	0	0	0	0	0	0	0	0
t_{12}	0	0	0.6	0	0	0	0	0	0	0	0	0

Table 4.8 Ranking of Criteria and Decision Options (by: Client)

		Options ranking scores		
Criteria	Importance	Option 1	Option 2	Option 3
t_1	VI	VG	G	P
t_2	I	G	N	VG
t_4	I	P	G	N
t_6	HI	VP	G	G
t_{10}	VI	VG	G	P

Table 4.9 Ranking of Criteria and Decision Options (by: Architect)

		Options ranking scores		
Criteria	Importance	Option 1	Option 2	Option 3
t_1	NVI	G	N	N
t_2	HI	N	VG	P
t_4	NVI	E	G	N
t_6	NVI	G	G	VP
t_{10}	I	VP	G	G

Table 4.10 Ranking of Criteria and Decision Options (by: BS.Engineer)

		Option ranking scores		
Criteria	Importance	Option 1	Option 2	Option 3
t_1	HI	G	G	P
t_2	I	P	N	E
t_4	VI	VP	G	N
t_6	NVI	G	P	VP
t_{10}	I	N	G	G

Table 4.11 Ranking of Criteria and Decision Options (by: Str.Engineer)

		Option ranking scores		
Criteria	Importance	Option 1	Option 2	Option 3
t_1	I	VG	N	G
t_2	NVI	N	P	G
t_4	I	P	G	N
t_6	NVI	N	VG	VP
t_{10}	HI	G	P	VG

After the utility calculations, the fuzzy sets of the best options from each decision maker's perspective are given as follows:

Client: $S_A=\{0.8/s_1, 1/s_2, 0.6/s_3\}$,

Architect: $S_B=\{0.8/s_1, 1/s_2, 0.8/s_3\}$

Building Service Engineer: $S_C=\{0.6/s_1, 1/s_2, 0.8/s_3\}$,

Structural Engineer: $S_D=\{0.8/s_1, 0.8/s_2, 1/s_3\}$

Combining the four opinions, the fuzzy set of the best option for all members of the decision making team is:

$S=\{0.76/s_1, 0.94/s_2, 0.8/s_3\}$,

Hence, the option 2 is the recommended choice.

4.7 Summary

This chapter has discussed the conceptual model and functionality of the proposed decision-making model and its underlying assumptions. The functional and information steps of the model have been described in detail and a simplified example has been presented to show how the model can be applied in practice, as well as the implementation context of the model. The benefits and limitations of the model will be discussed in the Evaluation Chapter. The development of a prototype software system for the collaborative decision-making model is described in the next chapter.

CHAPTER 5

DEVELOPMENT AND OPERATION OF THE PROTOTYPE SYSTEM

5.1 INTRODUCTION

This chapter describes the development and operation of the Web-based prototype system for collaborative decision-making. It includes the objectives, development environment, program organization, user-interface design, and key features of the system, as well as the approach adopted in writing the Java code. An example is presented to demonstrate the implementation of the prototype system in a computer-based environment.

5.2 OBJECTIVES OF IMPLEMENTATION

The prototype system is designed to facilitate collaborative decision-making within a virtual construction project team. It is intended to demonstrate the effectiveness of group decision-making using the Web-based system. The development of the decision-making system not only reflects the benefits of the implementation of concurrent engineering through IT but also manifests the applicability of fuzzy set theory to the construction management field. The specific objectives of the prototype system implementation are:

1. To link geographically distributed members of a construction project team via the system for a collaborative decision-making process;
2. To encourage objectivity and eliminate unhealthy behaviour in group decision-making;
3. To deal with the imprecision and uncertainties in decision-making practice;

4. To demonstrate the applicability of the system to a range of decision-making scenarios.

5.3 SYSTEM DEVELOPMENT

5.3.1 Development Environment

The tools selected for the system development were intended to facilitate functionality. The development of the system is based on this consideration. Details of the adopted hardware and software tools and the reasons for their choice are presented in the following section.

5.3.1.1 Hardware

Most decision-makers in the construction industry work daily with desktop or laptop computers. Thus, the target hardware for developing the system is a PC having access to the Internet. This enables the Client side of the Client-Server system to run. A PC that has the capacity for installing and running Virtual J++ is also needed to run the Server side of the system.

5.3.1.2 Software

As the Web-based prototype system aims to facilitate decision-making between members of a distributed project team, the first choice language for the system was Java. Java was formally introduced in May 1995 and it has been popular in the computer industry since then because of its high effectiveness on the World Wide Web (Ablan et al, 1997). The Web-based approach makes the system accessible wherever an Internet connection is available. JavaScript was not appropriate for the system since a considerable amount of mathematical computation concerning fuzzy sets theory is carried out in the system. In JavaScript, objects are built in but are not classes and cannot use inheritance. Java is object-oriented and everything in it is an extensible class that can use inheritance. This makes Java is far more competent for developing the system than JavaScript. Another shortcoming of JavaScript is that there are few libraries of standard code with which to build a system. A comparison between Java and JavaScript is contained in Table 5.1.

Table 5.1: Comparison Between JavaScript and Java (Weber, 1999)

JavaScript	Java
Code is interpreted by client (Web browser).	Code is compiled and placed on server before execution on client.
Object-based. Objects are built in but are not classes and cannot use inheritance.	Object-oriented. Everything is an extensible class that can use inheritance.
Data types need not be declared (loose typing).	Data type must be declared (strong typing).
Runtime check of object references (static binding).	Compile-time check of object references (dynamic binding).
Restricted disk access (must ask before writing a file).	Restricted disk access (levels of access set by user; cannot automatically write to disk).
Scripts are limited to Web browser functionality.	Compiled code can run either as a Web applet or a standalone application.
Scripts work with HTML elements (tags)	Can handle many kinds of elements (such as audio and video).
The language is rapidly evolving and changing in functionality.	Most major changes are complete.
There are few libraries of standard code with which to build Web applications.	Java comes with many libraries bundled with the language.

With regard to the Java applications used by the chairperson of a virtual construction project team, an FTP server was selected to install in the PC that runs the applications. FTP is used to send and retrieve files, which means that, the application user can download the data submitted by the team members via the Web-forms from the server and upload the aggregated information to the server. The part of the system used by the team chairperson is developed using Java applications instead of Applet-embedded Web-forms based on the consideration that Java applications do not need to be run within an external viewer. A Java application can be executed directly using a

Java interpreter. Therefore, the calculation carried out on the chairperson's PC would be subject to minimal interruption. The development language utilized in the system is Visual J++ as it was considered to have right graphical user-interface components so that it would be easier to create user-interfaces for the system.

5.3.2 System Organization

The system is organized into a Server side and a Client side. The Server side contains five Java application classes, which support five application forms and six text document classes. The text documents supply readable explanations when users want further information on the decision-making process. The Client side includes four applet classes and four HTML classes, which support four Web-forms. A File Transport Protocol (FTP) class is used to download and upload files from/to the server and it serves both the server side and client side. The system organisation is shown in Fig. 5.1.

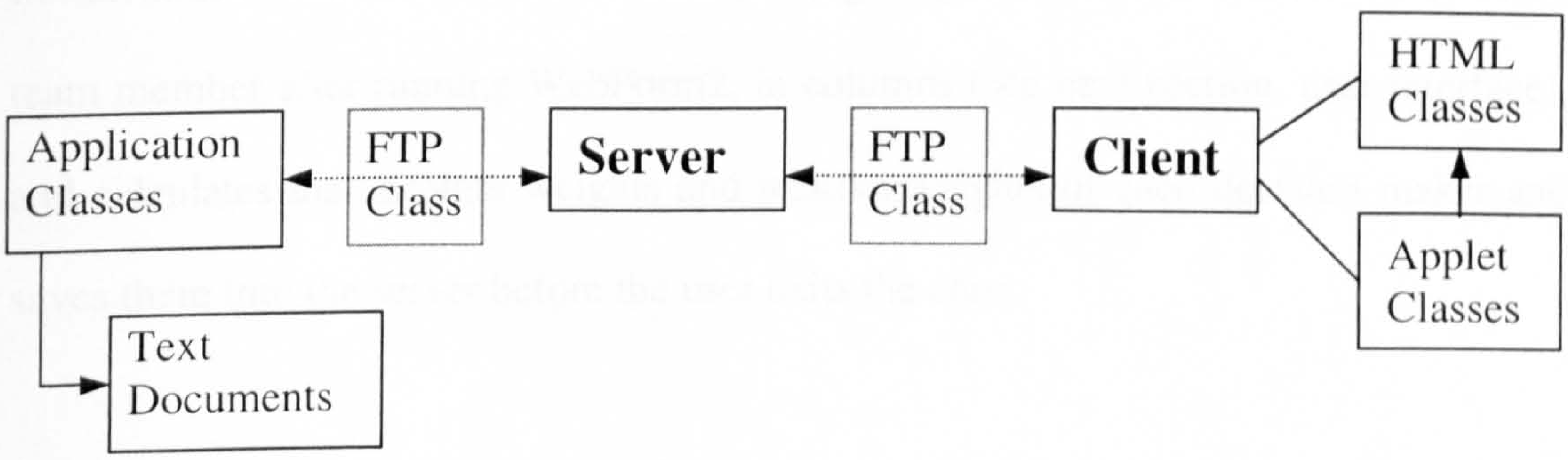


Fig. 5.1: System Organisation

5.3.2.1 Server Side

Application Classes

The five Java application classes were edited, compiled and debugged within Visual J++. A blank form with a standard menu can be created by following the wizards in the toolkit. The application classes work closely with the FTP server class. They all start by choosing 'debug/start' in the menu of Visual J++.

The first application class allows the information given by the users to be collected and sent to the server. The information includes project title, project location, decision-making issue, decision maker number and list, decision option number and list and decision-making start time.

When the second application class is initiated, it sets all the decision makers' role names in separate fields; and reads and displays the criteria saved in the server after running WebForm1. The class also allows the criteria rationalized by the user to be sent to the server after the user clicks the appropriate button.

Application class three traces the list of decision makers and displays it when it is initiated. The class downloads the sum of weightings of each decision maker by every team member after running WebForm2, in columns (see next section, user interface), and calculates the absolute weights and relative weights of each decision maker and saves them into the server before the user exits the class.

When the fourth application class is initiated, it reads and displays the criteria list saved in the server after running the application class two. The class, not only when it is initiated, traces the values of contribution degree between the criteria saved by every team member after running WebForm3, but also averages the values from team members' different weightings and displays the values. This is a rather time-consuming calculation process and it normally takes 30 seconds. The class selects the criteria used to evaluate decision options according to the averaged values using FSM (see Section 4.5.3.2) and saves the criteria to the server before the user leaves the class.

When the fifth application form is initiated, the class has the following information to trace from the server:

- The importance scores of each criterion used to evaluate decision options ranked by each team member, saved into the server after running WebForm4;
- The rankings of each decision option using each criterion, which is determined by applet class four, by each team member, saved into the server after running WebForm4;
- The relative weightings of each team member saved into the server after running application class three;
- The decision option list saved into the server after running application class one.

With the above information, the class carries out all the operations on fuzzy set theory described in Sections 4.5.5 and 4.5.6; then displays the fuzzy set of the best options and the optimal decision option as its final output.

Text Document Class

The text document class is actually included in the help menu of every application form. It allows the user to open six text documents that describe the tasks of the six decision-making steps (see Section 4.5) by choosing 'Help/Decision-Making Steps' in the menu of each application form. The design of the class is intended to help users understand the whole process of collaborative decision-making and beware which step is being undertaken.

5.3.2.2 Client Side

<u>HTML Classes</u>

The guidance for completing the four Web forms was developed within an HTML environment. Four HTML classes were used to design the content, font size, background colour etc. of the guidance texts of the four Web Forms. The texts are displayed as 'readable only'. The forms were set up on the Web through the four HTML classes and also, each HTML document had an applet inserted in it as an element.

<u>Applet Classes</u>

The four applet classes were edited using Symantec Visual café and then were moved to Visual J++ for compiling and debugging. This was because creating applet forms using Visual Café was more efficient. The Web forms can be run when compiled applet classes and HTML classes are put in the root drive of the author's PC.

The first applet class reads and displays the information saved after running ApplicationForm1, using text boxes (see 'User Interface') in Webform1. The information includes project title, project location, decision-making issue, decision maker number and list, decision option number and list and decision-making start time. Team members select their roles in the decision maker list as their ID for submission. The class also sends the three criteria given by each team member to the server after the user clicks the 'Submit' button.

The second applet class traces the list of decision makers from the server and displays it. The class requires the team member to specify his/her index in the list and record it as his/her ID when he/she submits inputs. The class gets the pairwise comparison values of decision-makers' importance and calculates the weightings assigned to each decision maker; and sends the weightings to the server.

When the third applet is started, its class recalls the criteria list saved in the server after running ApplicationForm2. The class also recalls the decision maker list, in which each team member selects his/her role as his/her ID for submission. The class records the degree to which each criterion contributes to others, as specified by each team member and sends the degree values to the server.

When the fourth applet is started, the class reads and displays the following information in the server:

- The criteria used to evaluate decision options determined after running ApplicationForm4;
- The decision options saved after running ApplicationForm1;
- The list of decision makers;

The information that the class sends to the server after the user clicks the 'submit' button includes:

- The importance scores of each criterion used to evaluate decision options;
- The rankings of each decision option using each criterion;
- Team member's ID (selected in the decision maker list).

FTP Class

The class configures the server onto the PC of the author and also specifies its directory, allowed user and password. The class closes the FTP connection after each download and upload, so a separate object is needed for each file downloaded or uploaded from or to the server. Since the same server data is still used, the class puts the creation of such an object into its own method, and then creates 'download' and 'upload' methods (see 'Code Development').

The data-flow dependencies of the forms supported by all the above-mentioned classes are illustrated in Fig. 5.2. The arrows linking the forms indicate the information dependency relation between the forms. The form an arrow points to downloads the information saved in the server after running the form(s) from which the arrow is pointing. A form may need information saved by more than one preceding form. A form can only be initiated when all the necessary information is available. Details of the graphical design of these forms are described in the next section.

5.3.3 User Interface Design

In comprehensive Human-Computer Interface (HCI) design, design principles are specified adhering to three types – user-oriented, application-oriented, and computer-oriented (Treu, 1994). A selected set of user-oriented design principles is highlighted below as design guidelines for the system (Treu, 1994).

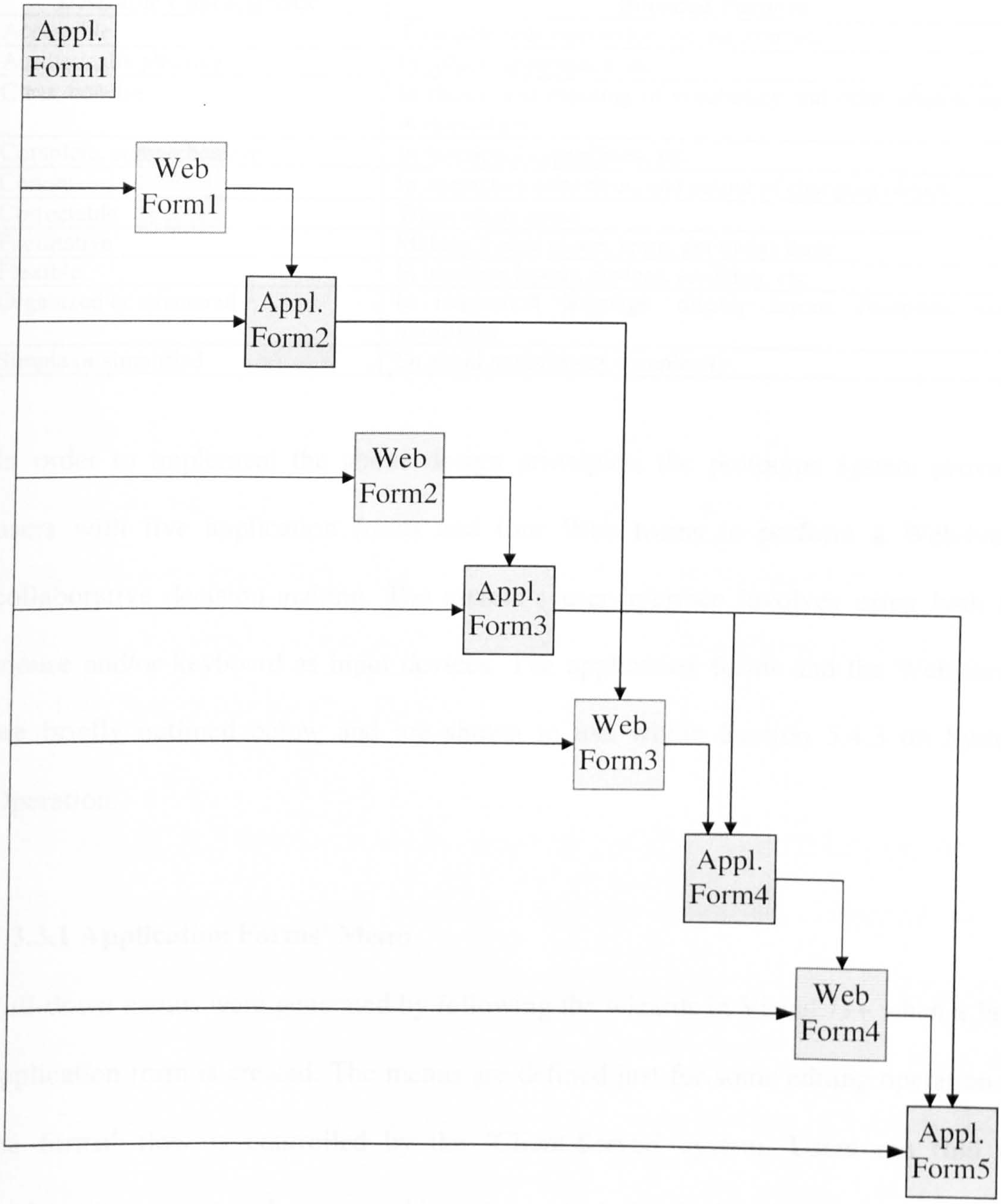


Fig. 5.2: Organization of Forms

Note: ' Appl. Form' stands for Application Form

Table 5.2 User-Oriented Design Principles (Treu, 1994)

Desirable Characteristic	Intended Purpose
Accessible	To enable user interaction via the interface
Aesthetically pleasing	In colour, appearance, etc.
Clear, concise	In choice and meaning of vocabulary and other objects used in interaction
Complete, comprehensive	In functional capabilities, etc.
Continuous	In interactive behaviour, and output of changing objects
Correctable	When errors occur
Facilitative	Making it ease to use, learn, get things done
Flexible	In interface layout, devices, scrolling, etc.
Organized or structured	In interaction language, display layout, functions, state transitions
Simple or simplified	To avoid unnecessary complexity

In order to implement the above design principles, the prototype system provides users with five application forms and four Web forms to perform a Web-based collaborative decision-making. The system's user-interface involves using both the mouse and/or keyboard as input devices. The application forms and the Web forms are briefly outlined below and are shown in use within Section 5.4.3 on System Operation.

5.3.3.1 Application Forms' Menu

Pull-down menus were generated by following the wizards in Visual J++ when a Java application form is created. The menus are defined just for some editing operation as the forms' flow is controlled by the 'Client-Server' system. Users can find an explanation of every decision-making step, which is displayed in message boxes, through 'Help/Decision-Making Steps'. The menu titles are self-explanatory and are easily selected using the mouse or keyboard.

5.3.3.2 User Input and Interaction of the Application Forms

To facilitate the data flow between the application forms and Web forms described in Section 5.3.2, the user-interface for input and interaction is designed based on the use of forms, which facilitate the collection and display of textual and graphical information delivered during a decision-making process.

ApplicationForm1: uses single-line text boxes to contain the user's input such as project title, decision-making issue etc. It also displays current time using a timer box (users do nothing for the timer unless not current time wanted). Users must separate multiple decision-making roles and options with new lines in their multi-line text boxes; as the system cuts them off when a hard return is read. Two buttons were designed for user exit. The 'Continue' button enables users to save the input to the server and leave the system while 'Exit' does nothing but quits. A note is put at the bottom of the form to remind users to ensure that all decision makers complete the next Web form before they can start the next application form.

ApplicationForm2: uses text boxes to display the list of decision makers and decision criteria obtained from the team members. The maximum number of decision makers was set at 10 for simplicity. Each multi-line text box contains the criteria collected from the team member in its corresponding single-line text box. It uses a big multi-line text box to contain the rationalized criteria. Likewise, the form also requires users to separate multiple criteria with new lines and provides two buttons for continuing and exiting.

ApplicationForm3: uses single-line text boxes to display the list of decision makers but uses a matrix formed by 10×10 text boxes to display weightings assigned to each decision maker. The first column displays every decision maker's weighting assigned by the first team member; the second column displays every decision maker's weighting assigned by the second team member, and so on. The system calculates and saves absolute weights and relative weights of team members when users click the 'Continue' button.

ApplicationForm4: uses single-line text boxes to display the criteria rationalized after running application form 2. The maximum criteria number was set to 15. The interaction matrix between the criteria, which is based on the average contribution of the whole team, is displayed in a 15×15 text-box matrix. The values in the first row in the matrix represent the degree to which the first criterion contributes to others; the values in the first column represent the degree to which other criteria contribute to the first criterion; and so on. The diagonal of the matrix should be empty. The 'Continue' button leads to the operation of FSM and saving of the recommended criteria used to evaluate the decision options. 'Exit' lets users quit the system without saving anything.

ApplicationForm5: uses two multi-line text boxes to display the integrated fuzzy set of the best options and the recommended decision option. Users can leave the system after completing an entire decision-making process using the 'Exit' button.

Examples are used to demonstrate the system's user-interface in more detail in the section, 'System Operation'.

5.3.3.3 Guidance in Completing Web Forms

All Web Forms are displayed and operated with the aid of a Web browser; hence no specialist menu is needed for operations/commands. Instructions are designed to guide users to fill the forms in efficiently. The instructions are written in HTML and are arranged at the top of the each Web Form. The screen prints of the four Web forms are shown in Figures. 5.3 - 5.6.

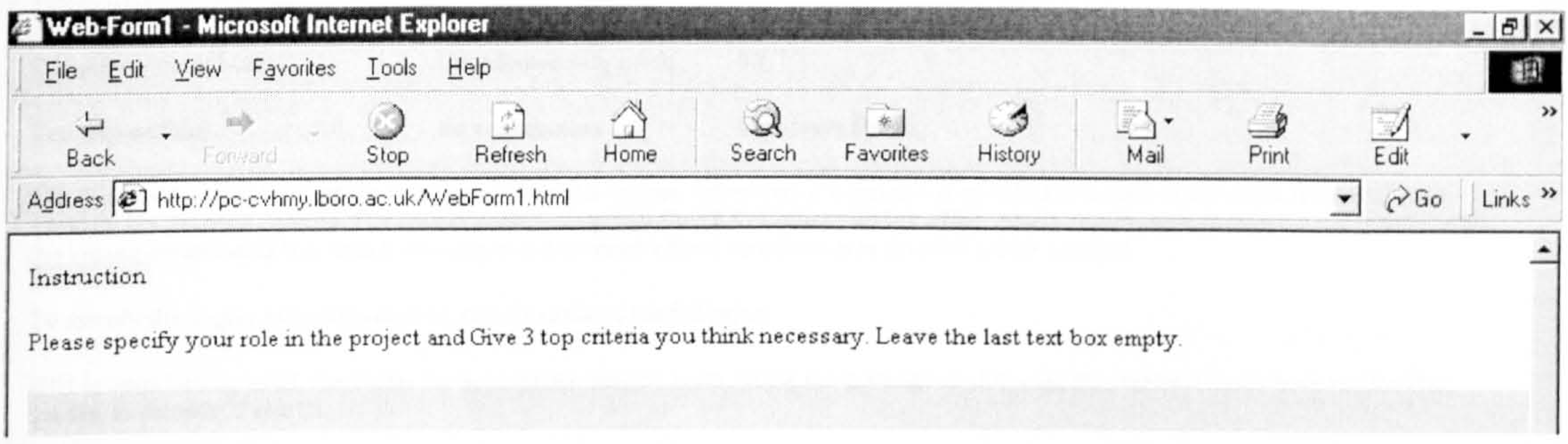


Fig. 5.3: Instruction in 'WebForm1'

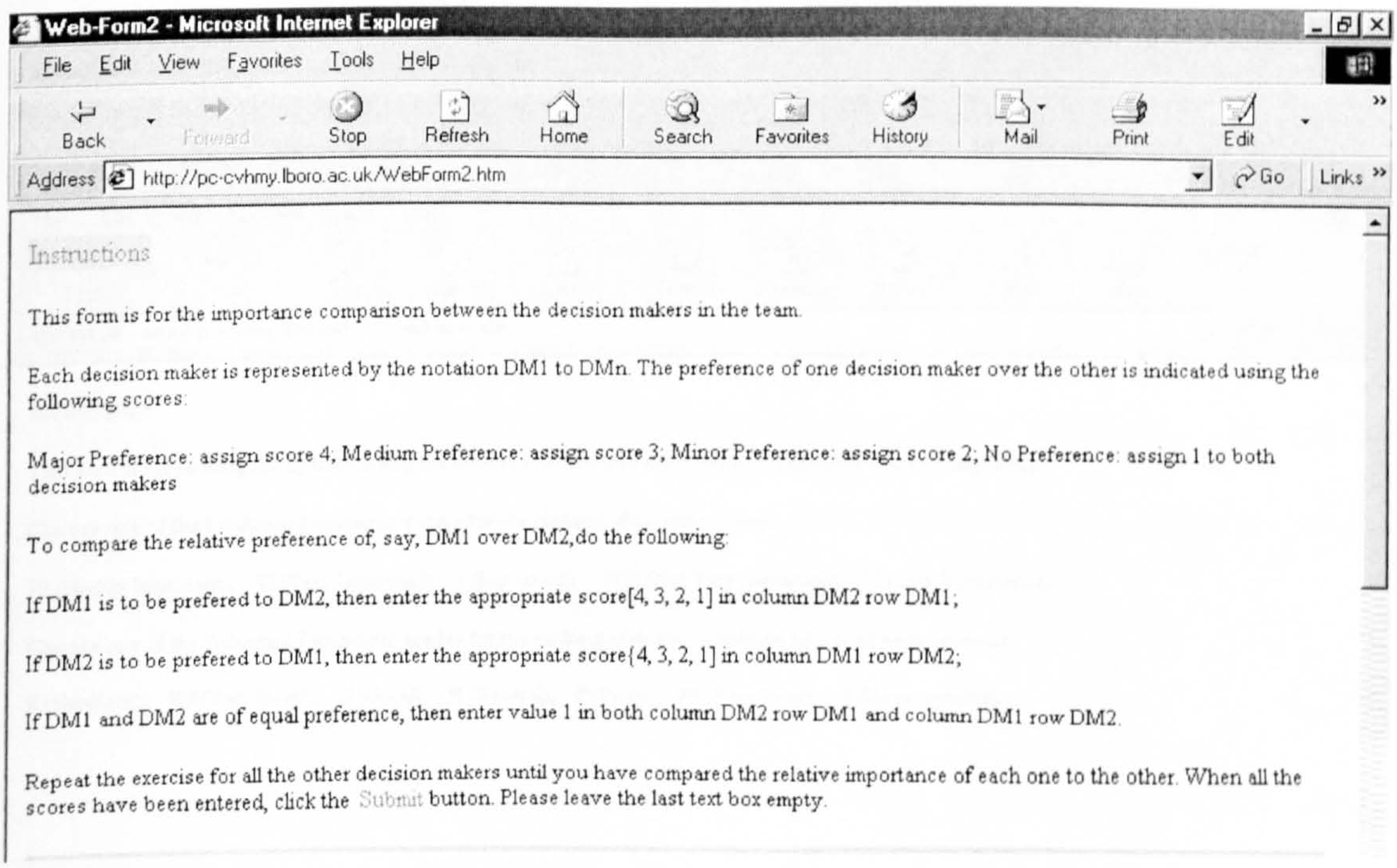
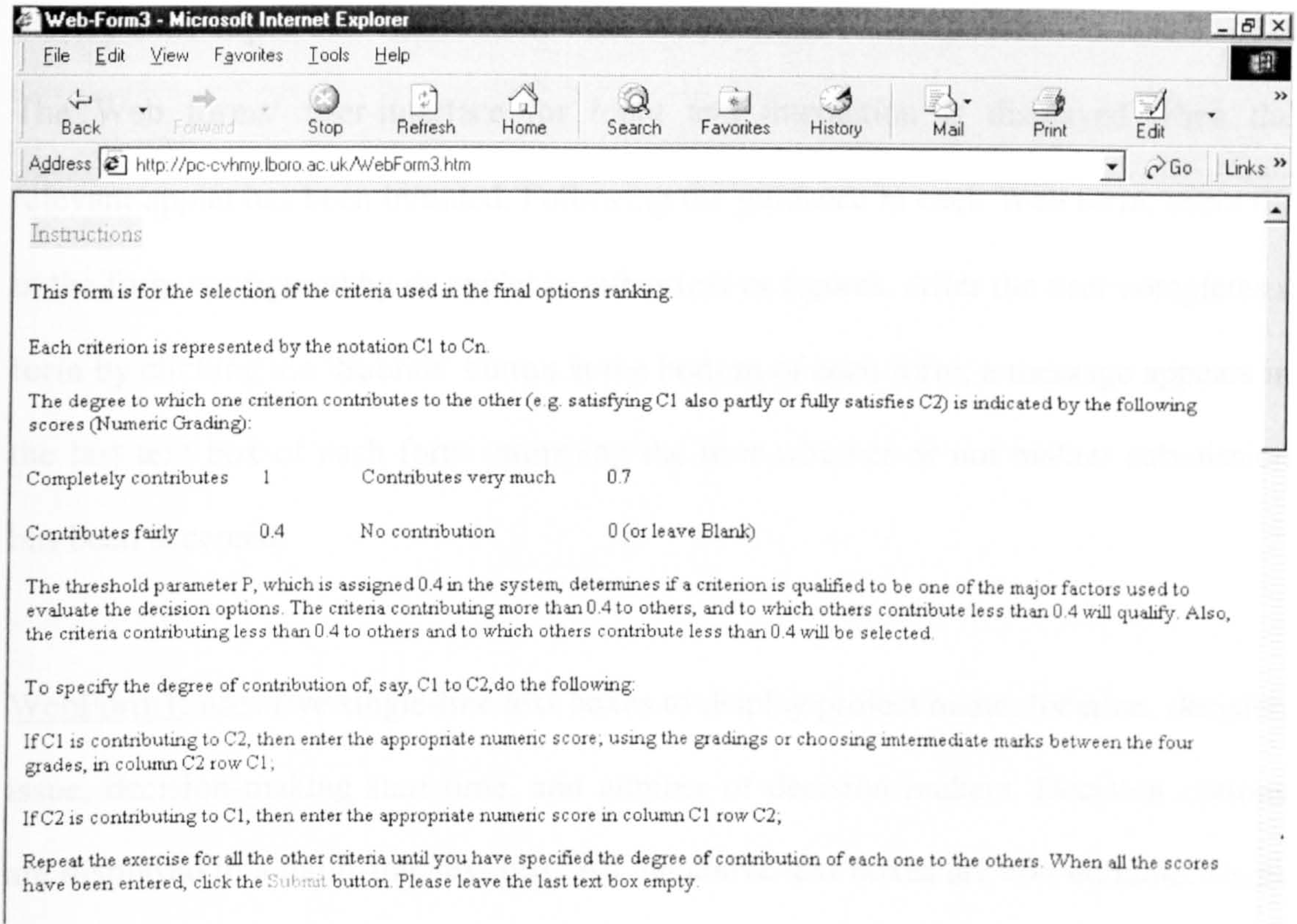


Fig. 5.4: Instruction in 'WebForm2'



Instructions

This form is for the selection of the criteria used in the final options ranking.

Each criterion is represented by the notation C1 to Cn.

The degree to which one criterion contributes to the other (e.g. satisfying C1 also partly or fully satisfies C2) is indicated by the following scores (Numeric Grading):

Completely contributes 1 Contributes very much 0.7

Contributes fairly 0.4 No contribution 0 (or leave Blank)

The threshold parameter P, which is assigned 0.4 in the system, determines if a criterion is qualified to be one of the major factors used to evaluate the decision options. The criteria contributing more than 0.4 to others, and to which others contribute less than 0.4 will qualify. Also, the criteria contributing less than 0.4 to others and to which others contribute less than 0.4 will be selected.

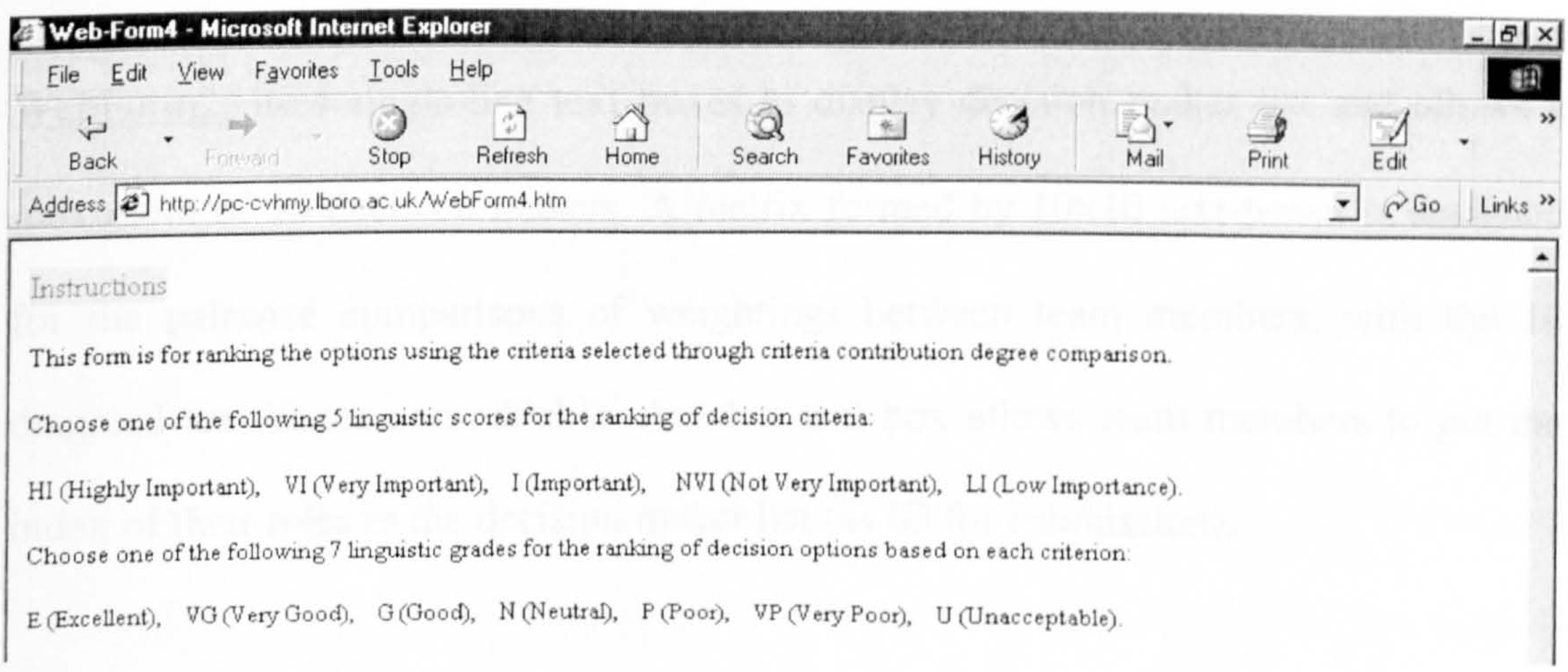
To specify the degree of contribution of, say, C1 to C2, do the following:

If C1 is contributing to C2, then enter the appropriate numeric score, using the gradings or choosing intermediate marks between the four grades, in column C2 row C1;

If C2 is contributing to C1, then enter the appropriate numeric score in column C1 row C2;

Repeat the exercise for all the other criteria until you have specified the degree of contribution of each one to the others. When all the scores have been entered, click the Submit button. Please leave the last text box empty.

Fig. 5.5: Instruction in 'WebForm3'



Instructions

This form is for ranking the options using the criteria selected through criteria contribution degree comparison.

Choose one of the following 5 linguistic scores for the ranking of decision criteria:

HI (Highly Important), VI (Very Important), I (Important), NVI (Not Very Important), LI (Low Importance).

Choose one of the following 7 linguistic grades for the ranking of decision options based on each criterion:

E (Excellent), VG (Very Good), G (Good), N (Neutral), P (Poor), VP (Very Poor), U (Unacceptable).

Fig. 5.6: Instruction in 'WebForm4'

5.3.3.4 User Input and Interaction with Web Forms

The Web forms' user-interface for input and interaction is displayed when the relevant applet has been initiated. Following the guidance in each Web form, users fill in the form configured by its applet in either text or figures. After the user completes a form by clicking the 'Submit' button at the bottom of each form, a message appears in the last text box of each form informing the user whether or not his/her submission has been accepted.

WebForm1: uses five single-line text boxes to display project name, location, decision issue, decision-making start time, and number of decision makers. Decision options are displayed in a multi-line text box. All the above text boxes are non-editable. Users specify their roles in the project in a combo box (as ID for submission), which contains the list of decision makers. Users are required to specify three criteria in a text box, using a new line for each criterion.

WebForm2: uses single-line text boxes to display decision maker list and allows a maximum of 10 decision makers. A matrix formed by 10×10 text-boxes is designed for the pairwise comparisons of weightings between team members, with the 10 diagonal text-boxes non-editable. Another text-box allows team members to put the index of their roles in the decision maker list (as ID for submission).

WebForm3: uses non-editable single-line text boxes to display the rationalized criteria (after running ApplicationForm2). The contribution degrees between the criteria, assigned by team members, are contained in a matrix formed by the 15×15 text-boxes.

A combo box that contains the list of decision makers is designed to identify the role of each team member (for submission ID).

WebForm4: Ten single-line text boxes are designed to hold the criteria used to evaluate decision options, obtained after running ApplicationForm4. Another five text boxes display the decision options specified in ApplicationForm1. A column of ten text-boxes allows team members to rank the importance of each criterion while another five columns of ten text-boxes allows team members to put the rankings of decision options based on each criterion, both in fuzzy linguistic expressions. The role of team members can be found in a combo box at the bottom of the form (for submission ID).

The interaction part of all the Web forms can be seen when the system operation is illustrated using an example (Section 5.4.3).

5.3.4 Code Development

The system development was facilitated by the use of Visual J++ and Symantec Visual Café, which have automatic code generation capability. The codes generated automatically when both the application forms and the Web forms are created using Visual J++ and Symantec Visual Café are not listed here because of space. They carry out standard functions including displaying the menu, screen layout, and the built-in controls (e.g. edit box/text box, combo box, label) etc. Only the codes handling the major decision steps in the system are listed here and codes representing similar functions are not repeated.

5.3.4.1 Server side

Text document class

Listing 5.1 shows the explanation message in the first text document displayed in a message box, which is catalogued in 'Help' menu bar in application forms.

```
private void menuItem2_click(Object sender, Event e)
{
	try{
		com.ms.wfc.io.File fInputFile = com.ms.wfc.io.File.open("Text1.txt");
		long nLength = fInputFile.getLength();
		MessageBox.show(fInputFile.readStringCharsAnsi((int)nLength));
		fInputFile.close ();
	}catch(com.ms.wfc.io.IOException e2)
	{
		MessageBox.show("File not opened properly\n"+e2.toString());
		System.exit(1);
	}
}
```

Listing 5.1 Class for Displaying Text Document 1

Application forms

Listing 5.2 shows that, after users press the 'Submit' button in 'ApplicationForm1', the information entered in the text-boxes is saved in the server. The information includes project title, project location, decision-making issue, decision-making starting time, decision maker list and decision options, and so forth.

```
private void button4_click(Object source, Event e)
{
	int optionNumber=Value.toInt(edit8.getText());
	String optionLines[]=new String[optionNumber];
	optionLines=edit6.getLines();
	String optionFileName[]=new String[optionNumber];
	try{
		Ftp.upload("page1_title.txt",edit2.getText());
		Ftp.upload("page1_location.txt",edit3.getText());
		Ftp.upload("page1_issue.txt",edit4.getText());
		Ftp.upload("page1_time.txt",(dateTimePicker1.getValue()).toString());
		Ftp.upload("page1_dmNumber.txt",edit7.getText());
		Ftp.upload("page1_role.txt",edit5.getText());
		Ftp.upload("page1_option.txt",edit6.getText());
```

```
            Ftp.upload("page1_opNumber.txt",edit8.getText());

            for(int i=0;i<optionNumber;i++)
            {
                    optionFileName[i]="page1_option"+i+".txt";
                    Ftp.upload(optionFileName[i],optionLines[i]);
            }
        }catch(Exception e1)
        {
                System.err.println(e1);
                e1.printStackTrace();
        }
        this.dispose();
        Application.exit();
}
```

Listing 5.2 Class for Saving Information in 'ApplicationForm1'

The codes in Listing 5.3 enables 'ApplicationForm2' to be initiated and downloads the decision maker list and the criteria specified by all the team members completing 'WebForm1', from the server. The list of decision makers is displayed in the 10 single-line text boxes and all the 3-line criteria collected from each team member are displayed in the corresponding text box.

```
private void setRolesField(Edit edit,int role)
        throws java.io.IOException
{
        edit.setText(Ftp.download(role + ".txt"));
}

private void setMultipleRoleFields(Edit[] edits)
{
        for (int i = 0; i < edits.length; ++i)
        {
                try{
                        setRolesField(edits[i],i);
                }catch (java.io.IOException e)
                {
                        System.err.println("Role"+i+"failed to download");
                }
        }
}

private void readCriteriaIntoField(Edit edit,int index)
            throws java.io.IOException
{
        BufferedReader input =new BufferedReader(new
                                java.io.StringReader(Ftp.download(index+"Form1.txt")));
        String criteria[]=new String[3];
        for(int i=0;i<3;i++)
```

```
        {
                criteria[i]=input.readLine();
        }
        edit.setLines(criteria);
}

private void setMultipleCriteriaFields(Edit[] edits)
{
        for (int i = 0; i < edits.length; ++i)
        {
                try{
                        readCriteriaIntoField(edits[i],i);
                }catch (java.io.IOException e)
                {
                        System.err.println("Criteria "+i+" failed to download");
                }
        }
}

public Application_Form2()
{
        super();
        //Required for Visual J++ Form Designer support
        initForm();

        int teamSize=0;
        try{
                teamSize=java.lang.Integer.parseInt(Ftp.download("page1_dmNumber.txt"));
        }catch(java.io.IOException ieo2)
        {
                ieo2.printStackTrace();
        }catch(NumberFormatException nfe)
        {
                nfe.printStackTrace();
        }

        //download roles
        Edit edits1[]=new Edit[]{edit1,edit2,edit3,edit4,edit5,edit6,edit7,edit8,edit9,edit10,edit11};
        Edit edits11[]=new Edit[teamSize];
        for(int i=0;i<teamSize;i++)
        {
                edits11[i]=edits1[i];
        }
        setMultipleRoleFields(edits11);

        //download raw criteria raised by the team
        Edit edits2[]=new Edit[]{edit26,edit27,edit28,edit29,edit30,edit31,edit32,edit33,edit34,edit35};
        Edit edits22[]=new Edit[teamSize];
        for(int i=0;i<teamSize;i++)
        {
                edits22[i]=edits2[i];
        }
        setMultipleCriteriaFields(edits22);

        wordWrapMenu.setChecked(editText.getWordWrap ());
        Application.addOnIdle(new EventHandler(this.Application_Form2_Idle));
}
```

Listing 5.3 Class for Downloading List of Decision Makers and Criteria in 'ApplicationForm2'

5.3.4.2 Client side

The codes in Listing 5.4 enable 'WebForm1' to download the information saved in the server after running 'ApplicationForm1'. The information, which includes project title and location, decision-making issue and starting time, number of decision makers, is displayed in single-line text boxes and the decision option list is displayed in a multi-line text-box. The list of decision makers is displayed in a combo box.

```
try{
        textField1.setText(Ftp.download("page1_title.txt"));
        textField2.setText(Ftp.download("page1_location.txt"));
        textField3.setText(Ftp.download("page1_issue.txt"));
        textField4.setText(Ftp.download("page1_time.txt"));
        textField5.setText(Ftp.download("page1_dmNumber.txt"));
        textArea1.setText(Ftp.download("page1_option.txt"));

        BufferedReader input = new BufferedReader(new
                        StringReader(Ftp.download("page1_role.txt")));
        String role = input.readLine();
        while (role != null)
        {
                choice1.add(role);
                role = input.readLine();
        }
}catch(java.io.IOException ioe)
{
        ioe.printStackTrace();
}
```

Listing 5.4 'WebForm1' Downloading Information from the Server

Listing 5.5 shows what happens after users press 'Submit' button in 'WebForm1'. The 3-line criteria specified by team members are saved into the server, with the role selected by the team member in the combo box as his/her ID. After the saving process finishes, a message is displayed in the text box at the bottom of the form.

```
class SymAction implements java.awt.event.ActionListener
{
        public void actionPerformed(java.awt.event.ActionEvent event)
        {
```

```
                Object object = event.getSource();
                if (object == button1)
                        button1_Action(event);
        }
}

void button1_Action(java.awt.event.ActionEvent event)
{
        try{
                Ftp.upload((index+".txt"),role);
                Ftp.upload((index+"Form1.txt"),textArea2.getText());
        }catch(IOException e1)
        {
                e1.printStackTrace();
        }
          textField6.setText("Your submission has been accepted. You can now exit the
                                        system. Thank you");
}
```

Listing 5.5 'WebForm1' Uploading Criteria

5.3.4.3 FTP Class

Listing 5.6 shows how the FTP class carries out the function of unloading and downloading files to and from the server. The socket-based server class is not presented here because of space.

```
class Ftp
{
                /*
                 * This is a utility class: no instances should be made, so the
                 * constructor is private.
                 */
                private Ftp()
                {
                }
                /*
                 * Configuration data. Change this to alter the server/directory, etc.
                 */
                private static final String server = "pc-cvhmy.lboro.ac.uk";
                private static final String user = "cvhmy";
                private static final String password = "hello";
                private static final String directory = "decision1";
                /*
                 * Useful debugging utility
                 */
                private static final boolean doDebug = true;
                private static final void debug(String s)
                {
                        if (doDebug)
```

```
			{
				System.err.println(s);
			}
		}

		private static Linlyn makeLinlyn()
		{
			return new Linlyn(server,user,password,directory);
		}

		public static String download(String filename) throws IOException
		{
			debug("Downloading " + filename);
			String result = makeLinlyn().download(filename);
			debug("Downloading " + filename + " complete");
			return result;
		}

		public static void upload(String filename,String contents) throws IOException
		{
			debug("Uploading " + filename);
			makeLinlyn().upload(filename,contents);
			debug("Uploading " + filename + " complete");
		}
}
```

Listing 5.6 The FTP Class

5.4 SYSTEM OPERATION

5.4.1 Context

As stated in the preceding chapters, the prototype system is aimed at collaborative decision-making within a multi-disciplinary construction project team. It is also assumed that the participants in a decision-making activity/task are geographically distributed, as is often the case in real life.

For real-life decision-making on any construction issue, there is usually a leader, such as the project manager, who manages the whole decision-making process. This team leader, referred to as 'chairperson' in some chapters, controls the application forms in the system. The team members staying in different places visit the project Web site where the Web forms are displayed.

The suggested way to start the system is that the chairperson completes 'ApplicationForm1', and then informs his/her team members via email of the Website where 'WebForm1' is displayed. The team members only need to open 'WebForm1', fill it and leave the Website. The other application forms and Web forms are called in turn successively until 'ApplicationForm5' gives the optimal decision solution as the system's final output. Fig. 5.7 shows how the system follows with running the application forms and Web forms inserted in each major step and sub-step. The forms in the flowchart are not presented in exactly the same order as they run because the data dependency between the forms is not necessarily sequential (see Fig. 5.2).

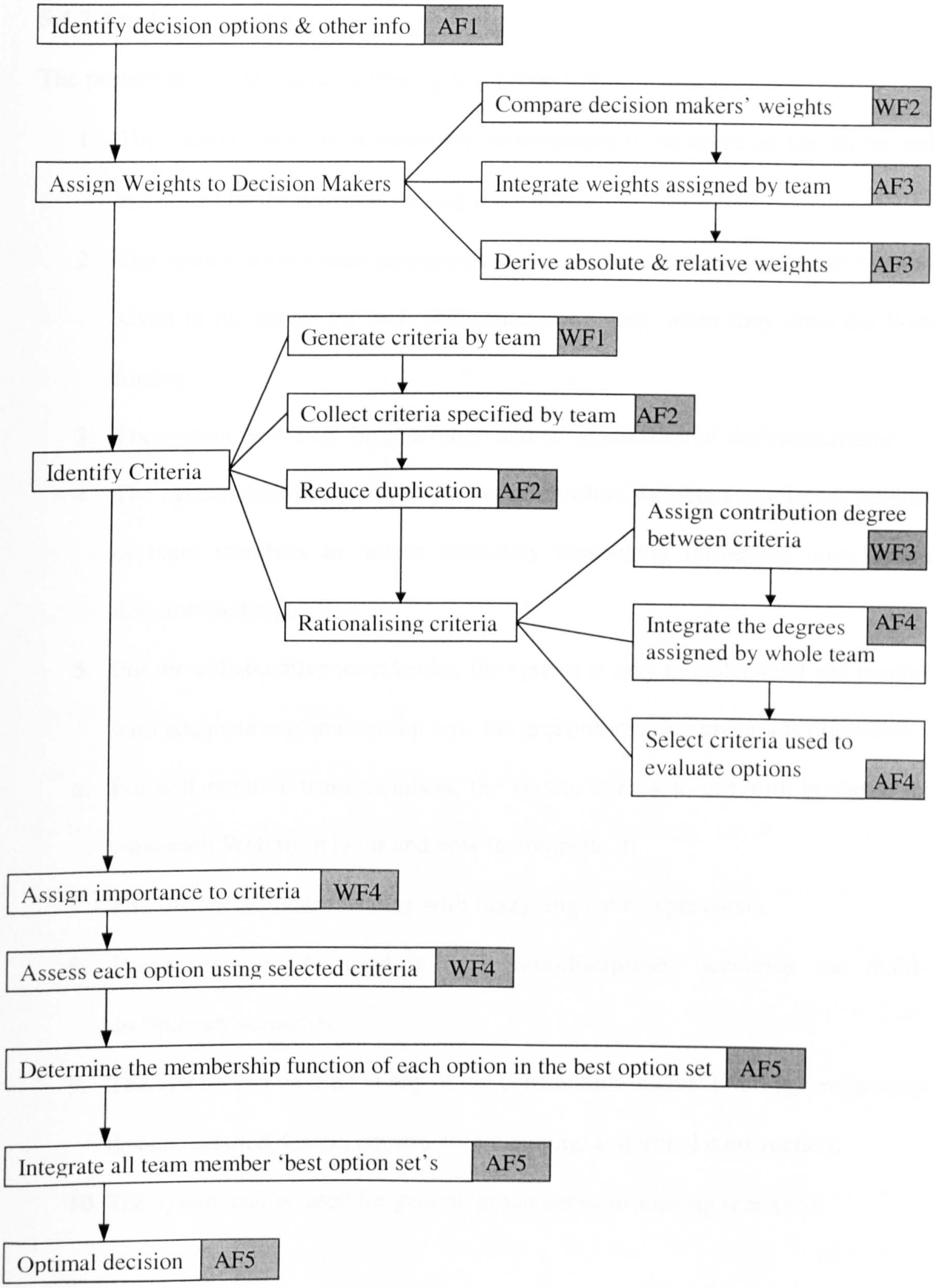


Fig. 5.7: Flowchart of the System Operation

Note: 'AF' stands for 'ApplicationForm'; 'WF' stands for 'WebForm'.

5.4.2 Key Features of the System

The prototype system has the following key properties:

1. The system allows team members' submissions to be saved on the server and controlled by the decision-making team leader;
2. The system allows team members to have access to the necessary information saved in the server for each decision-making step, when they open the Web forms;
3. The system facilitates the generation and rationalization of decision criteria;
4. The system facilitates the calculation of absolute weights and relative weights of team members to reduce unhealthy personality influences upon group decision-making;
5. For the collaborative team leader, the system is easy to understand and control with adequate explanations on how the decision-making process is organised;
6. For collaborative team members, the system is easy to use with guidance on what each Web form is for and how to complete it;
7. The system facilitates dealing with fuzzy linguistic expressions;
8. The system can be used in both intra-disciplinary scenarios and multi-disciplinary scenarios;
9. The system can be used in any of the construction stages: briefing, preliminary design, detailed design, construction planning, and actual construction;
10. The system can be used for generic group decision-making scenarios.

These features are manifested in the computer-based example demonstrated in the next section.

5.4.3 Example

The example in Section 4.6 (same scenario but different data) is input to the prototype system to show the system's working and its principal features during a collaborative decision-making process. The example is based on a hypothetical scenario, for simplicity, in which 4 decision-makers (client, architect, structural engineer, building service engineer) select a window design type from three alternatives. It is also assumed that the decision-makers have all got the detailed description of the three decision options. Thus, the chairperson specifies the options as Window type 1, 2, and 3 in 'ApplicationForm1'. For briefness, only the four Web forms completed by the 'client' are shown. This means that each Web form is filled four times before the chairperson launches the following application form.

The user interface of 'ApplicationForm1' is shown in Fig. 5.8. The light edit boxes (except the date time box) are blank when the form is started. Project title, project location, decision-making issue, number of decision makers, number of decision options, decision maker list, and decision option list are entered in their requested positions. The above-specified information is sent to the server after the 'Continue' button is pressed. If users click the 'Exit' button, they can exit the system without their entries being saved on the server.

'WebForm1' is shown in Fig. 5.9. The form displays some of the information saved by 'ApplicationForm1' on the server and leaves the light text box at right bottom corner blank when it is initiated. The 'Client' selects his/her role in the combo box and types in 3-line criteria: initial cost, easy to obtain material for window, and maintaining privacy of occupants. After clicking the 'Submit' button, a message

'Your submission has been accepted. You can now exit the system. Thank you' appears in the text box at the bottom of the form.

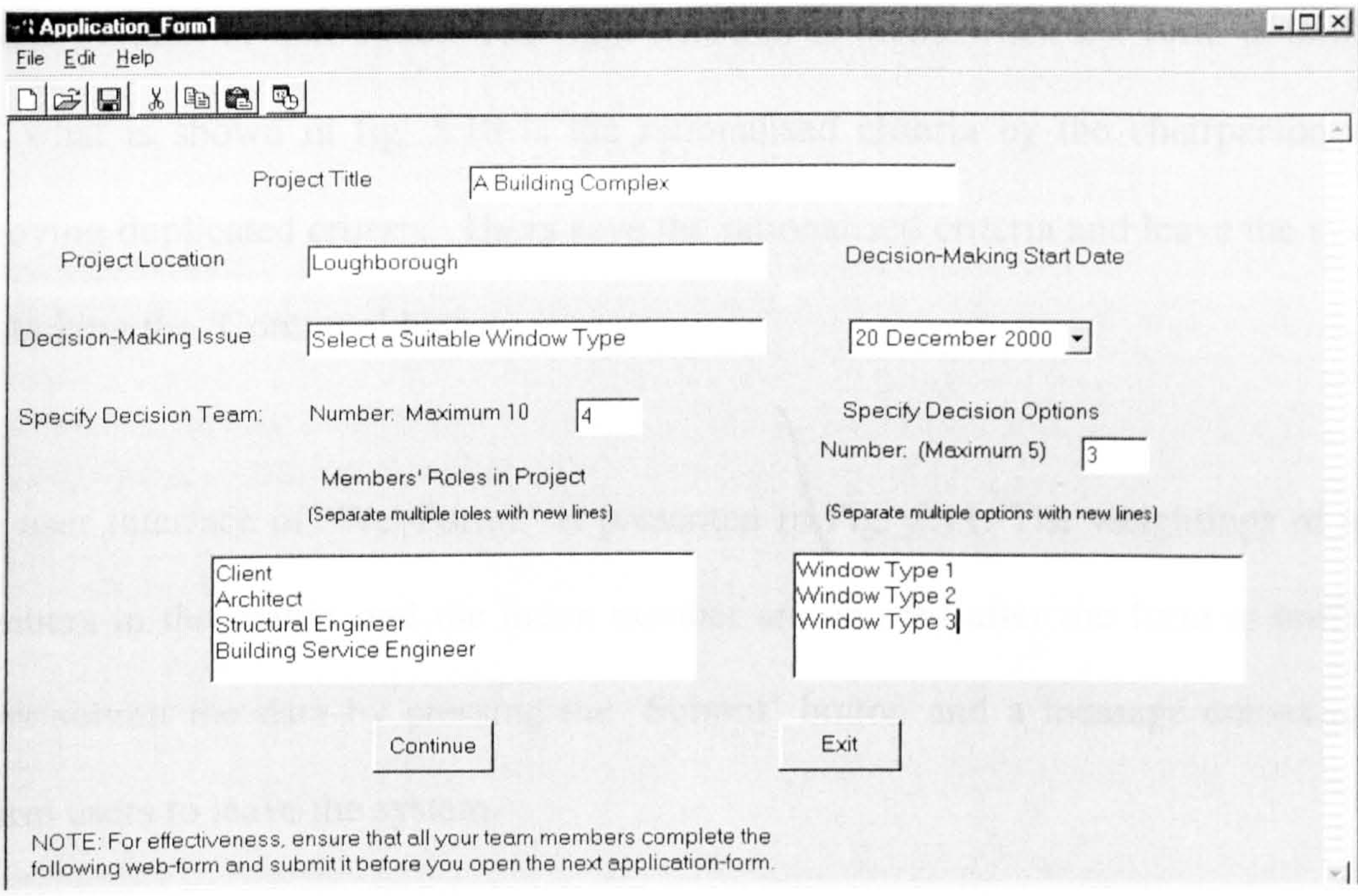


Fig. 5.8: 'ApplicationForm1' in 'Window Selection' Example

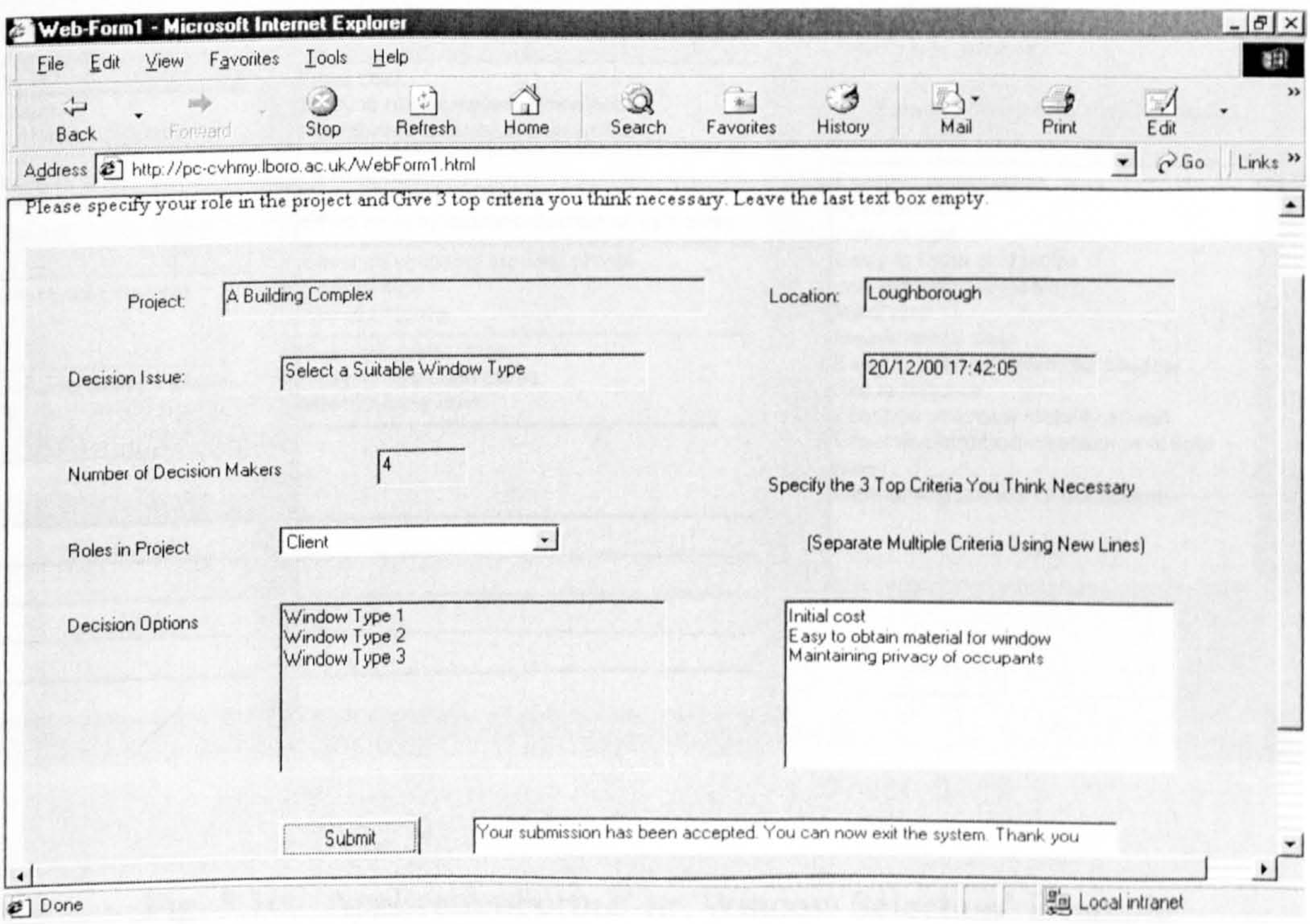


Fig. 5.9: 'WebForm1' in 'Window Selection' Example (filled by 'client')

Fig. 5.10 shows 'ApplicationForm2' that displays the list of decision makers in the left column of text-boxes and that the criteria submitted by the decision makers in the middle column of text-boxes. The right text box is blank when the form is initiated and what is shown in fig. 5.10 is the rationalised criteria by the chairperson after removing duplicated criteria. Users save the rationalised criteria and leave the system by clicking the 'Continue' button.

The user interface of 'WebForm2' is presented in Fig. 5.11. The weightings of team members in the matrix and the index number are entered after the form is initiated. Users submit the data by pressing the 'Submit' button and a message comes up to inform users to leave the system.

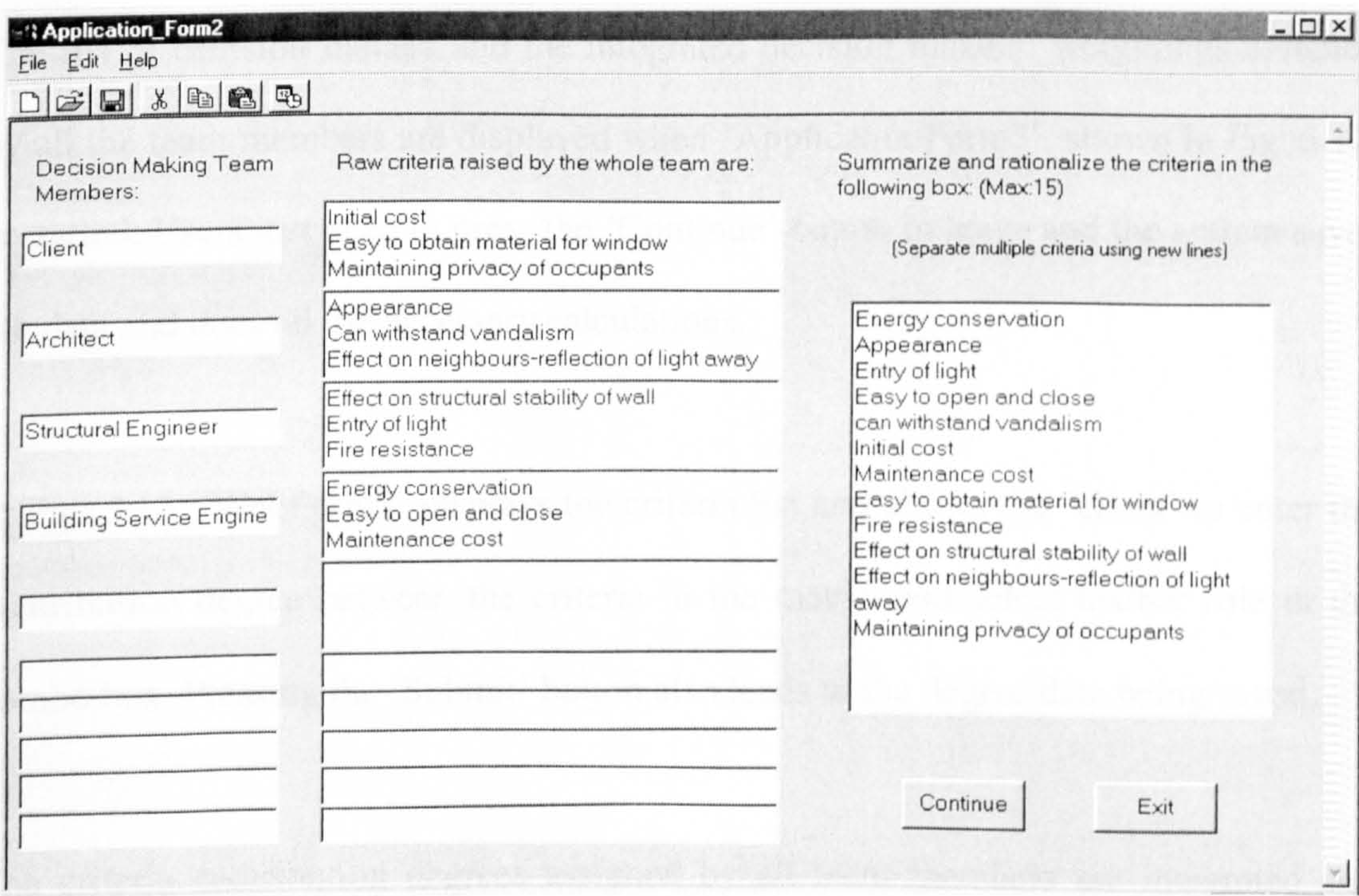


Fig. 5.10: 'ApplicationForm2' in 'Window Selection' Example

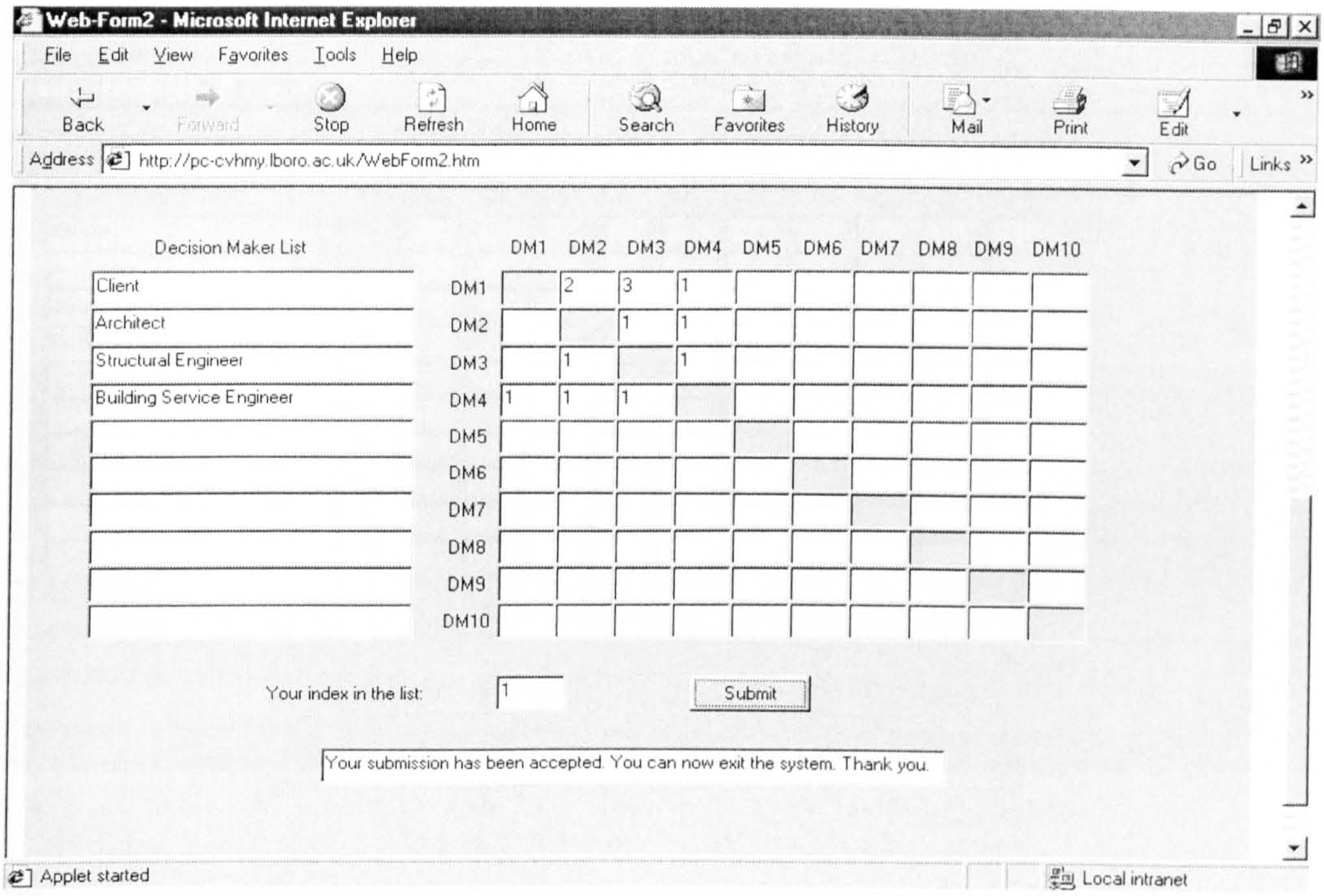


Fig. 5.11: 'WebForm2' in 'Window Selection' Example (filled by 'client')

The list of decision makers and the integrated decision makers' weightings assigned by all the team members are displayed when 'ApplicationForm3', shown in Fig. 5.12, is started. Users just need to press the 'Continue' button to leave and the system saves the data and does all the necessary calculations.

In Fig. 5.13, 'WebForm3' displays the criteria list and allows the 'client' to enter the contribution degree between the criteria in the matrix and select his/her role in the combo box. Pressing the 'Submit' button also leads to the degree data being saved.

The criteria contribution degrees assigned by all team members are integrated and displayed in Fig. 5.14, 'ApplicationForm4'. The form also displays the list of decision criteria in the left column of text boxes. Users just hit the 'Continue' button to allow the system to determine the criteria used to evaluate decision options.

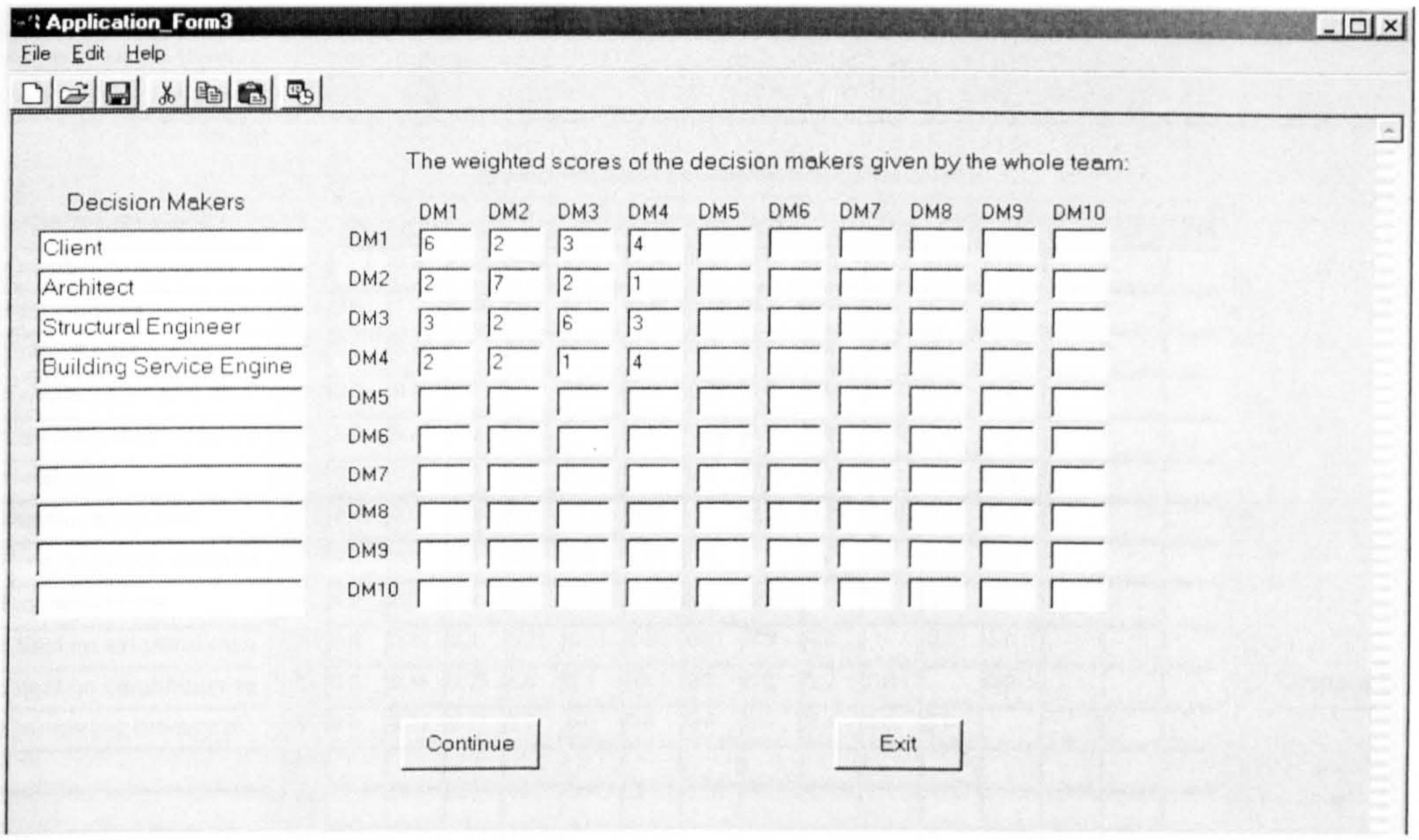


Fig. 5.12: 'ApplicationForm3' in 'Window Selection' Example

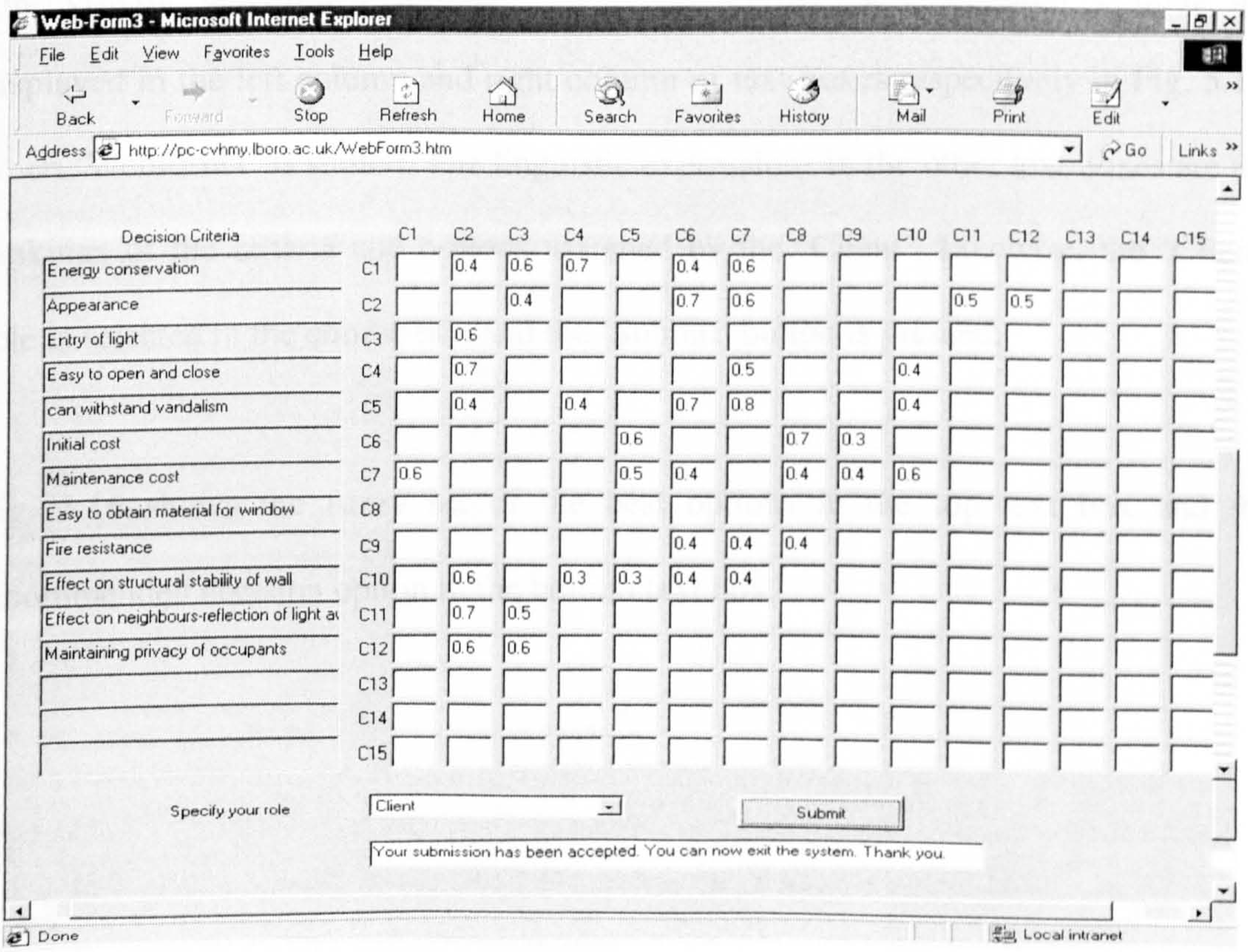
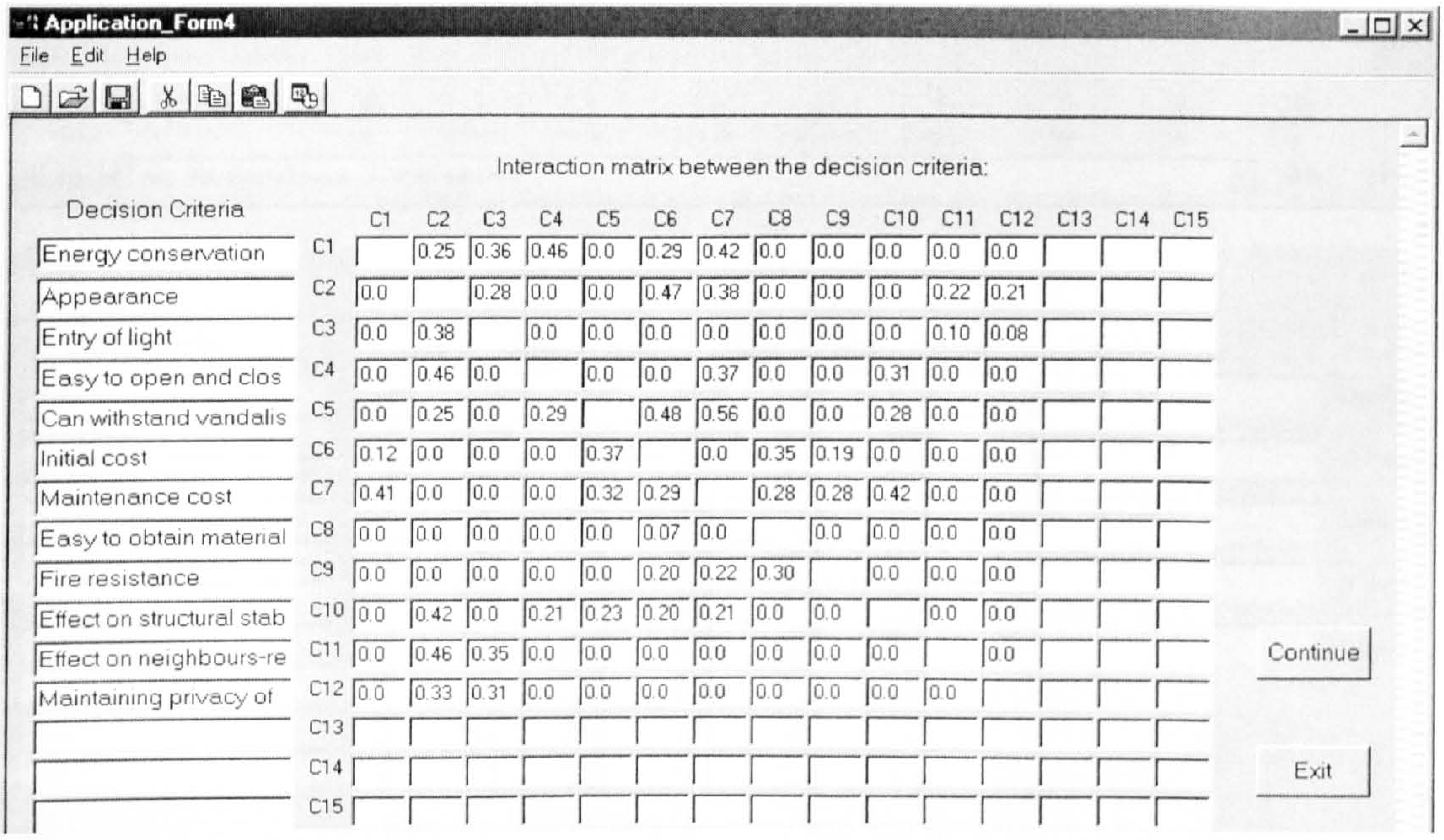


Fig. 5.13: 'WebForm3' in 'Window Selection' Example (filled by 'client')


Application_Form4

File Edit Help

Interaction matrix between the decision criteria:

Decision Criteria		C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	C14	C15
Energy conservation	C1		0.25	0.36	0.46	0.0	0.29	0.42	0.0	0.0	0.0	0.0	0.0			
Appearance	C2	0.0		0.28	0.0	0.0	0.47	0.38	0.0	0.0	0.0	0.22	0.21			
Entry of light	C3	0.0	0.38		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.10	0.08			
Easy to open and clos	C4	0.0	0.46	0.0		0.0	0.0	0.37	0.0	0.0	0.31	0.0	0.0			
Can withstand vandalis	C5	0.0	0.25	0.0	0.29		0.48	0.56	0.0	0.0	0.28	0.0	0.0			
Initial cost	C6	0.12	0.0	0.0	0.0	0.37		0.0	0.35	0.19	0.0	0.0	0.0			
Maintenance cost	C7	0.41	0.0	0.0	0.0	0.32	0.29		0.28	0.28	0.42	0.0	0.0			
Easy to obtain material	C8	0.0	0.0	0.0	0.0	0.0	0.07	0.0		0.0	0.0	0.0	0.0			
Fire resistance	C9	0.0	0.0	0.0	0.0	0.0	0.20	0.22	0.30		0.0	0.0	0.0			
Effect on structural stab	C10	0.0	0.42	0.0	0.21	0.23	0.20	0.21	0.0	0.0		0.0	0.0			
Effect on neighbours-re	C11	0.0	0.46	0.35	0.0	0.0	0.0	0.0	0.0	0.0	0.0		0.0			
Maintaining privacy of	C12	0.0	0.33	0.31	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0				
	C13															
	C14															
	C15															

Continue

Exit

Fig. 5.14: 'ApplicationForm4' in 'Window Selection' Example

The criteria determined through 'ApplicationForm4' and decision options are displayed in the left column and right column of text boxes respectively in Fig. 5.15, when 'Webform4' is started. The linguistic expressions in the other text boxes are the rankings of the criteria and options assigned by the 'Client'. Likewise, the 'Client' role is selected in the combo box and the 'Submit' button is pressed.

Fig. 5.16 shows the fuzzy set of the best options in the top text box and the recommended decision option in the bottom text box.

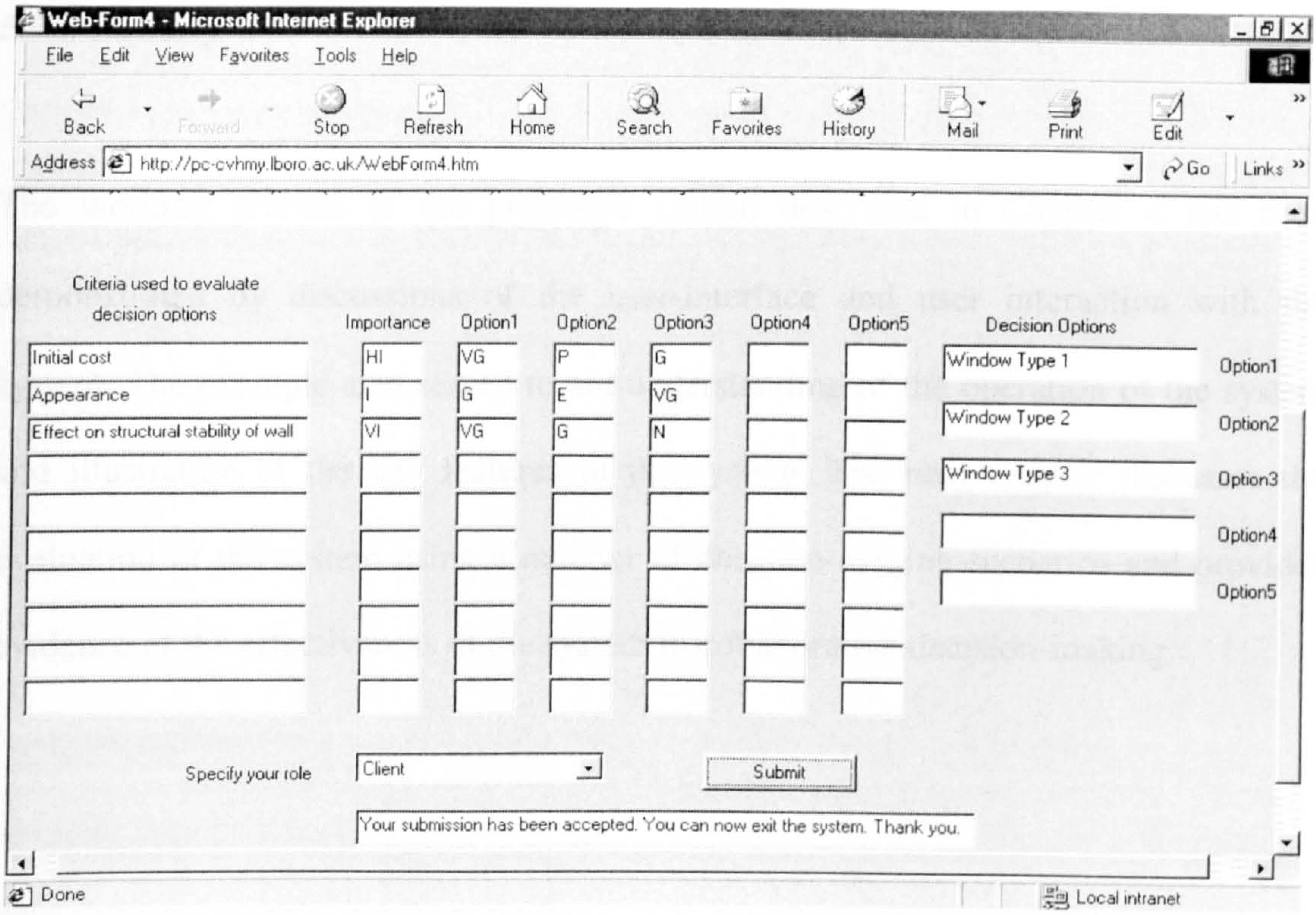


Fig.5.15: 'WebForm4' in 'Window Selection' Example (filled by 'client')

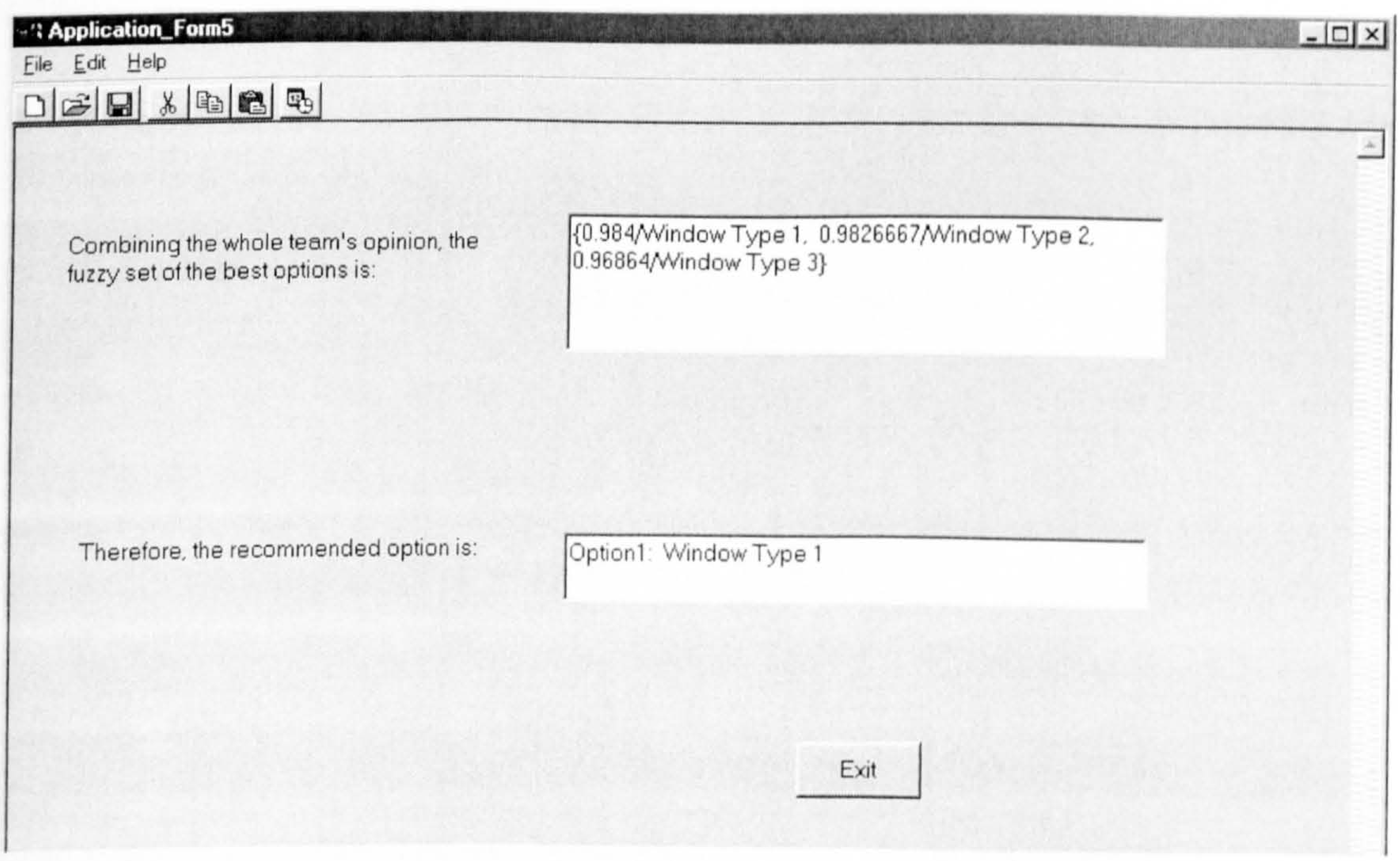


Fig. 5.16: 'ApplicationForm5' in 'Window Selection' Example

5.5 Summary

The working process of the prototype system described in Chapter 4 has been demonstrated by discussions of the user-interface and user interaction with the system. The example also served to aid understanding of the operation of the system and illustration of the key features of the system. The next chapter discusses the evaluation of the system using a number of decision-making scenarios and provides evidence of the effectiveness of the system in collaborative decision-making.

CHAPTER 6

SYSTEM EVALUATION

6.1 INTRODUCTION

This chapter describes the evaluation of the prototype decision-making system, and provides two examples for the evaluation of its practical application. This is followed by an analysis of the evaluation results based on questionnaires completed by the evaluators. The benefits and limitations of the system are also discussed.

6.2 EVALUATION OBJECTIVES

Many publications (such as Eason & Olphert, 1996; Andriessen, 1996; and Bannon, 1997; and Bogia et al., 1997) give an overview of potential issues to be evaluated in relation to interaction technology and information systems. A group decision-making system, as social interaction, implies always the existence of certain input elements transformed through an interaction process, and resulting in some kinds of outputs and feedback. In these processes three interaction levels are involved (Andriessen, 1996):

1. The interaction between a user and a tool;
2. The interaction between users, mediated by a tool;
3. The organisational context, which provides the input and interacting context for the other two levels and is the recipient of the results of the task activity.

In terms of the goals for the development of a group decision-making system, McGrath (1990) distinguished three types:

1. To make separate environments more like a single (i.e. face to face) environment by overcoming space and time separations.
2. To improve the efficiency of cooperative work by providing more communication and coordination mechanisms.
3. To increase the capacity of interdependence by improving the accessibility of shared information.

Miles et al. (1998) classified the evaluation of engineering knowledge-based systems into two main types and this classification is applicable within the information systems field. The two types are verification and validation, which are defined as follows (Miles et al., 1998):

- Validation is the process, which determines whether or not a system meets the required specification and is suitable for its intended purpose. Validation ensures that the software has been formulated in the intended manner.
- Verification is the process of ensuring that the product does not contain any technical errors. Verification ensures that the software has been formulated correctly.

In the light of the above, the aim of the prototype system's evaluation process was to establish the answers to the following questions:

1. Is the collaborative decision-making process adequate or does it need to be extended or modified?
2. Is the system coming up with the right answers?
3. Is the decision-making logic consistent with that of the experts?
4. Is it easy for users to interact with the system?
5. What facilities and capabilities do the users need?

Based on these considerations, the specific objectives of the evaluation of the prototype system were:

1. To check whether any objective or subjective reasoning aspects of collaborative decision-making have been missed during the decision-making process.
2. Find and correct any errors or aspects of the prototype system, which are confusing or misleading.
3. To assess the performance of the prototype system in a number of collaborative decision-making scenarios involving either a single discipline or a multi-disciplinary team. This includes checking the overall rationality and accuracy of the output of the prototype system.
4. To assess the suitability of the developed system for its intended working environment. This includes evaluating the developed system's efficiency and checking the quality of the user interface.
5. To review the suitability of the adopted approach to system development and, in particular, the extent to which the application of fuzzy set theory improves collaborative decision-making within a construction project team.

6.3 EVALUATION METHODOLOGY

6.3.1 Choice of Evaluation Procedure

With regard to the evaluation of computer-supported cooperative work, Andriessen (1996) distinguished evaluation into 'formative' and 'summative' depending upon the stage at which it occurs. According to his definition, evaluation is 'formative' when it occurs during system design process and results in improvements of the system.

'Summative' evaluation is evaluation of a ready-made system in practical use. This distinction is necessary because the choice of evaluation strategies and techniques depends heavily on whether it is for formative purposes or summative ones.

In setting up an evaluation study, it is generally agreed that four aspects of choice are actually implied. These are:

1. Research paradigm;
2. Research strategy;
3. Techniques of data collection;
4. Type of analysis.

The above four aspects found in the evaluation of computer-supported interaction systems fall into four research traditions, which have been addressed by many researchers (Monk et al. 1996, Sellen 1994, Tang and Isaacs 1993, Van der Velden 1992, Andriessen and Van der Velden 1993):

1. Analysis of human-computer interaction, in other words, analysis of the extent to which the system-interface influences system effectiveness. Performance, observational (event-marking), psycho-physiological and questionnaire methods for evaluation have been developed in this regard.
2. Analysis of communication structure and behaviour, in other words, analysis of the extent to which a system influences the way people interact and exchange information. Three sub-level approaches can be found:
   - Analysis of the conversational structure or of communicative behaviour. This analysis is often based on very precise observations, video registration and event coding, or on other registration techniques.
   - Analysis of conversation content. Many coding schematas exist.

- Questionnaire ratings, particularly of 'social presence' and of 'awareness' of the setting of the other participants.

3. Group interaction analysis, in other words, analysis of the effect of the media application on cooperative tasks and group processes. This type of analysis is based on various kinds of observation and registration techniques and on data from questionnaires.
   - Activity registration by participants themselves or automatic logging by the system. On the basis of this type of data social network can be performed.
   - Interaction-content coding based on observation techniques and event marking.
   - Many questionnaires concerning aspects of group interaction in general have been developed.
4. Media choice and media role. This type of research is most often done through questionnaires and interviews, sometimes supported by logging media use.

6.3.2 Evaluation Procedures

Although as mentioned above, various evaluation techniques are available, only the approaches appropriate for the system are adopted. The evaluation proceeded through the following stages:

1. Pilot evaluation: User's feedback at an early stage of the system implementation is important and the easy way to obtain this was to use a group of researchers. A generic group decision-making scenario was set up for the pilot evaluation. The comments and suggestions from the researchers involved were useful in the improvement of the system.

2. Construction-specific evaluation: The final evaluation was carried out to simulate a multi-disciplinary project team, which involved four academic staff in the Department of Civil and Building Engineering in the University with considerable experience of the construction industry.

6.3.3 Questionnaire Design

A questionnaire was designed so that the performance of the system in collaborative decision-making could be assessed, and the system's efficiency and the quality of the user-interface evaluated. The questionnaire was divided into three sections; Section A requested information about the participant's professional role and about their experience. Section B contained a total of 20 questions about various aspects of the system; these were grouped into the following sub-headings: team work, applicability to practical decision-making case, management of system interaction, efficiency, and a general section. For each question, participants were asked to tick the box that best represents their assessment on a scale of 1 (poor) to 5 (excellent). Section C requested comments on ways to improve the system, and allowed for further comments. A sample of the evaluation questionnaire is provided in Appendix A3.

6.4 THE EVALUATION

This phase contains the details of the two decision-making scenarios and the evaluation of the prototype decision-making system using them.

6.4.1 Evaluation 1: Generic Scenario

The presumed decision-making issue was to select a venue for a Christmas dinner party from four options. The participants included two researchers in the department, one in another university and one working in industry. This arrangement was for testing if different network users can access the server. The participants also had different operating systems on their PCs.

The author was involved in the evaluation acting as a moderator/team leader. The decision-making process was started with the team leader specifying decision options, which were Pizza Hut, an English pub, an Indian restaurant, and a Thai restaurant, plus other background details (shown in Fig. 6.1).

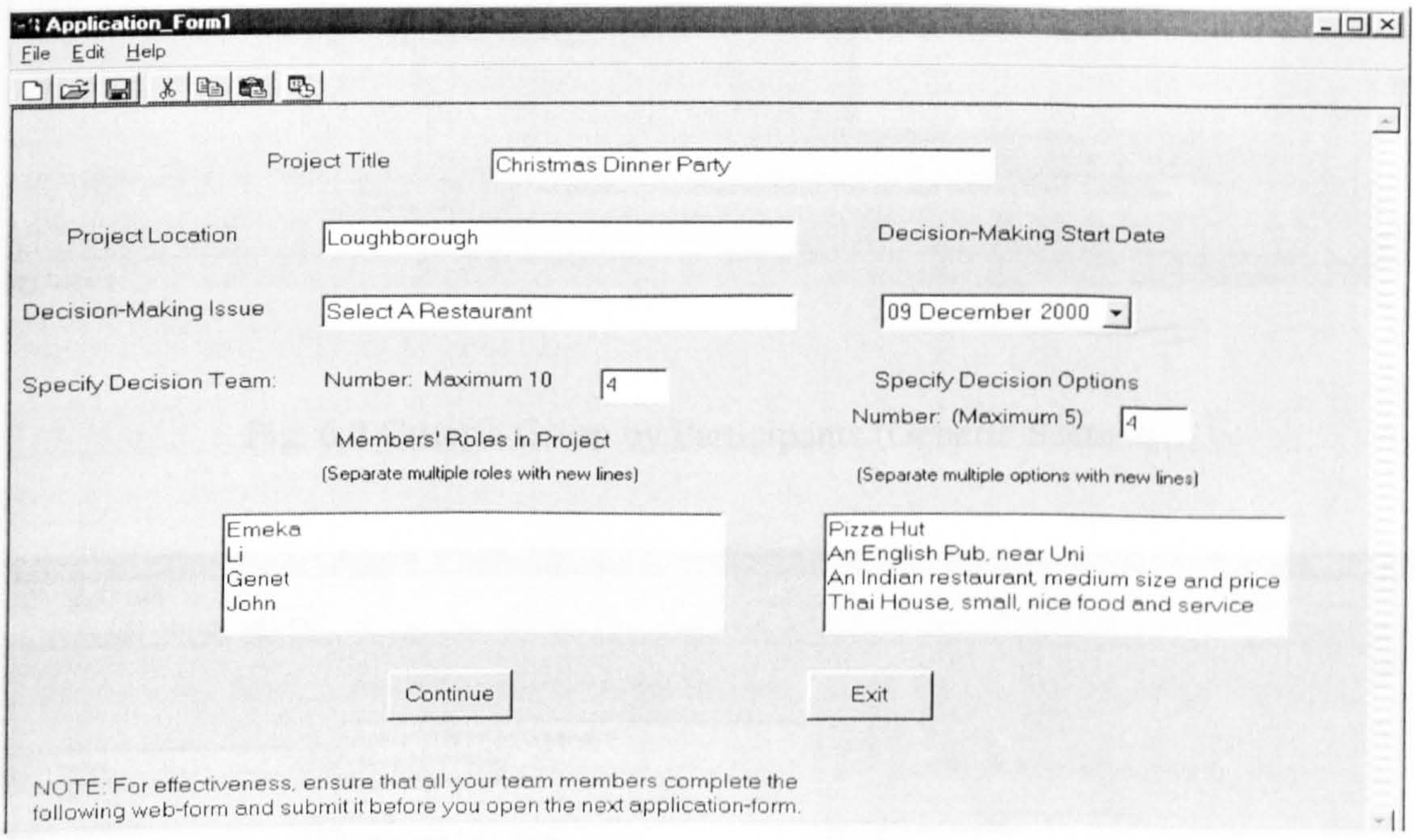


Fig. 6.1 Basic Information about the Decision Issue (Generic Scenario)

The participants then opened the WebForm1's URL in the email sent by the team leader and gave their three top criteria for selecting the party venue in the form (an example is shown in Fig. 6.2). The system collated the submission of the whole team and the team leader rationalised the criteria to avoid duplication (Fig.6.3). There were in total eight criteria sent to the server after rationalisation: food quality, price, distance, service quality, seating, cleanliness, smoke-free, and privacy.

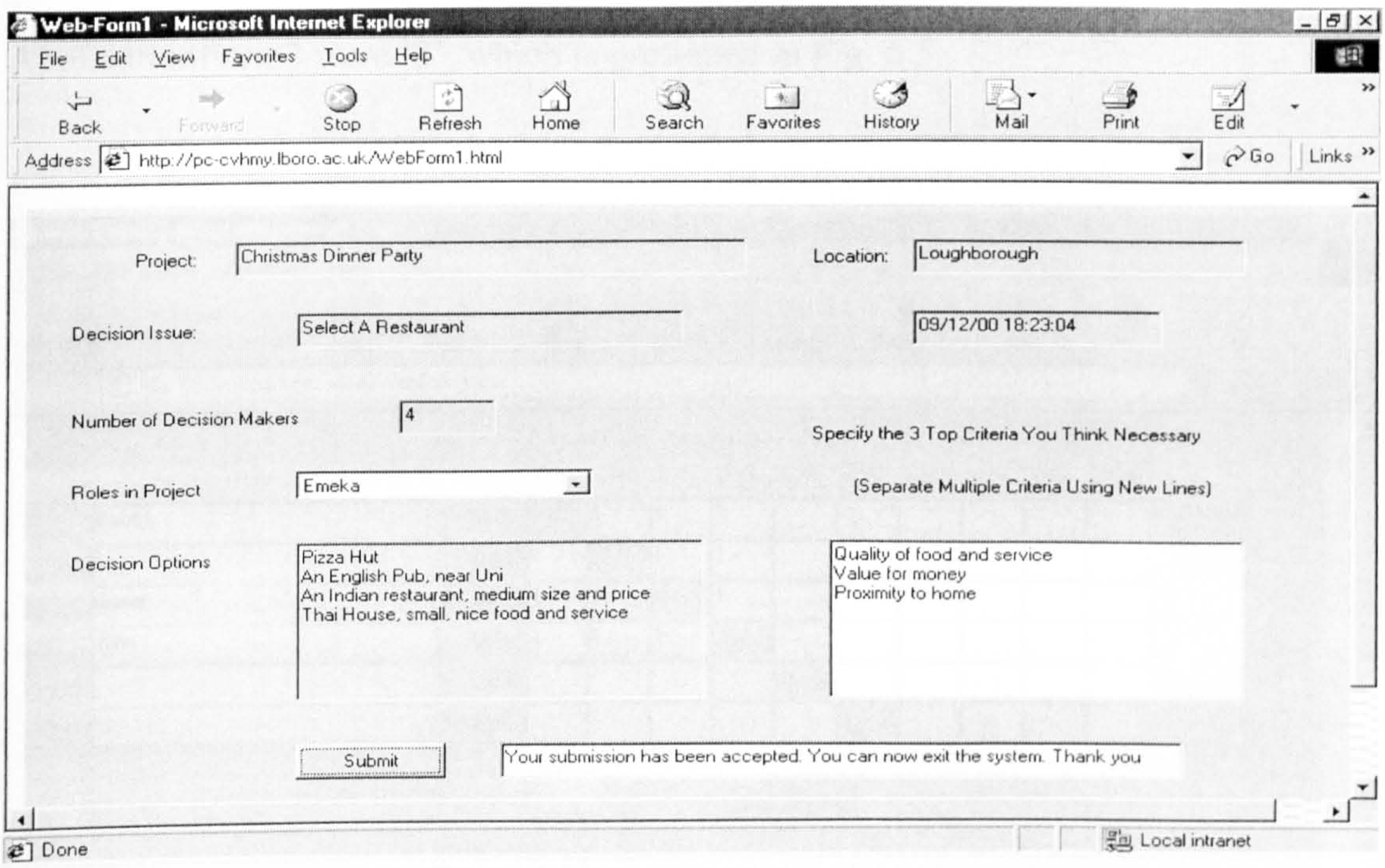


Fig. 6.2 Criteria Given by Participants (Generic Scenario)

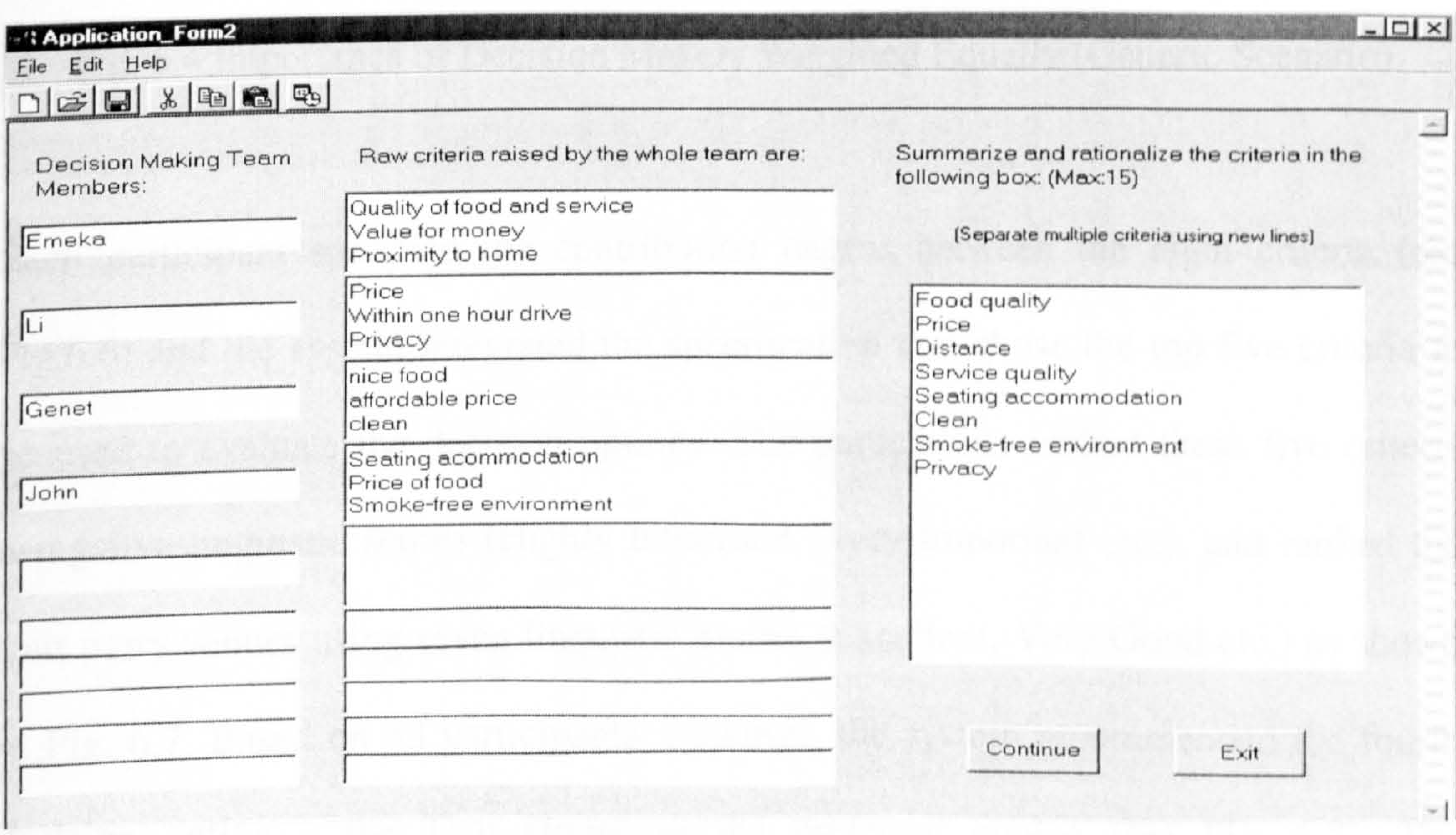


Fig. 6.3 Criteria Collated by the System (Generic Scenario)

The team members weighted the importance of each decision maker for the decision-making issue, for which every participant had equal weighting. Thus all figure inputs in WebForm2 were '1' (Fig. 6.4) and the integrated importance figures in ApplicationForm3 were '3', which is presented in Fig. 6.5.

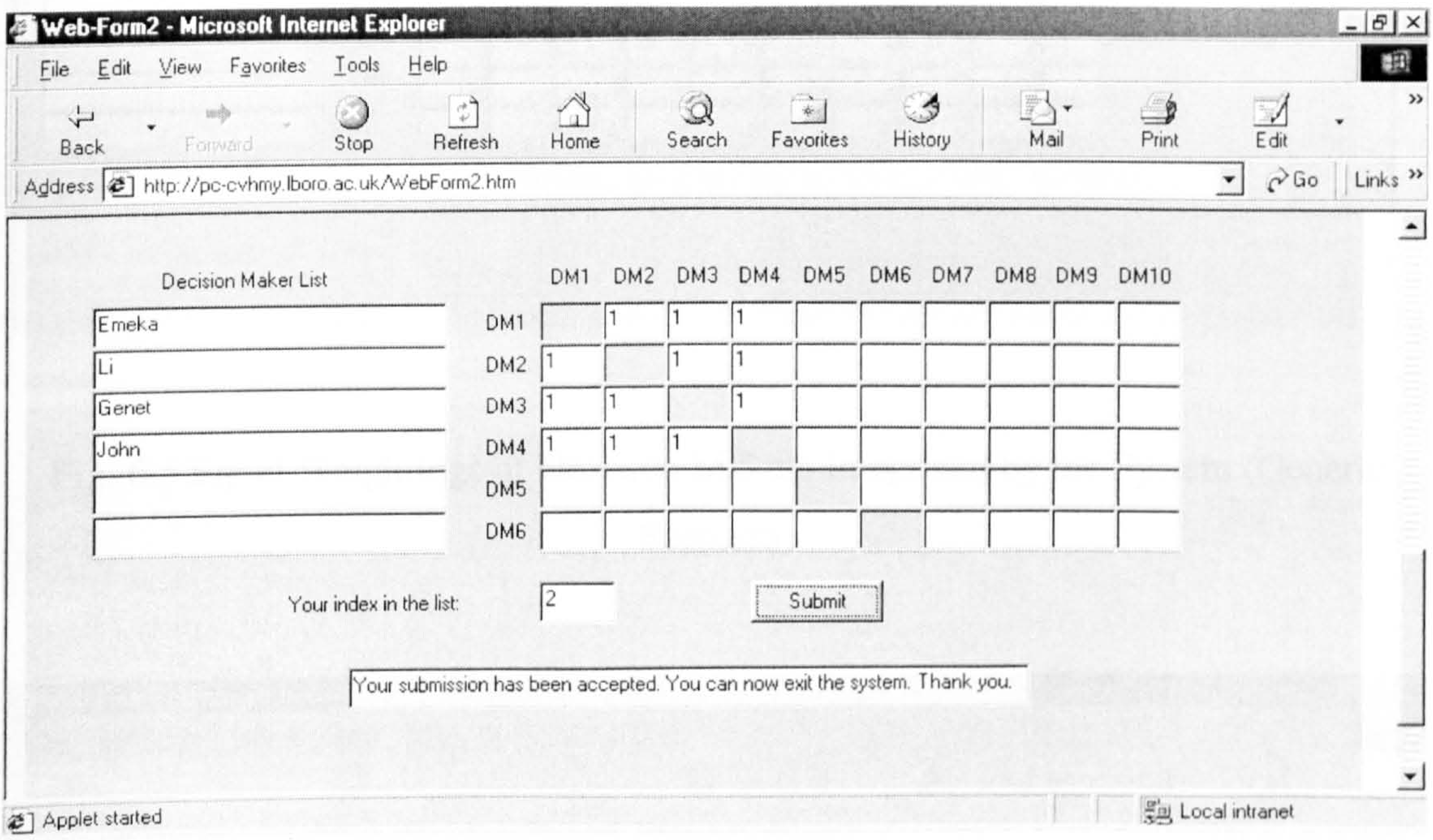


Fig. 6.4 Importance of Decision Makers Weighted Equally (Generic Scenario)

Each participant specified the contribution degree between the eight criteria (see Fig.6.6) and the system integrated the specification and chose the top five criteria to be used to evaluate the decision options. The participants ranked these five criteria using five linguistic scores (Highly Important, Very Important etc.), and ranked the four party venues using seven linguistic grades (Excellent, Very Good etc.) as shown in Fig. 6.7. Based on all participants' rankings, the system recommended the fourth decision option – the Thai House as the preferred choice (see Fig. 6.8). The recommended option was sent to all participants via email.

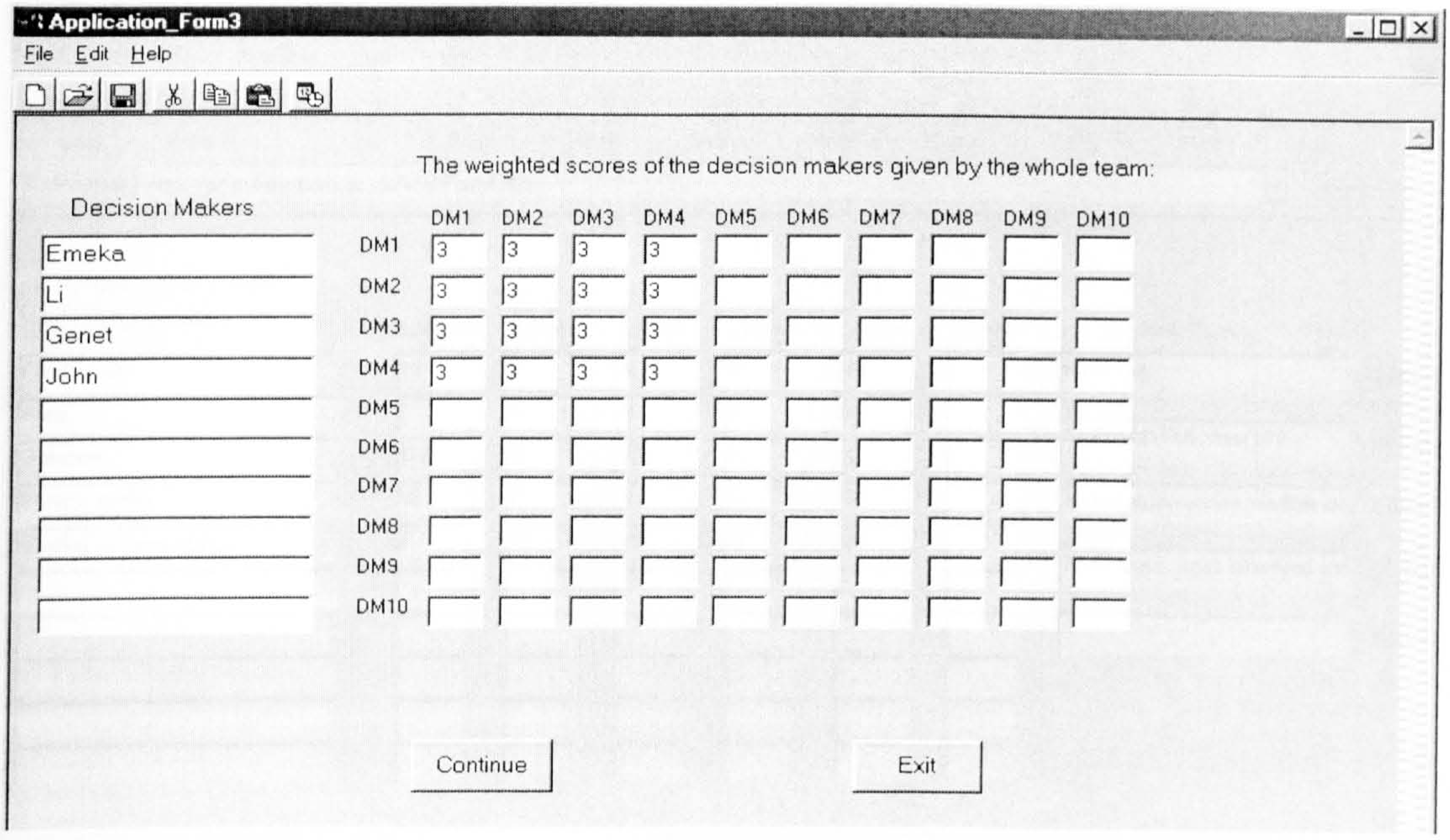


Fig. 6.5 Equal Weightings of Decision Makers Integrated by the System (Generic Scenario)

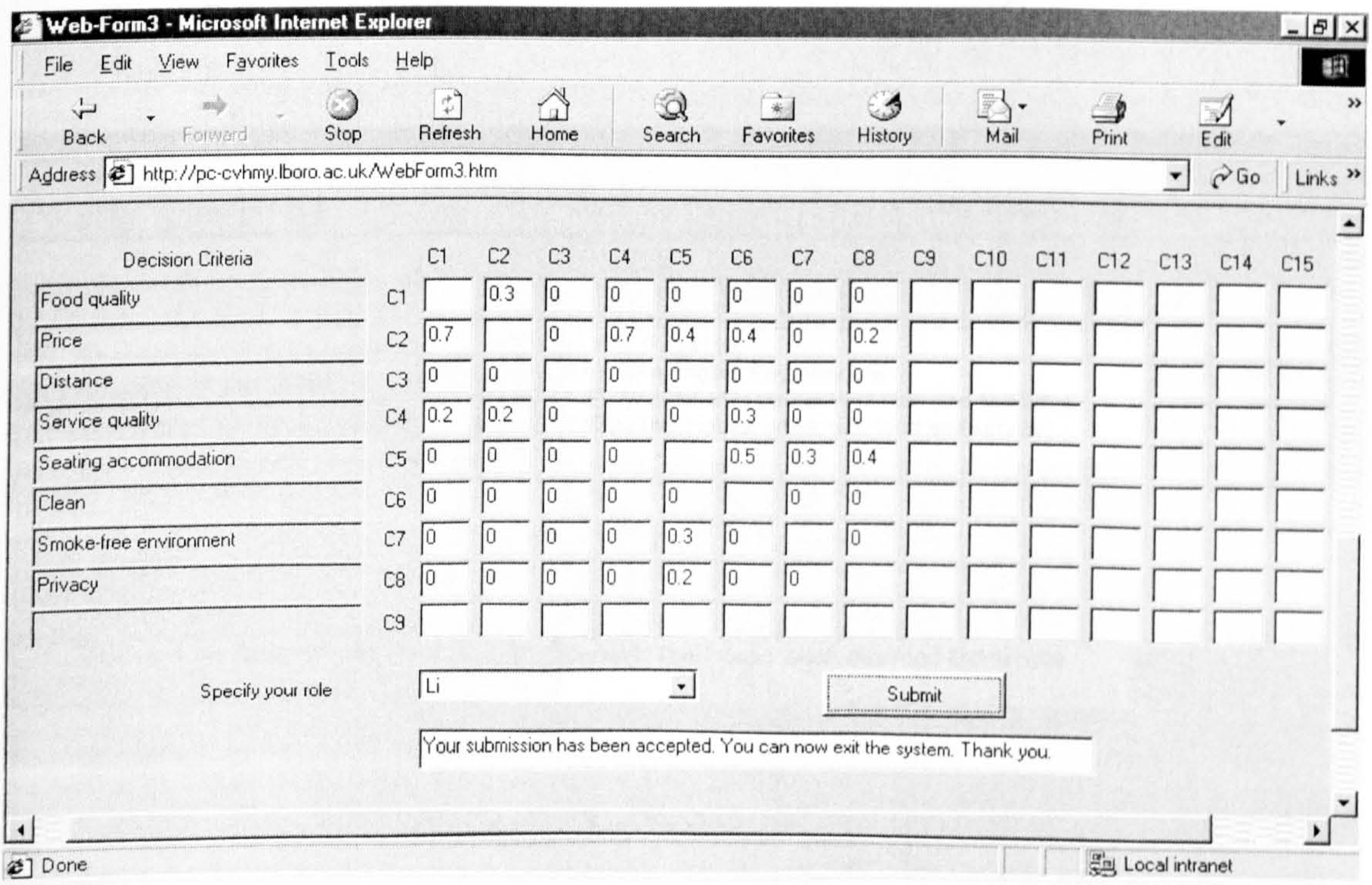


Fig. 6.6 Contribution Degrees between Criteria Specified (Generic Scenario)

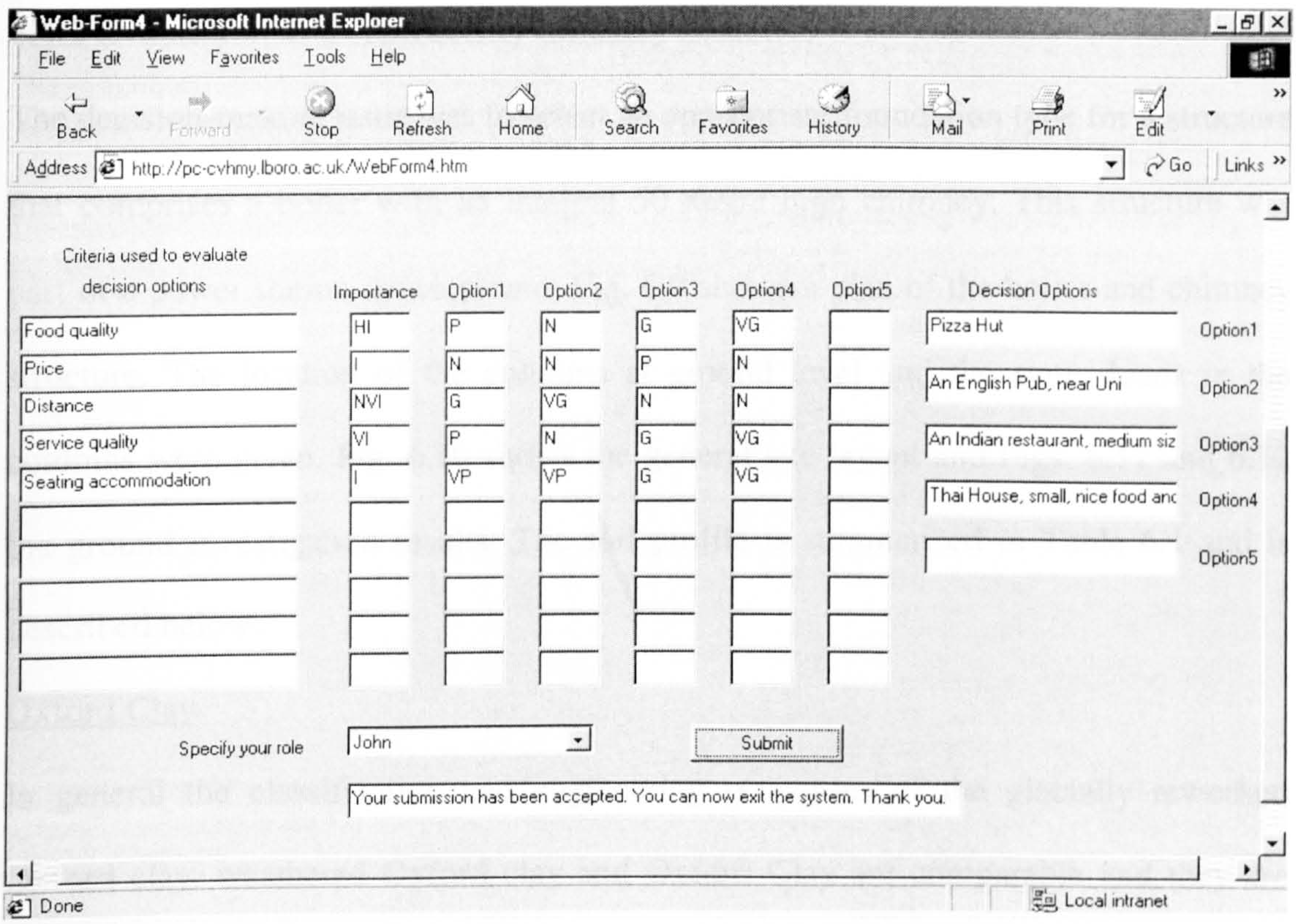


Fig. 6.7 Criteria and Options Ranked by the Participants (Generic Scenario)

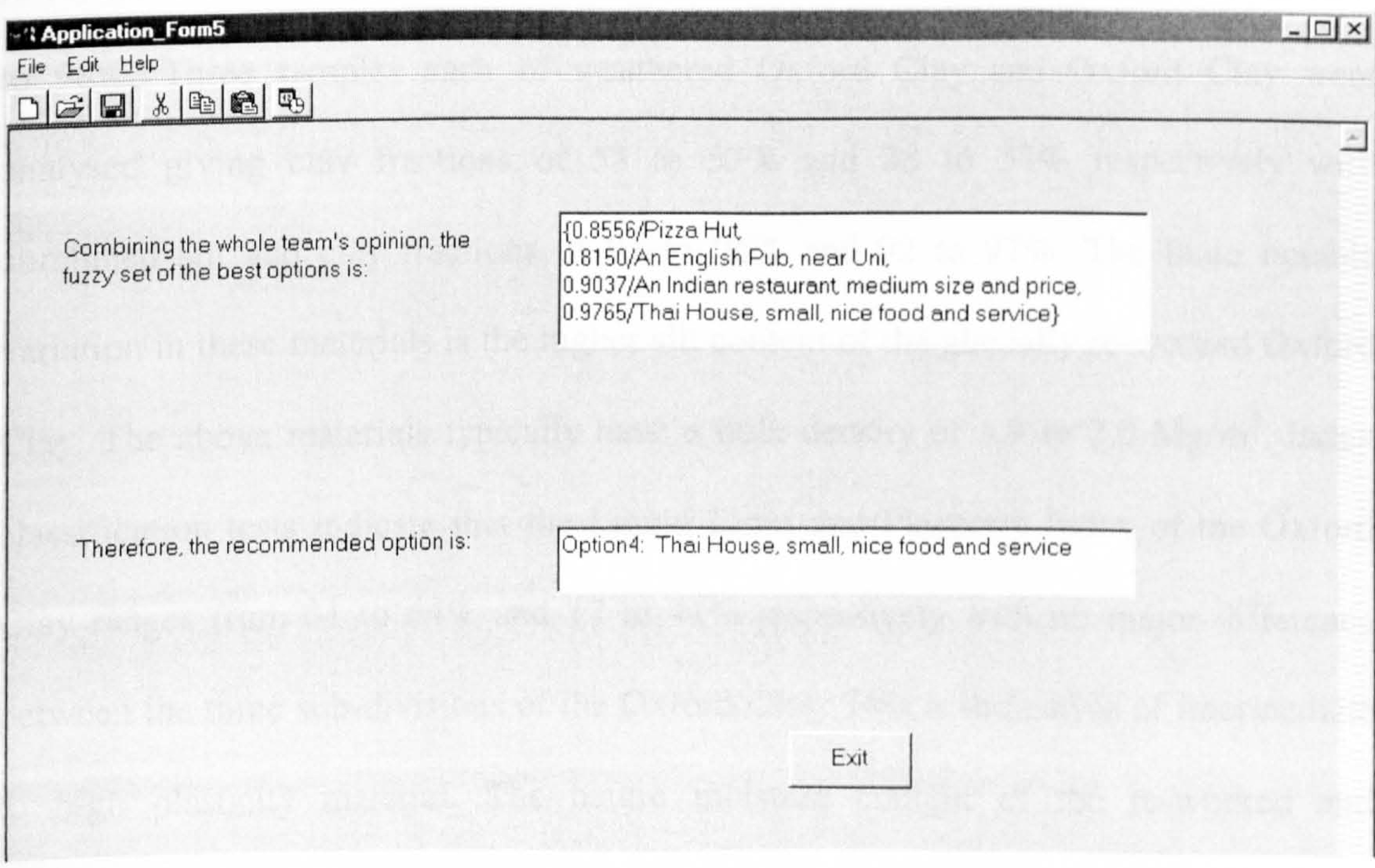


Fig. 6.8 Preferred Option Recommended by the System (Generic Scenario)

6.4.2 Evaluation 2: Construction Industry Scenario

The decision-making issue was to select an appropriate foundation type for a structure that comprises a boiler with an integral 50 metre high chimney. This structure was part of a power station development. Fig. 6.9 shows a plan of the boiler and chimney structure. The location of the columns at ground level and the static loads in the columns were given. Fig. 6.10 shows the general site layout and Figs. 6.11 and 6.12 the ground investigation results. The soil profile is summarised in Table 6.1 and is described below:

<u>Oxford Clay</u>

In general the classification and engineering properties of the glacially reworked Oxford clay, weathered Oxford clay and Oxford Clay are comparable and they are therefore reported together. However where difference occurs the strata are discussed separately. Sedimentation analyses were carried out on two samples of glacially reworked Oxford Clay fractions of 23% and combined silt and clay fractions of 95% to 98%. Three samples each of weathered Oxford Clay and Oxford Clay were analysed giving clay fractions of 53 to 57% and 38 to 57% respectively with combined silt and clay fractions of 91 to 96% and 92 to 97%. The main notable variation in these materials is the higher silt content of the glacially re-worked Oxford Clay. The above materials typically have a bulk density of 1.9 to 2.0 Mg/m^3. Index classification tests indicate that the Liquid Limit and Plasticity Index of the Oxford Clay ranges from 31 to 64% and 17 to 41% respectively with no major difference between the three sub-divisions of the Oxford Clay. This is indicative of intermediate to high plasticity material. The nature moisture content of the re-worked and weathered Oxford Clay was found to be in the range 22 to 28%, and in Oxford Clay 12 to 27%.

Table 6.1 Summarised Soil Profile In Construction Industry Evaluation

Depth to Base of Stratum (m)	Approximate Range of Thickness (m)	Description
1.2-1.8	0.6-0.8	Topsoil with black, grey and orange bands of pulverised fuel ash, coal ash and gravel clinker, sandy clay with bricks and plastic bags. (TPs 2 and 3, BHs 3,5, and 9) (MADE GROUND)
0.6-0.8	0.35-0.7	Black and Brown mottled clayey sandy fine to coarse flint gravel (BH 6, TPs 4 and 5). (MADE GROUND)
0.7-4.3	0.4-4.3	Firm brown or dark grey mottled brown slightly sandy silty clay with some fine to coarse flint and coal gravel (BHs 1-6 and 9, TP1) (MADE GROUND)
2.0	1.2	Soft to firm brown sandy CLAY with some fine to medium gravel (BH7, 7A) (ALLUVIUM)
5.2	3.2	Medium dense to dense yellow brown fine to coarse GRAVEL (BH7, 7A) (TERRACE GRAVELS)
2.0-4.7	0.4-1.95	Firm orange brown mottled light grey structureless silty CLAY with occasional medium gravel sized carbonate nodules and rootlets (BH1-6, 8 and 9) (GLACIALLY REWORKED OXFORD CLAY)
5.0-7.2	2.3-4.2	Firm orange brown mottled light grey thinly laminated extremely to very closely fissured CLAY with grey greying on fissures and with selenite crystals and occasional thin bands from hard to very weak silt/siltstone (BHs 1-6, 8 and 9) (WEATHERED OXFORD CLAY)
Not proven	Not proven	Stiff to very stiff light green/grey thinly laminated CLAY with occasional shells and closely spaced fissures becoming very stiff to hard dark grey green thinly laminated CLAY with occasional shells and shell fragments (BHs 1-4 and 8) (OXFORD CLAY)

The decision-making team was required to choose from four decision options:

1. A large raft over the whole area. It would have to be deep. Its rough size is 22m×15m×3m.
2. Individual pile-caps with piles
3. Strips (2 number) with piles
4. Large raft and piles (raft would be shallower than the one in option 1)

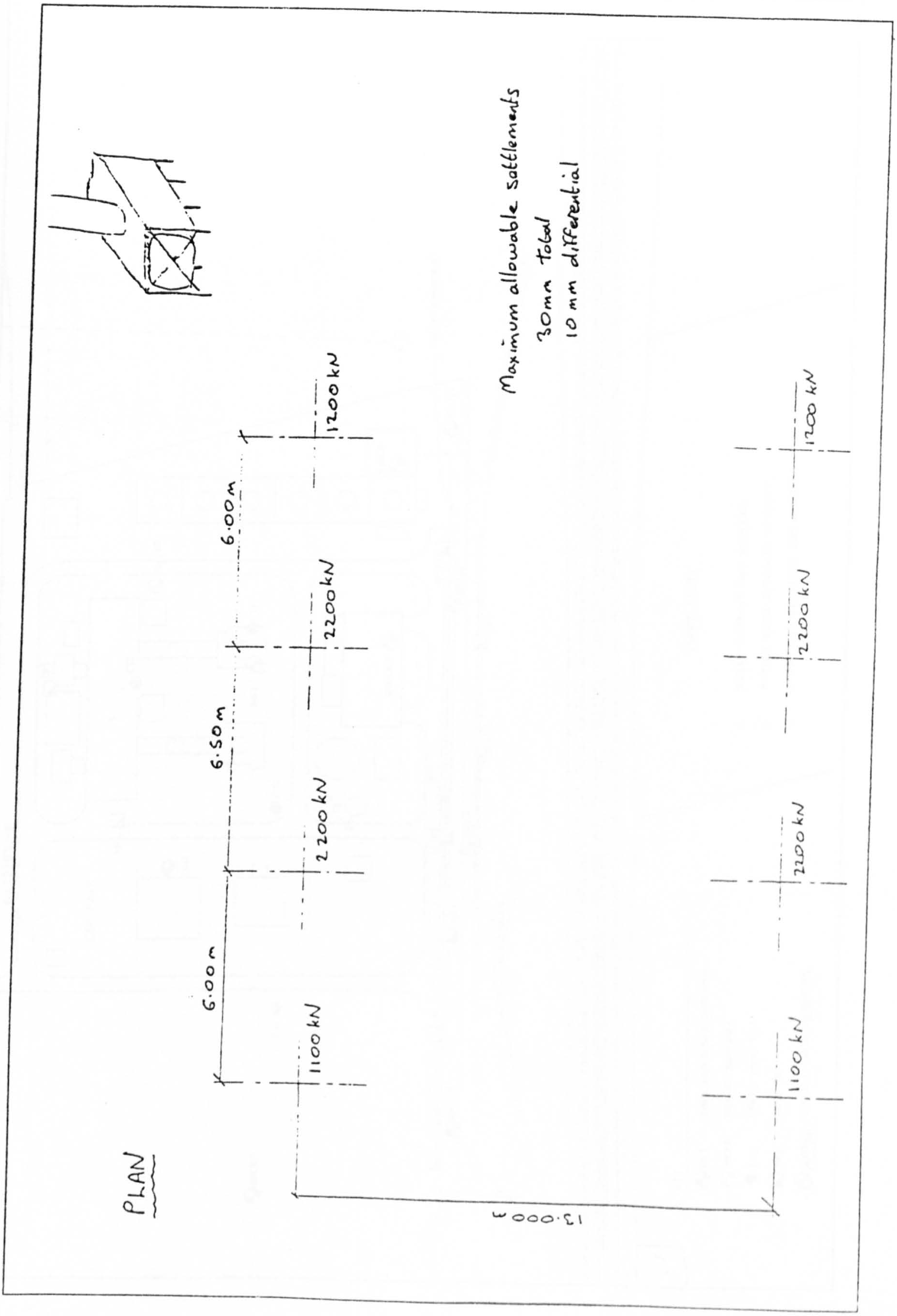


Fig. 6.9 Location of Columns and Loads

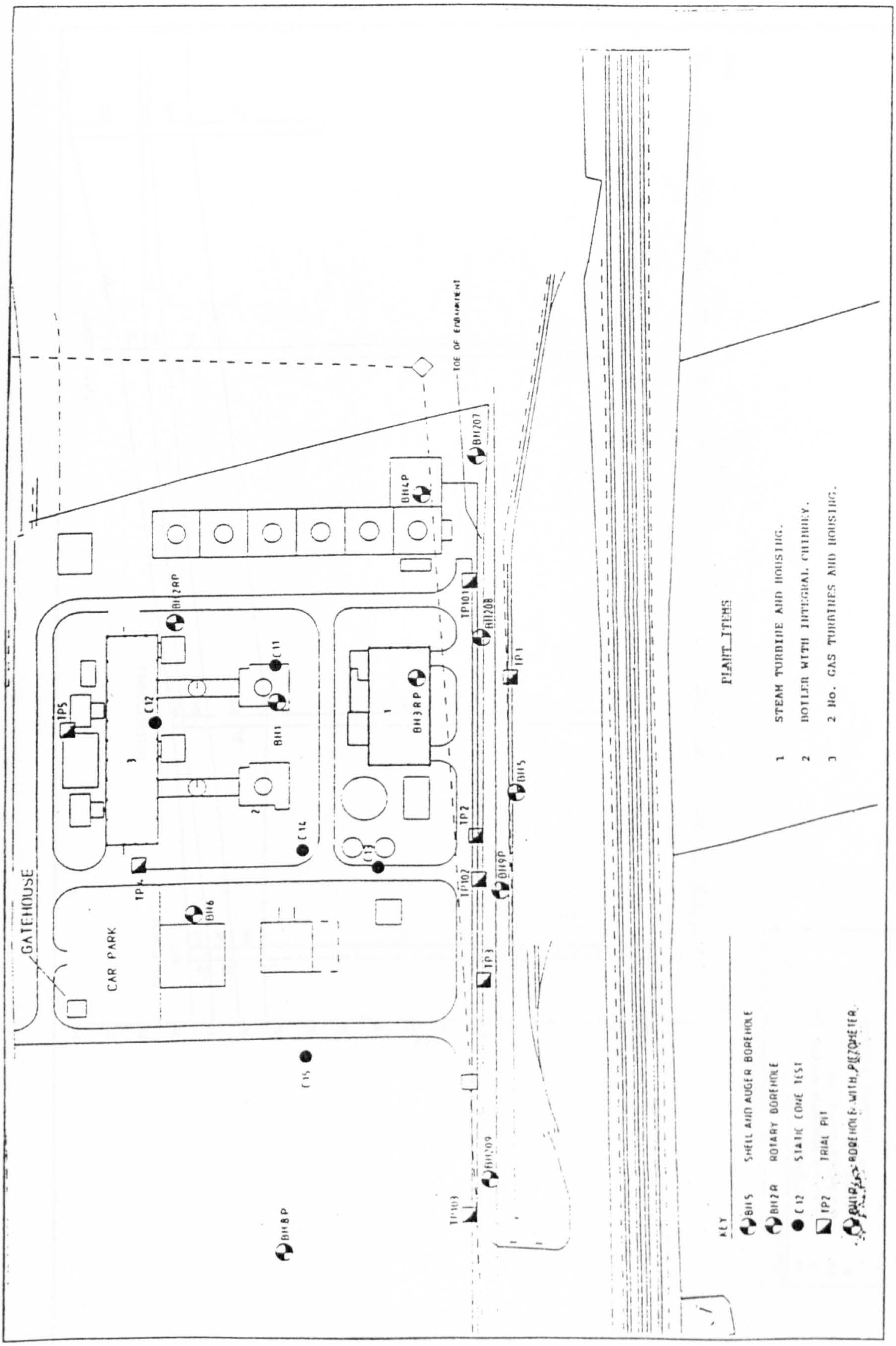


Fig. 6.10 Location of Exploratory Holes

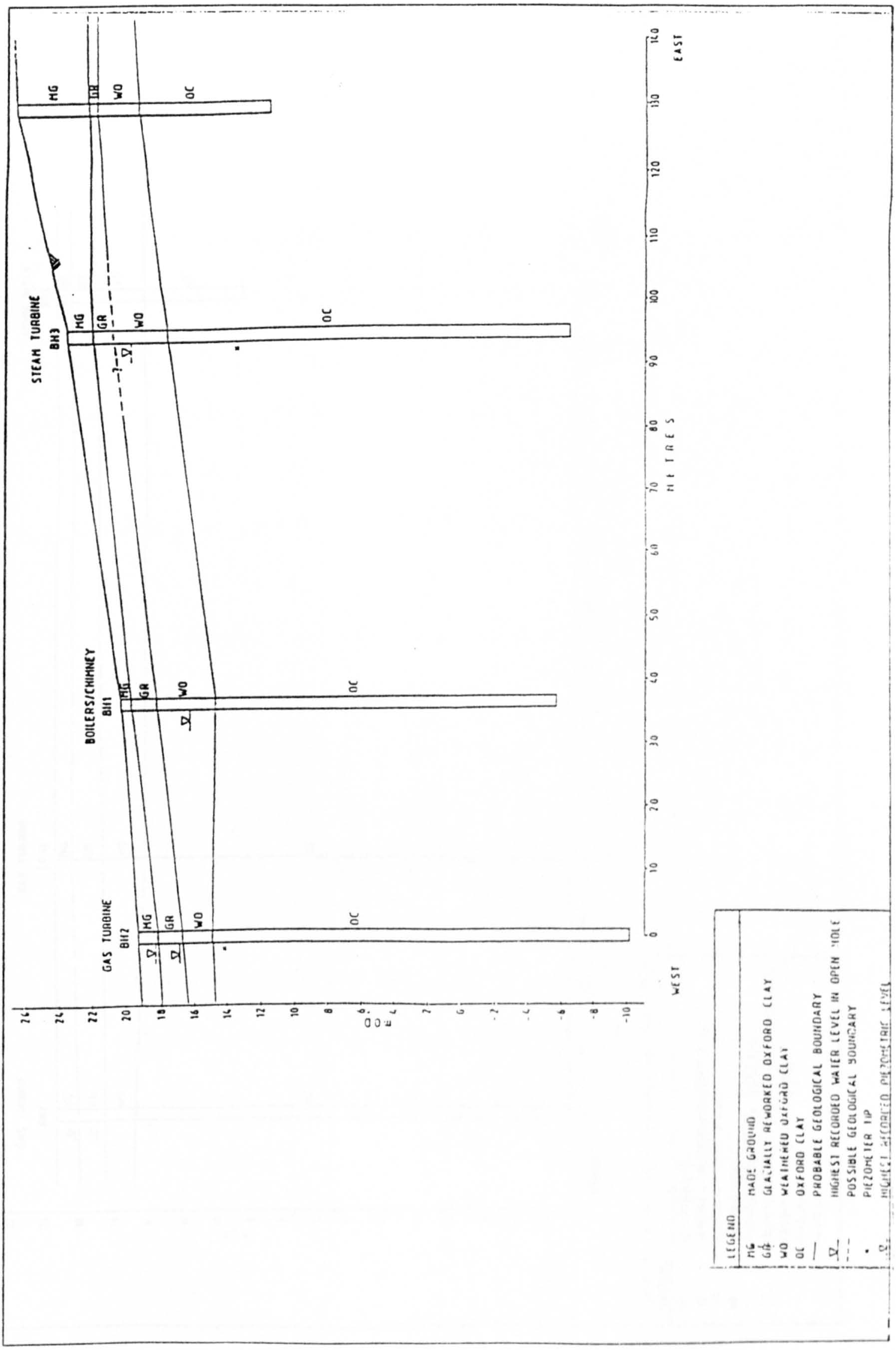


Fig. 6.11 Cross-Section through Gas Turbine, Boilers and Steam Turbine

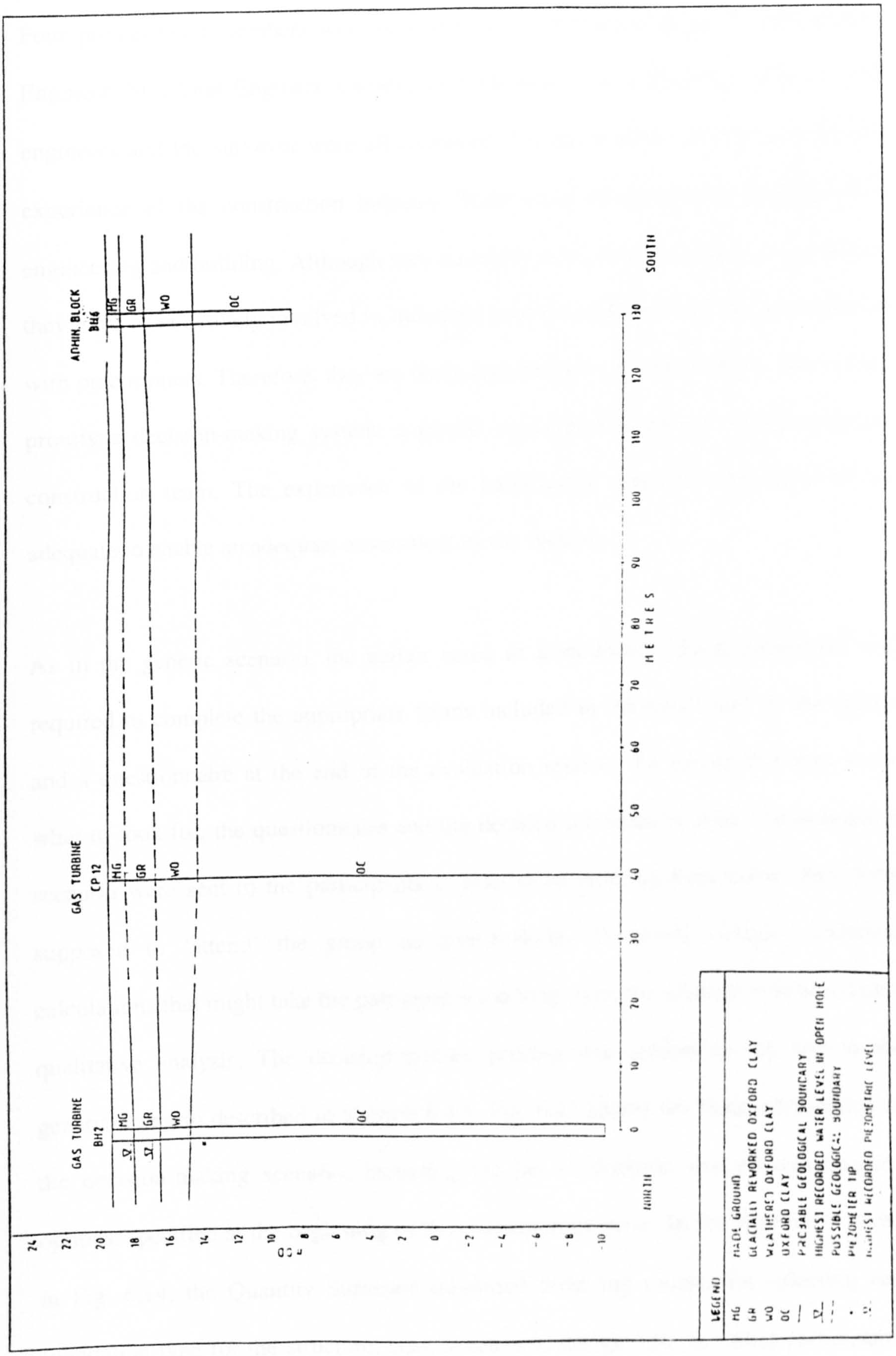


Fig. 6.12 Cross-Section through Gas Turbines

Four project team members were involved in the decision-making: a Geotechnical Engineer, Structural Engineer, Construction Manager, and a Quantity Surveyor. The engineers and the surveyor were all chartered. The participants all had considerable experience of the construction industry. Their areas of experience included civil engineering and building. Although they currently work in an academic environment, they have been actively involved in industrial practice and have had close connection with practitioners. Therefore, they are fairly representative of the potential users of the prototype decision-making system: a project manager and his/her multidisciplinary construction team. The experience of the participants was also considered to be adequate to enable an adequate assessment of the system.

As in the generic scenario, the author acted as a moderator. Each participant was required to complete the appropriate forms included in the email sent by the author and a questionnaire at the end of the evaluation session. To ensure that they knew what to look for, the questionnaire and the detailed information about the evaluation scenario were sent to the participants at least three working days before they were supposed to 'attend' the group decision-making. To avoid complex technical calculations that might take the participants too long time, the scenario was based on a qualitative analysis. The decision-making process was similar to the one in the generic scenario described in Section 6.4.1. Fig. 6.13 shows the basic information of the decision-making scenario, including the list of decision makers and decision options, specified at the beginning of the evaluation exercise. In the Web form shown in Fig. 6.14, the Quantity Surveyor submitted three top criteria for selecting best foundation type for the structure: cost, speed, and design criteria. Other participants' submissions can be seen in Fig. 6.15, which presents the whole team's criteria collated by the system.

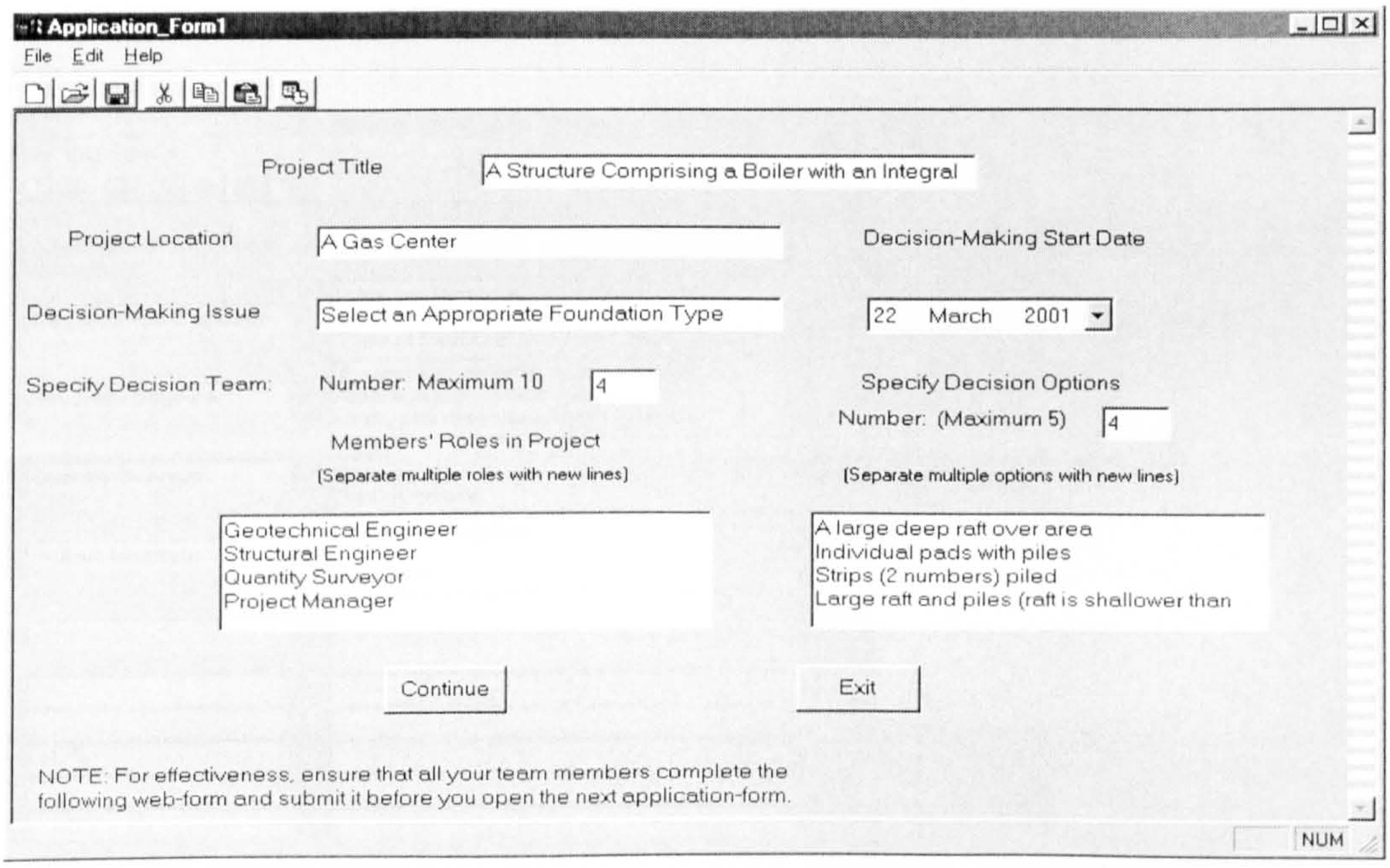


Fig. 6.13 Basic Information about the Decision Issue (Construction Industry Scenario)

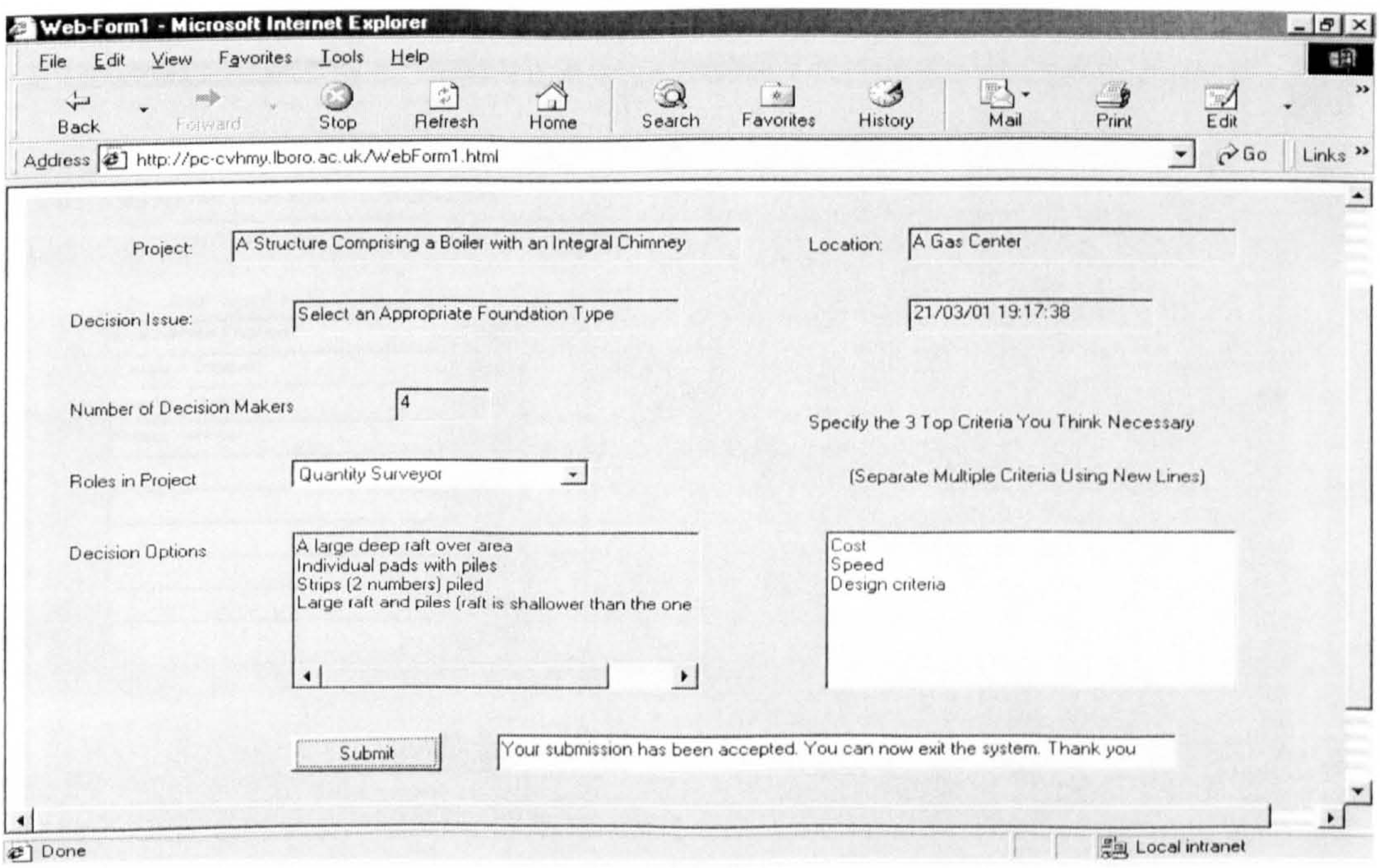


Fig. 6.14 Criteria Given by Quantity Surveyor (Construction Industry Scenario)

All participants weighted the importance of each member of the decision-making team by completing the form shown in Fig. 6.16; the example shown was filled in by the Geotechnical Engineer.

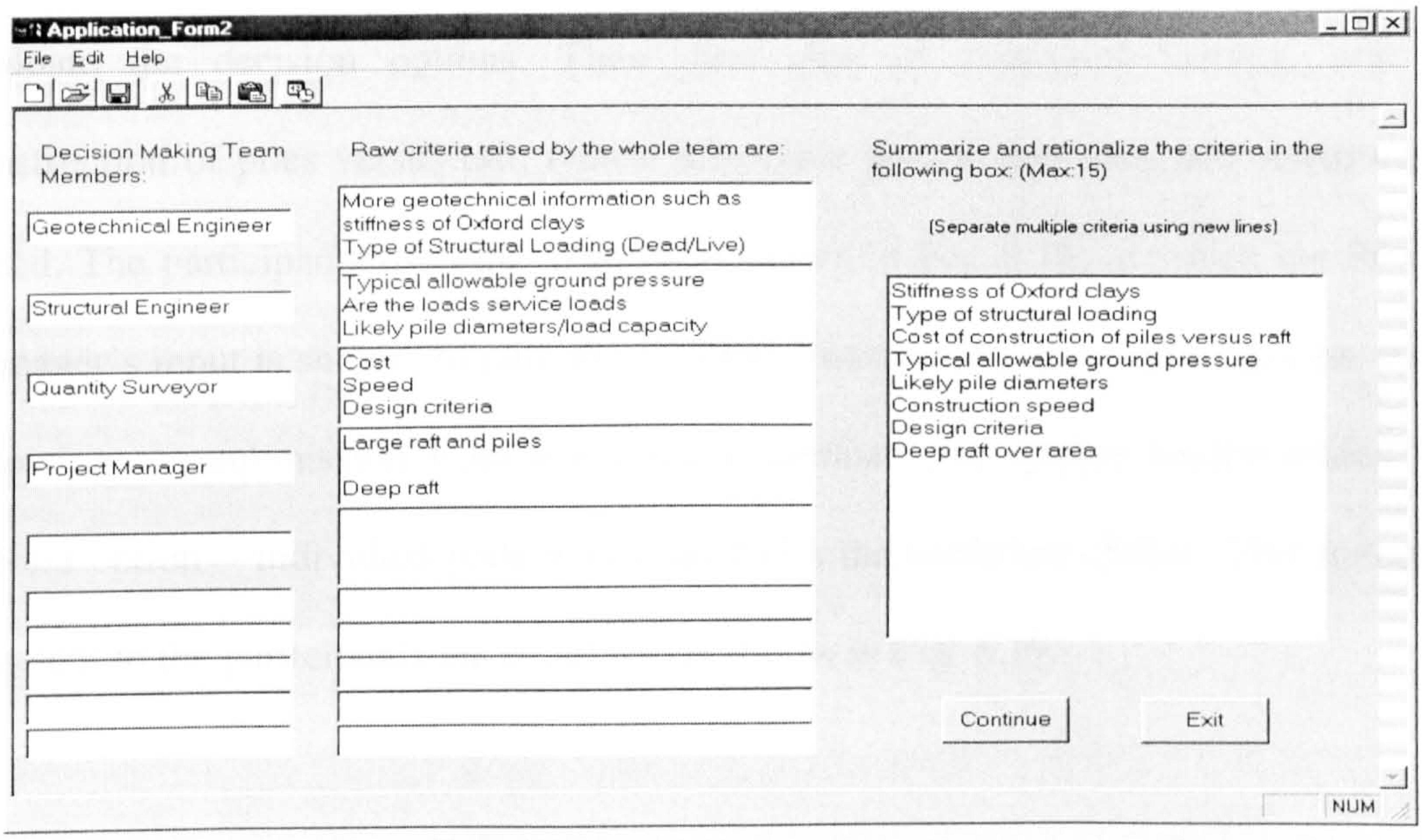


Fig. 6.15 Criteria Collated by the System (Construction Industry Scenario)

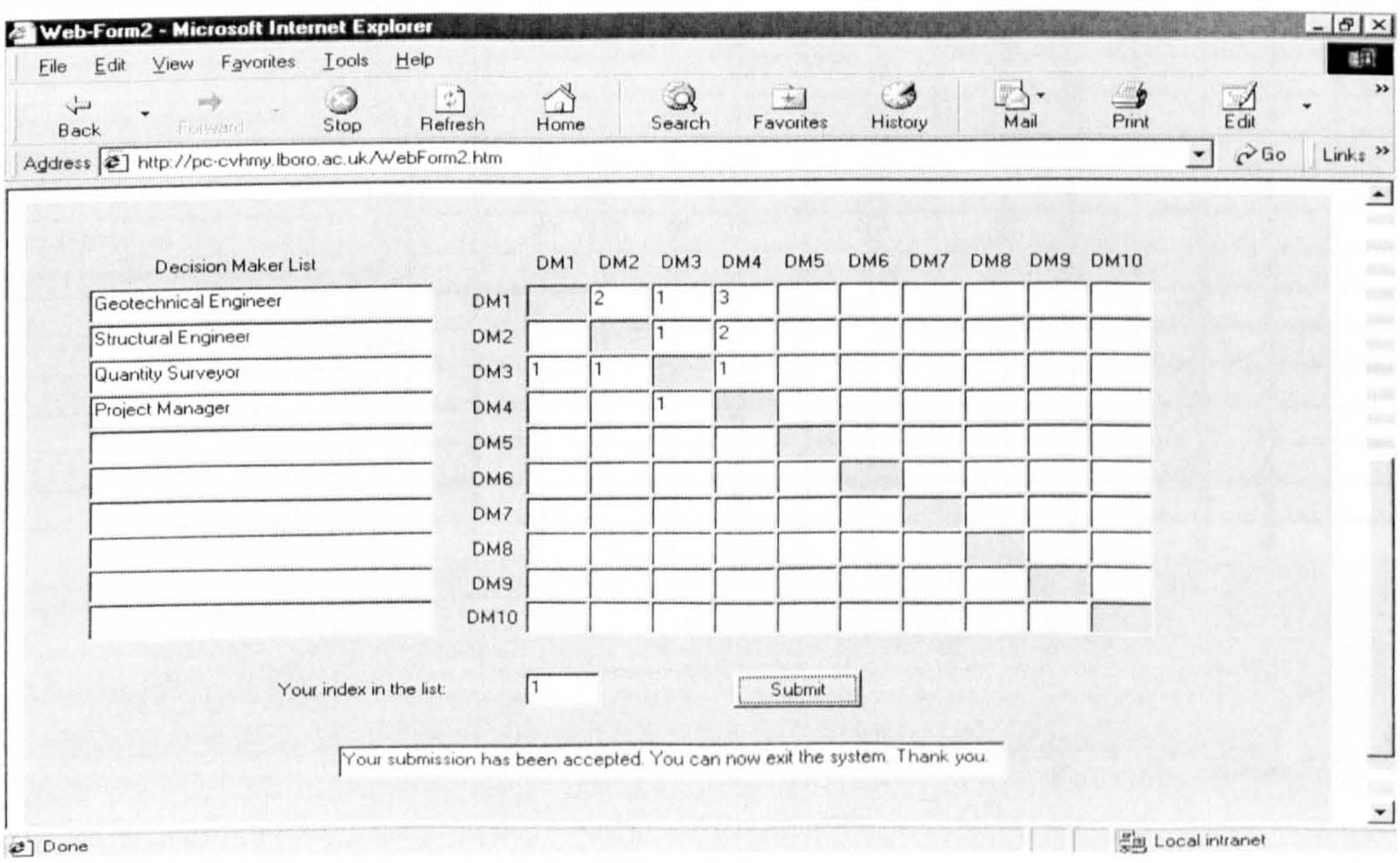
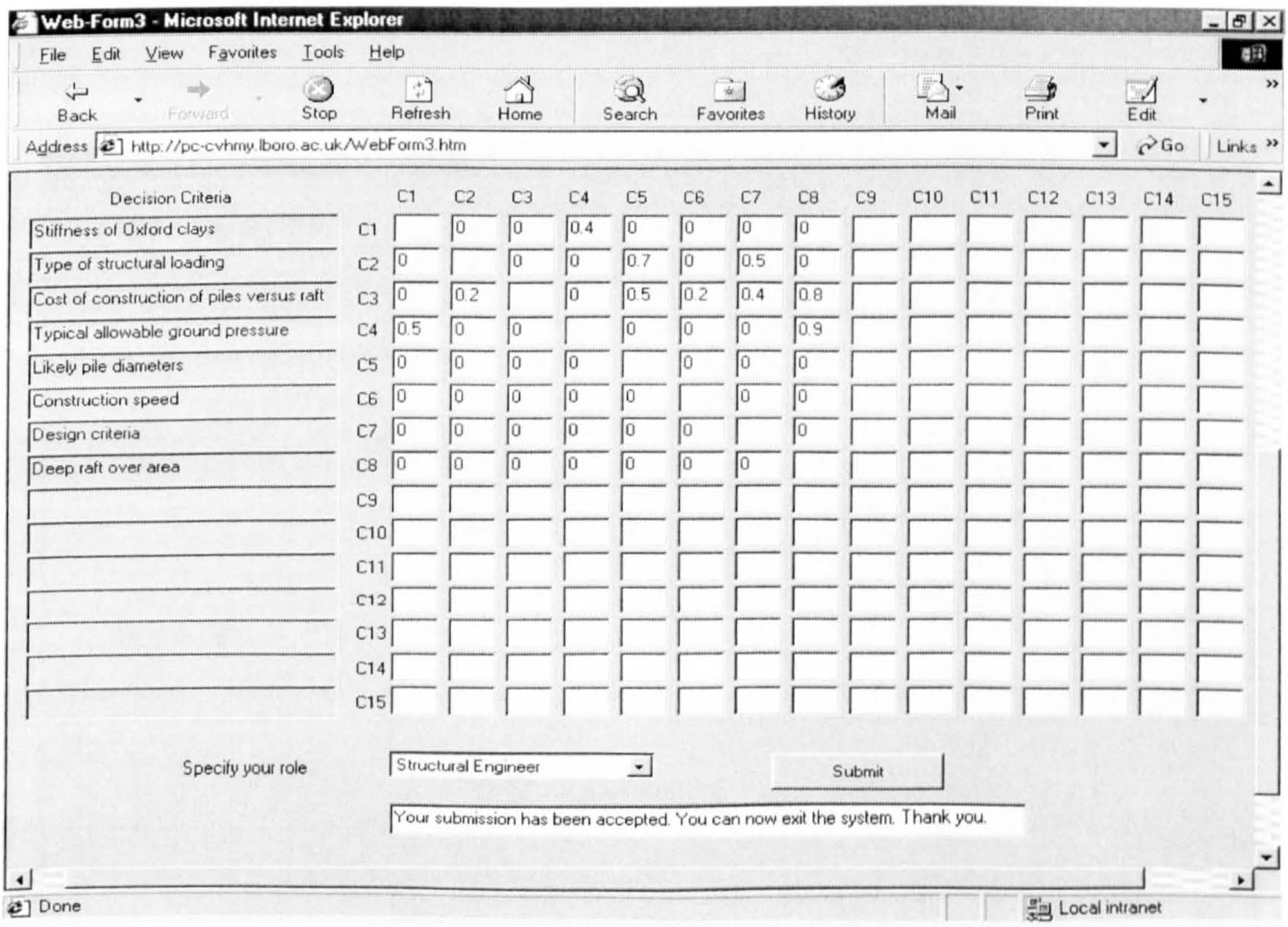


Fig. 6.16 Importance of Decision Makers Weighted by Geotechnical Engineer

(Construction Industry Scenario)

Furthermore, all participants graded the contribution degree between the criteria using the form shown in Fig. 6.17, which shows the input provided by the Structural Engineer. After integrating the importance weightings of the team members and the contribution degree between the criteria, the system chose four criteria to be used to evaluate the decision options. These are: type of structural loading, cost of construction of piles versus raft, typical allowable ground pressure, and construction speed. The participants used the Web form shown in Fig. 6.18, in which the Project Manager's input is shown, to rank the selected criteria and the decision options. After receiving the submission from every team member, the system recommended the second option – individual pads with piles to be the preferred choice. This outcome was sent to the participants via email and is shown in Fig. 6.19.



Decision Criteria		C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	C14	C15
Stiffness of Oxford clays	C1		0	0	0.4	0	0	0	0							
Type of structural loading	C2	0		0	0	0.7	0	0.5	0							
Cost of construction of piles versus raft	C3	0	0.2		0	0.5	0.2	0.4	0.8							
Typical allowable ground pressure	C4	0.5	0	0		0	0	0	0.9							
Likely pile diameters	C5	0	0	0	0		0	0	0							
Construction speed	C6	0	0	0	0	0		0	0							
Design criteria	C7	0	0	0	0	0	0		0							
Deep raft over area	C8	0	0	0	0	0	0	0								
	C9															
	C10															
	C11															
	C12															
	C13															
	C14															
	C15															

Fig. 6.17 Contribution Degree between Criteria Specified (Construction Industry Scenario)

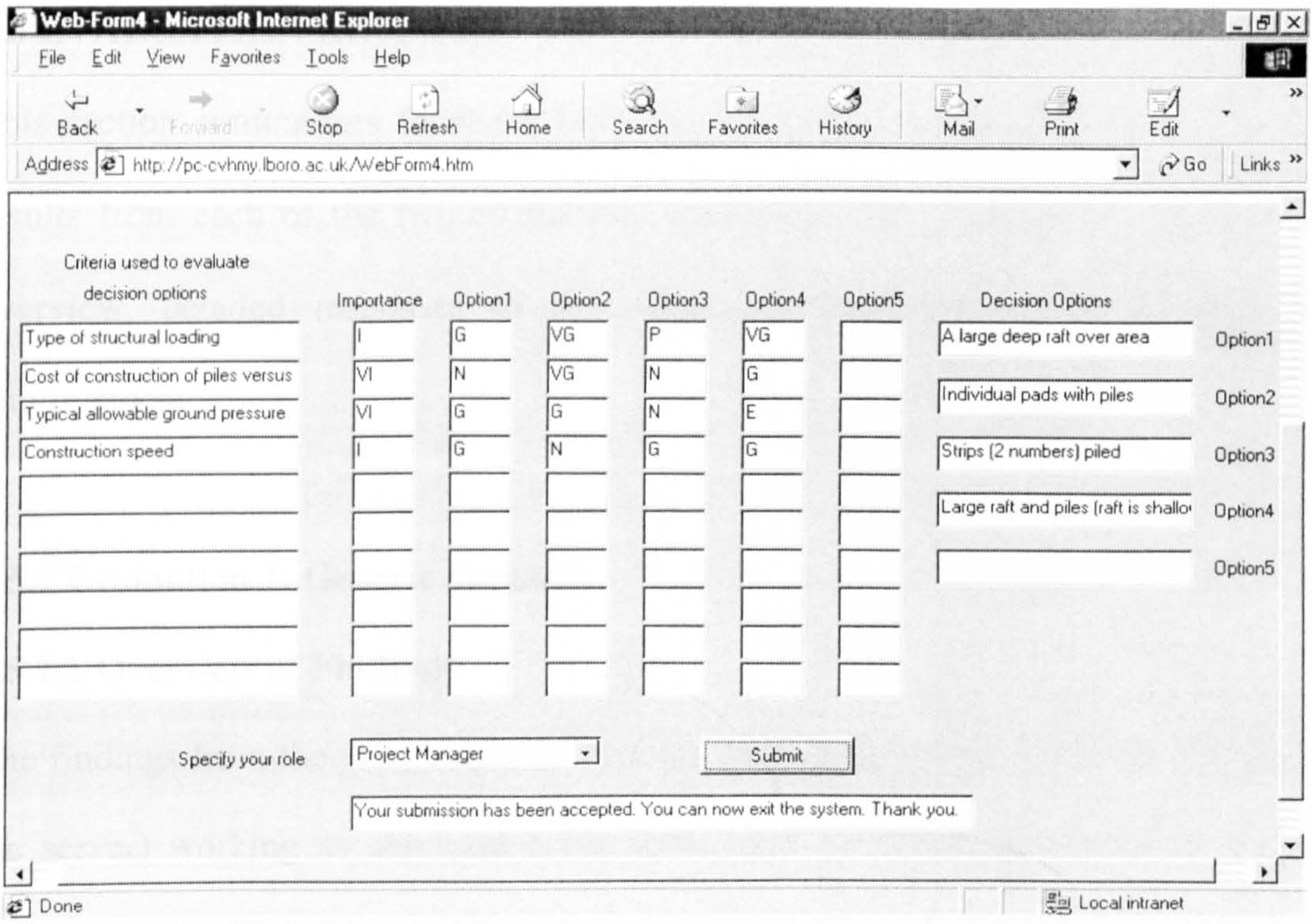


Fig. 6.18 Criteria and Options Ranked by the Project Manager (Construction Industry Scenario)

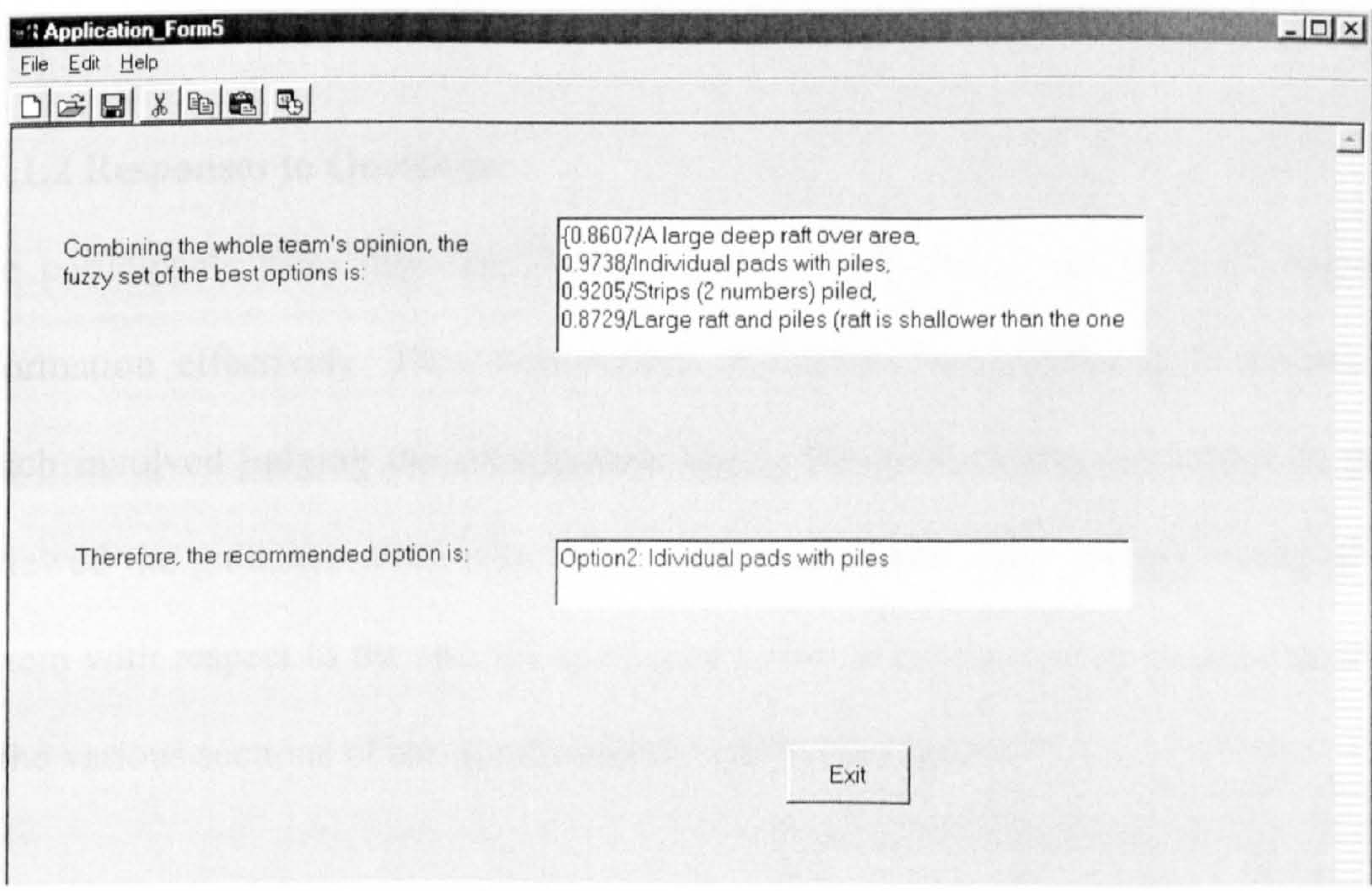


Fig. 6.19 Preferred Option Recommended by the System (Construction Industry Scenario)

6.5 EVALUATION RESULTS

This section summarises feedback from the evaluation participants. It includes the results from each of the two evaluations undertaken. The presentation includes an overview, detailed responses to the evaluation questions, and suggestions for improvement.

6.5.1 Evaluation 1: Generic Scenario

6.5.1.1 Overview of Findings

The findings from the pilot evaluation mainly include the system network (especially the server) working as anticipated and some ideas for improving the guidance for completing the Web forms. The performance of the system was judged to be highly satisfactory. The rating of the questions in the questionnaire showed that the prototype decision-making system can adequately fulfil the function for it was designed in generic decision-making scenarios.

6.5.1.2 Responses to Questions

The participants were impressed with the way the Client-Server system integrated information effectively. They experienced difficulties in completing WebForm3 – which involved judging the contribution degree between criteria, and most of them reviewed the guidance more than once. Table 6.2 provides the average rating of the system with respect to the specific questions in the questionnaire. A detailed analysis of the various sections of the questionnaire is presented below:

Table 6.2 Summary of Feedback Questionnaire in Generic Scenario

		Ranking (out of 5)	
TEAM WORK		Avg.	%
1	How well does the system facilitate group decision making by geographically distributed project team members?	4.25	85
2	How well does the system encourage objectivity in group decision-making?	4.00	80
3	How well does it eliminate unhealthy behaviour in group decision-making?	4.00	80
4	How appropriate is the role of the decision-making team leader as implemented in the system?	3.50	70
APPLICABILITY TO PRACTICAL DECISION-MAKING CASE			
5	How appropriate are the linguistic terms for ranking decision criteria/options?	4.25	85
6	How well does the system deal with fuzzy linguistic expressions during the practical decision-making process?	3.75	75
7	How accurately does the system structure actual decision-making procedure (any major aspects/steps missed or unnecessary)?	4.00	80
8	How appropriate are the limitations on numbers of team members, criteria and solution options in the system?	3.75	75
9	How accurate was the final decision suggested by the system?	4.00	80
MANAGEMENT OF SYSTEM INTERACTION			
10	How attractive is the graphical user interface of the system?	3.50	70
11	How easy is the use of the system?	3.50	70
12	How easy/clear are the instructions for completing the forms?	3.25	65
13	To what extent does the system allow the choice of the optimum decision option?	4.00	80
14	How easily can the system's output be understood?	4.25	85
EFFICIENCY			
15	How convinced are you that the system can be used easily within a project team, particularly in a concurrent engineering environment?	4.00	80
16	How efficient is the overall method for decision-making within a construction project team?	4.00	80
17	To what extent does the fuzzy-based approach adopted in the system benefit collaborative decision-making within a construction project team?	4.25	85
GENERAL			
18	Rate how confident you are with computers (generally)	4.25	85
19	How generic do you consider the system to be?	4.25	85
20	What is your overall rating of the system?	4.00	80

<u>TEAMWORK</u>

The high ranking (85%) for the first question reflected that the Web-based system effectively facilitated group decision-making by geographically distributed team members. The individual scores were 4, 5, 4, and 4 respectively. It was also accepted by the participants that the pairwise comparison of the team members' importance encouraged objectivity and eliminated unhealthy behaviour in group decision-making. The participants all gave a score of 4 to questions 2 and 3 in the questionnaire. The scores for the fourth question in the questionnaire were slightly lower – 3, 3, 4, and 4. This was because the whole system, which includes both the Client part and the Server part, was only demonstrated to the two participants in the department. The other two participants in another university and in industry were not able to view the Server part, which is designed to be managed by the leader of the decision-making team. The author described the function of the Server part via telephone and email so as to enable them to answer the fourth question in the questionnaire – with a score of 3 each.

APPLICABILITY TO PRACTICAL DECISION-MAKING CASE

The linguistic terms used for ranking decision criteria and options in the system were regarded as appropriate by all the participants who gave it high marks. The ability of the system to handle fuzzy linguistic expressions also positively impressed the participants who rated it with the individual marks 5, 4, 3, and 3. The highest mark was made by one of the researchers who fully understood the working of the system. The system did not miss any major steps for the specific scenario but one of the participants pointed out that the team size designed in the system might be too big (maximum 10 team members) for a collaborative construction project team. The system's output generally matched what the participants anticipated. The four individual marks were 5, 4, 4, and 3 for the accuracy of the final decision option recommended by the system.

MANAGEMENT OF SYSTEM INTERACTION

Two of the participants thought that the user-interface of the system was attractive and scored it 4 out of 5, while the other two suggested that WebForm3 (specifying criteria contribution degree) could be improved. The 'ease of use of the system' was scored 4 and 3 by two pairs of participants. This was probably due to the instructions for completing the form being a little difficult for first-time users. This was reflected in the participants' response to the question 12 – 'is the instruction easy/clear?' - in the questionnaire (average 65%). However, the participants were convinced (average 80%) that the system allowed the optimum decision option to be chosen and understood the output of the system quite easily (average 85%).

EFFICIENCY

All the participants were convinced that the system could easily be used in a concurrent engineering environment and gave it a score of 80% (four people scored it 4 out of 5). The efficiency of the overall method for decision-making within a construction project team was also scored 4 by every participant. The responses to the question on the extent to which the fuzzy-based approach adopted in the system benefits collaborative decision-making were very positive, with an average of 85%. The individual scores were 5, 4, 4, and 4. These scores firmly established the effectiveness of the prototype system in improving the efficiency of collaborative decision-making.

GENERAL

The system was considered very generic – at an average level of 85% and the overall rating the system received was 4 out of 5 (80%), which was based on four individual scores of 4.

6.5.1.3 Suggestions for Improvement and Other Comments

The suggestions and comments mainly concentrated on improvements to the user-interface. They are summarised as follows:

- The wording in the instructions for completing the forms could be improved;
- Could a slide slot of values be used instead of filling in values manually in the Web forms?
- In WebForm3 (specifying contribution degree between criteria), the diagonal text boxes should be shadowed and non-editable as they were in WebForm2;
- The text boxes in Webform3 appeared complex and time-consuming;
- Could the best decision option recommended be seen on the Web as well?

Some of these suggestions and comments were addressed immediately, e.g. wording adjusted in the guidance for completing the forms, while others were left for future work.

6.5.2 Evaluation 2: Construction Industry Scenario

6.5.2.1 Overview of Findings

The findings from the construction industry evaluation include positive responses from the evaluators and their suggestions and comments on the performance of the prototype decision-making system. The evaluators were generally satisfied with the performance of the system although they did suggest some necessary improvements to the system for some particular decision-making situations. Some of the ideas were very constructive for future improvements to the system. The rankings the system received showed that the system is considered an appropriate and effective decision-making tool for collaborative construction project teams.

6.5.2.2 Responses to Questions

Table 6.3 provides the average rankings of the effectiveness of the system with respect to the specific questions in the questionnaire. In most areas, the average rating was 3.5 and above out of 5. The highest average rating of the system was 4 out of 5 (80%), and the lowest was 3.25 out of 5 (65%). The details of these scores are discussed below:

TEAMWORK

The evaluators were convinced that the system could facilitate group decision-making by geographically distributed project team members with an average rating of 3.5 out of 5 (70%). Both the Project Manager (PM) and the Geotechnical Engineer (GE) gave a score of 4 to this aspect while the Structural Engineer (SE) and the Quantity Survey (QS) scored it 3. The SE and QS believed that the Internet was an easy way to link remote working team members but there was not enough information included in the Web forms in the scenario, which also affected their responses to later questions. The evaluators supported the idea that the system encourages objectivity and eliminates unhealthy behaviour in group decision-making with an average score of 80%. The highest score of 5 for question 2 in the questionnaire came from the GE while the lowest (3) came from the QS and the PM. The individual scores for question 3 were 5

(GE), 4 (PM), 4 (QS), and 3 (SE). The appropriateness of the role of the decision-making team leader received relatively low ratings (4, 4, 3, 3) because the evaluators were not involved in using the Server part in the system.

Table 6.3 Summary of Feedback Questionnaire in Construction Scenario

		Ranking (out of 5)	
TEAM WORK		Avg.	%
1	How well does the system facilitate group decision making by geographically distributed project team members?	3.50	70
2	How well does the system encourage objectivity in group decision-making?	4.00	80
3	How well does it eliminate unhealthy behaviour in group decision-making?	4.00	80
4	How appropriate is the role of the decision-making team leader as implemented in the system?	3.50	70
APPLICABILITY TO PRACTICAL DECISION-MAKING CASE			
5	How appropriate are the linguistic terms for ranking decision criteria/options?	3.75	75
6	How well does the system deal with fuzzy linguistic expressions during the practical decision-making process?	3.66	73
7	How accurately does the system structure actual decision-making procedure (any major aspects/steps missed or unnecessary)?	3.00	60
8	How appropriate are the limitations on numbers of team members, criteria and solution options in the system?	4.00	80
9	How accurate was the final decision suggested by the system?	3.75	75
MANAGEMENT OF SYSTEM INTERACTION			
10	How attractive is the graphical user interface of the system?	3.50	70
11	How easy is the use of the system?	3.25	65
12	How easy/clear are the instructions for completing the forms?	3.25	65
13	To what extent does the system allow the choice of the optimum decision option?	4.00	80
14	How easily can the system's output be understood?	4.00	80
EFFICIENCY			
15	How convinced are you that the system can be used easily within a project team, particularly in a concurrent engineering environment?	3.75	75
16	How efficient is the overall method for decision-making within a construction project team?	3.50	70
17	To what extent does the fuzzy-based approach adopted in the system benefit collaborative decision-making within a construction project team?	4.00	80
GENERAL			
18	Rate how confident you are with computers (generally)	4.25	85
19	How generic do you consider the system to be?	3.75	75
20	What is your overall rating of the system?	3.75	75

APPLICABILITY TO PRACTICAL DEICISON-MAKING CASE

The fuzzy linguistic expressions used in the system were considered appropriate with an average rating of 75% (4, 4, 3, and 3 individually) but on 'how well does the system deal with the expressions', the GE and the PM gave a score of 4, the SE a score of 3 while the QS stated that he did not know. This was due to a lack of understanding of the system. A relatively low score (60%) was given to the accuracy with which the system structures the actual decision-making procedure; this was mainly because of the lack of detailed technical data to support option ranking (in WebForm4) for the specific geotechnical problem. The structural engineer deemed that some steps were missed (e.g. geotechnical engineer and quantity surveyor must exchange technical data, which must also be passed to structural engineer and project manager, before the decision options were ranked). However, as stated earlier (see Section 4.3), it is assumed that team members have had full details of decision options before the decision-making starts. Although the question 'appropriateness of the limitations on numbers of team members, criteria, and options in the system' was given a high ranking (80%), the PM suggested that team members in a real construction project team do not normally exceed 5 (maximum number was set at 10 in the system). The PM believed that the final decision suggested by the system was completely accurate (a score of 5) while the GE scored it 4, while the QS and the SE gave a score of 3.

MANAGEMENT OF SYSTEM INTERACTION

The graphical user-interface was rated at 70% generally while somewhat lower ranking (65%) was given for the ease of use of the system and the clarity of the guidance for completing the forms. Several suggestions and comments addressed the improvement of the user-interface and are discussed in the next section. The evaluators were convinced that the system allowed the optimal decision option to be chosen and gave it an average rating of 80% (all scored it 4 individually). They also found that the system's output was easy to understand (the screen print of the last form on the Server side showing the outcome of the decision was sent to the evaluators via email).

EFFICIENCY

The PM, GE, and SE all considered that the system could be used easily within a concurrent engineering environment, with a rating of 4 out of 5 (80%) while the QS rated it 3 out of 5 (60%). This was probably because the QS is usually concerned about the cost of a construction project and is often short of further information for ensuring a most economic option. The efficiency of the overall method for decision-making was given an average rating of 3.5 out of 5 (70%), with individual scores of 4 (PM), 4 (GE), 3 (SE), and 3 (QS). However, all the four evaluators scored the system 4 out of 5 (80%) on the extent to which the fuzzy-based approach adopted in the system benefits collaborative decision-making within a construction project team. As with the responses of the participants in the Generic Scenario to this question, the positive rating further confirmed the necessity for, and appropriateness of, the prototype system.

GENERAL

The system was considered applicable to wide range of decision-making scenarios with a rating of 3.75 out 5 (75%). The SE and QS agreed that more information should be provided for complex technical decision-making issues. The system received an overall rating of 3.75 out of 5, which demonstrates that the system is generally an effective tool for specific construction industry decision-making scenarios.

6.5.2.3 Suggestions for Improvement and Other Comments

Below is a summary of the comments made by the evaluation participants on ways to improve the prototype system. To facilitate ease of reading, some of the comments have been slightly edited:

Team Work

- a section might be added for showing who decided what, e.g. after WebForm1 (i.e. make ApplicationForm2, which collects raw criteria inputs from the whole team, Web-based)
- consider the situation where the members of a team are located in different countries *(Note: the prototype system is currently able to cope with this)*

Applicability to Practical Decision-Making Case

- some decision-making steps were missed

Management of System Interaction

- some of the forms need slightly better explanations
- there are terms that need to be explained from the start, e.g. criteria
- a function could be added to automatically reject rogue data
- data input for forms to be made simpler through pull-down menus

- the form that involves two decision stages (WebForm4) is best separated to reflect the two stages

Efficiency

- more team interactivity might be needed

General

- cookies could be added to save the information locally (in Web forms) so that decision makers can input data at different times

It is evident that most suggestions relate to system interaction, which indicates that there is still considerable room for improvements to the user interface. The comments on 'team work' area show that the participants desire more transparent communications in the group decision-making environment and tools to facilitate that. The comments on 'applicability to practical decision-making case' were actually targeted at the evaluation scenario rather than the prototype system itself. Since there was inadequate technical data included for the decision options, some of the participants (particularly the engineers) found it difficult to make decisions without more data. Furthermore, it was suggested that the ranking requested in WebForm4 (see Fig. 6.18) should be divided into two level decisions. For example, if 'raft' option was selected, some of the criteria would become irrelevant (although they would still be relevant to 'plies'). This is also the major reason for the suggestion under 'efficiency'. Most of the participants required cost data from the QS before ranking the decision options. This is a constructive point for the system to enhance its ability to cope with complex technical cases. The comment under the 'general' area also concerned the user interface, which is the major area that was suggested for improvement.

6.5.3 Benefits of the System

Although there is room for improvement, the prototype decision-making system provided an effective tool for collaborative decision-making by members of a distributed construction project team. Its effectiveness can be linked to the rankings of the questions in the questionnaire. The average rankings of the questions in the four major areas (from both evaluations) are:

- Team work: 3.69 (74%)
- Applicability to practical decision-making case: 3.55 (71%)
- Management of system interaction: 3.5 (70%)
- Efficiency: 3.83 (76%)

Overall ranking: 3.75 (75%).

Through the evaluation of the system, several practical benefits of the system were demonstrated. These include:

- The system can be utilised by distributed construction project teams to facilitate group decision-making on key issues in a project;
- The unhealthy influence of personality clashes in group decision-making situations can be avoided, allowing for an objective and rational assessment of decision-making options;
- The preference of decision makers can be expressed in natural language terms using a wide set of linguistic variables and modifiers;

- The generic nature of the system makes it applicable to a range of decision-making situations, ensuring wider applicability than conventional knowledge-based systems;
- The system relies on the knowledge of the decision makers thereby ensuring that their function is not usurped by the system and that they remain in control of the decision-making process. This is critical for the validity and acceptability of the outcome of the group decision-making process;
- The system encourages members of a decision-making team to think more carefully about the decision-making criteria and the decision alternatives;
- The system allows team members to revise their contributions by re-filling the Web forms when they discover mistakes or if things have changed.

6.5.4 Limitations of the System

The comments made by the evaluation participants have highlighted some of the limitations of the system, which include:

- The system does not provide variable decision levels/sub-steps when further discussion is needed in a complex technical situation;
- Data cannot be recalled after submission by team members from the client side to the server side. This is due to the Internet security issues. The system, however, allows users to complete a new form which supercedes an earlier submission;
- The application forms can only be opened when adequate information has been received from the preceding Web forms. If the information is less than needed, there is only a procedural message generated by Visual J++, rather than a warning message generated by the system itself. Users of the

application forms may think that the system has 'crashed'. This could be avoided by adding an appropriate function or warning message in the system.

Commentary

The evaluation involved the author acting as a moderator/project manager for the team. In an ideal situation this role would be fulfilled by the lead team member. This was not possible in this case, as there was no time available to train team members to operate and manage the decision-making system.

6.6 DISCUSSION

6.6.1 Results

Overall, the evaluation results are very positive. The participants in both evaluations were satisfied with the performance and effectiveness of the prototype decision-making system. The rankings received from the feedback questionnaire confirmed that the system is suitable to a wide range of decision-making situations although some improvements are needed for some particular complex situations. The system's performance showed that it is able to fulfil all the requisite functions efficiently. Suggestions and comments have been given on various aspects of the system and could form the basis of further work.

From the results of both the pilot evaluation and the construction industry evaluation, it is evident that the objectives set out in Section 6.2 have been achieved, as below:

- All the key objective or subjective reasoning aspects of collaborative decision-making in generic construction scenarios are covered by the system;

- All known errors have been located by the author, during and after the two evaluations. Where appropriate, these have been corrected;
- To assess the performance of the prototype system, a generic decision-making scenario was used in the first evaluation while the second construction-specific scenario involved a multi-disciplinary team. The ratings received in the 'applicability to practical decision-making case' area reflected the overall accuracy of the output of the prototype system – on average 75.8%;
- An average rating of 75.3% was obtained by averaging the rankings in 'management of system interaction' and 'efficiency' in the two feedback questionnaires. This demonstrates the suitability of the developed system for its intended working environment;
- On the question 'to what extent does the fuzzy-based approach adopted in the system benefit collaborative decision-making within a construction project team?', the first group rated the system as high as 85% while the second group rated it at 80%. These figures proved that the adopted approach were ideally suited to the system development.

6.6.2 Comparison of the Two Evaluation Scenarios

There was some variability in the judgement of the evaluators in the two evaluations. One of the reasons for this is that different people have different views of the same things. This is inevitable. On balance, however, the evaluators in the generic scenario were more generous than those in the construction scenario. This is probably reflective of the fact that the second scenario was more realistic (and, therefore, more complex) than the first scenario. Other reasons may include the following:

- The participants in the first evaluation understood the system better since the author often discussed the system during its development, especially with the researchers in the department;
- The participants in the first evaluation had more time for explanation and demonstration than those in the second.

However, the feedback from the second evaluation was more, both in terms of quantity and depth. The suggestions and comments from the first group centred on the user-interface while those from the second group covered nearly every aspect of the system. This is probably because of:

- The scenario in the first evaluation was generic and not specific to the construction field;
- There were not as many complex criteria and technical data involved in the first scenario as in the second one.

6.6.3 Appropriateness of Evaluation Approach

Both the two evaluations were considerably successful. This was manifested by how well the system coped with the two different decision making scenarios and the positive responses obtained from the evaluators. Although there were limitations in some difficult decision-making steps, the evaluators were of the view that future improvements of the system would further facilitate collaborative decision-making within the construction industry for both generic and complex situations. The chosen methodology helped test all aspects of the system required in the evaluation objectives. The reflection from the whole evaluation process include:

- It was a good way to test a Web-based system using people in different organisations and on different operating systems;

- The two scenarios chosen with completely different considerations helped establish the system's suitability for a wide range of decision making situations;
- The questionnaire covered all the major aspects of the system that needed to be tested and was useful for obtaining all the essential feedback from the evaluators;
- The evaluators for the construction industry scenario all had considerable experience in the field and this ensured a relative accurate assessment of the system;
- Both groups of evaluators rated their confidence in the use of computers highly at 85%. Finding people possessing right level of computer knowledge is vital for the evaluation of a Web-based decision-making system. The evaluation approach was right in this regard, although it is recognised that in a real construction setting, not all team participants may be computer-literate.

The evaluation approach had some limitations with regard to the following:

- The pilot evaluation should have been conducted earlier, making it more 'formative';
- A full demonstration for all the evaluators before the start of the evaluation would have been helpful. This was not possible due to time constraints.

In addition, it was hoped that the prototype system could have been tried out on a real project. Unfortunately, there was no access to such a project. This could be done as part of further evaluation and refinement of the system.

6.7 SUMMARY

This chapter has described the evaluation of the prototype collaborative decision-making system, using both a generic and a construction industry scenario. The system has been evaluated in four key areas: how well it facilitates teamwork, its applicability to a practical decision-making case, its management of system interaction, and efficiency. Although the system has some limitations, the evaluation result has shown that the system effectively facilitates collaborative decision-making by a geographically distributed team. Overall, the system's performance was rated highly at 75%.

CHAPTER 7

SUMMARY AND CONCLUSIONS

7.1 INTRODUCTION

This chapter concludes this research project, which focused on the application of fuzzy logic to collaborative decision-making in the construction industry. The investigation resulted in the development of a Web-based collaborative decision making system for construction project teams. This chapter summarises the findings of the research, and the development, implementation and evaluation of the resulting prototype decision-making system. It concludes that a Web-based decision-making system using fuzzy logic is an effective tool for collaborative construction project teams. The chapter ends by making recommendations for further work.

7.2 GENERAL SUMMARY

The aim of the research project was to investigate the applicability of fuzzy logic principles to collaborative decision-making in construction project teams. The investigation was based on the need to facilitate collaborative decision-making within construction project teams where team members are geographically distributed. It focused on the development of a fuzzy-based prototype decision-making model and the development of its Web-based decision-making system. Various tasks and strategies were adopted to achieve the defined objectives of the research. These included: extensive literature review, a pilot industry survey, participation at seminars and conferences to interact with other researchers and professionals in similar research areas, and rapid prototyping.

The review on concurrent engineering and collaborative decision-making revealed that the concept and principles of Concurrent Engineering (CE) are being adopted in the construction industry, and that collaborative decision-making is important in the implementation of CE. However, it was also revealed that existing approaches to collaborative decision making do not adequately address the problems, particularly when the disparate priorities of project team members are expressed in fuzzy linguistic terms, during collaborative decision-making in construction project teams. The literature also suggested that there was a lack of effective tools to facilitate decision-making by members of a geographically distributed project team.

Fundamental theories of fuzzy sets and systems were reviewed. The key concepts and principles adopted in the development of the model, such as linguistic variables, linguistic modifiers and the extension principle, were highlighted. The study showed that fuzzy systems have advantages for tackling uncertainties and imprecision, for which conventional crisp theory and deterministic approaches are not well suited. Fuzzy systems have been widely applied in many areas such as social science, medicine and engineering control. However, the application of fuzzy systems in construction remain few and most studies concern structural engineering issues. Some existing approaches in other disciplines do involve the application of fuzzy system theory to solving decision-making issues but they either do not support group decision-making, only consider the degree of consensus between team members, or do not address multi-criteria decision-making. Limitations were found in the existing studies that intend to develop decision-making systems using fuzzy system theory. Particularly, for group decision-making, there is a lack of effective tools to integrate team members' views in a virtual environment. Some decision support systems developed for the construction industry are only interested in specific issues and do not address the use of fuzzy system theory in decision-making. Furthermore, they are not generic systems that are applicable to a broad range of collaborative decision-making scenarios. There was, therefore, a need to investigate and develop a collaborative decision-making system for construction project teams based on fuzzy logic.

The pilot survey carried out with a selection of industry practitioners confirmed the existence of fuzziness during collaborative decision-making in the construction industry and provided other constructive information. The information included the various stages at which collaborative decision-making takes place; the fact that collaborative decision-making is necessary at both intra-disciplinary and multi-disciplinary levels; as well as current decision-making procedures and techniques.

The investigation into the fundamental theories of collaborative decision-making and fuzzy logic, related studies, and the pilot industry survey, established the base and focus of a fuzzy-based decision-making model for collaborative construction project teams. However, the model had two structural revisions and several minor alterations, following suggestions and discussions with the academic staff involved in the research, fuzzy logic experts, and other researchers at conferences and workshops. The approach adopted a number of concepts and operational principles of fuzzy sets theory, and adapted rationalizing techniques (such as Fuzzy Structural Modelling) from other studies. The model was developed into an Internet-based software using Java. The resulting prototype decision-making system comprises two parts as follows:

1. Server Side: consists of five Java application forms. It allows the leader of the decision-making team (usually the Project Manager) to specify the basic details of the decision-making issue (such as decision options, team members involved, etc.) and to transmit these to all team members. Also, the server enables the leader to collect the information that the team members send (such as decision criteria, importance of decision makers, contribution degree between criteria, and rankings of decision options based on the agreed). It then proceeds with operations and calculations using fuzzy set theory based on the information. The system finally recommends the preferred decision via the server and communicates this to all members of the decision-making team. Textual information placed in the application forms aids users to understand the decision-making steps taking place during the whole decision-making process.
2. Client Side: serves the decision-making team members by providing four Web forms in which four Java applets are embedded. During the decision-making process, the application forms and the Web forms are initiated in turns. The team members receive information that the leader sends to them and submit any inputs required at the client side. The input submitted, as numeric values or in fuzzy linguistic terms, is saved by the server once the user hits the appropriate button in the forms. The Web forms at the client side could be viewed and completed wherever the Internet connection is available. There is guidance at the top of each Web form for completing the forms, written using HTML.

The implementation of the prototype decision-making system revealed that collaborative decision-making in construction project teams can be performed with the aid of a Web-based decision-making system and that fuzzy logic can be applied to tackle the uncertainties and imprecision in the decision-making process. A generic scenario and a construction industry scenario were used to evaluate the prototype decision-making system. The two evaluations were carried out with selected researchers (working in universities and industry) and academic staff in the department with considerable experience of the construction industry. The evaluation confirmed that, in spite of the improvements required to make the system more robust, it does proffer many benefits in facilitating collaborative decision decision-making in construction.

7.3 SUMMARY OF THE SYSTEM'S ADVANTAGES

The advantages (over conventional approaches to group decision-making) that the prototype decision-making system offers to construction project teams, especially members that are geographically distributed, can be summarised as follows:

- It is an effective tool for collaborative decision-making between team members staying in different locations (even different countries) when physical meetings are inconvenient and/or expensive;
- It provides a natural way to express preference for decision makers when information is inadequate or numeric scores are inappropriate;
- It supports objectivity in group decision-making by enabling team members to select the optimal decision alternative without the unhealthy personal biases, influences and conflicts often present in collocated project teams;

- It is a generic tool that could be used for a wide range of decision-making situations and at all stages in a construction project;
- It encourages team members to bring their own disciplinary or individual views or information to the collaborative decision-making process;
- It enhances collaborative working because of the server that integrates the whole team's opinion and sends feedback to each team member;
- It saves time for practitioners in their busy schedule as the team members can complete the Web forms whenever they are available;
- There is the potential for cost savings as the system can facilitate quicker collaborative decision making;
- It provides the basis for further applications of fuzzy logic in decision-making in construction industry;
- It represents a considerable improvement to the existing group decision-making processes in the construction industry.

In real construction practice, decision-making often relies on a lot of technical data. In the five stages of construction (Evbuomwan and Anumba, 1996), especially the design stage; every discipline needs to do some calculations. The calculations may be related, e.g. the structural engineer needs data from the geotechnical engineer during the design of a building. During or before a decision-making session, the data need to be exchanged and discussed. The prototype system does not have in-built provision for communication between individual decision makers during the decision-making process and this may make ranking decision options difficult in some complex cases. However, there is nothing to stop members of the team discussing by telephone, email or other means before completing the Web forms.

Another limitation of the prototype system, as currently implemented, is that the number and flow of the application forms and the Web forms is fixed. In complex decision-making scenarios, there may be need for more flexibility to better represent the sub-steps during the decision-making process.

7.4 CONCLUSIONS

The following conclusions can be drawn from the research:

1. Concurrent Engineering is being adopted in the construction industry and its implementation is reliant on appropriate support for collaborative decision-making;
2. Collaborative working can be enhanced with the support of appropriate IT applications;
3. Fuzzy logic offers great potential for application to collaborative decision-making; but current fuzzy logic-based approaches do not adequately address collaborative decision-making, particularly in the construction field;
4. The prototype decision-making system presented in this thesis represents a unique and innovative approach to collaborative decision-making in construction project teams that:
    - serves as a Web-based medium for integrating the views of geographically distributed members of a construction project team when a physical meeting is inconvenient, time-consuming, and expensive;
    - is distinct from existing decision support systems and group decision support systems as it does not store any specific knowledge about the

decision-making issue; as such, it can be used for a wider range of decision-making scenarios;

- has successfully utilised fuzzy set theory for dealing with fuzzy linguistic expressions during the decision-making process in collaborative construction project teams. This has been achieved through adopting a series of definitions and operational principles of fuzzy set theory and adapting an existing technique – Fuzzy Structural Modelling (FSM);

5. Java development tool packages such as Virtual J++ and Symantec Visual Café, do have capabilities that can be very helpful in rapid prototype development.

7.5. RECOMMENDATIONS FOR FURTHER RESEARCH

This research project has revealed a number of areas for further research and development. These are discussed with respect to the prototype application, fuzzy-based collaborative decision-making, and concurrent engineering in construction.

7.5.1 The Prototype Collaborative Decision-Making System

A number of ways in which the prototype decision-making system can be enhanced include the following:

1. Further improvements to the system with respect to:
   - automating the generation of sub-decision-making steps from an initial set of primary decision-making steps;
   - integration of comprehensive online communication facilities to help decision makers communicate bilaterally, if necessary;

- enhancing user-friendly functions to smooth away system implementing difficulties, e.g., examine and reject improper data, generate a warning message when the system has insufficient inputs, display estimated data processing time;
- improvements to the user interface through better screen layout, better user guidance, and choosing data from supplied ranges rather than typing in data.

2. Further investigation of more uncertain or imprecise facets that collaborative decision-making teams may have in any particular construction stages and add more functions to the system to enable it to cope with more specific situations while retaining its generic feature;
3. Further testing using a wide range of live projects is still necessary as the feedback from these can further demonstrate the system's applicability to different decision-making scenarios;
4. Exploration of possible linkages with other packages, such as geotechnical information systems, material cost systems, or specific knowledge-based systems. This might benefit decision-making on some specific issues.

7.5.2 Fuzzy-Based Collaborative Decision-Making

Areas for further research with respect to the application of fuzzy logic to collaborative decision-making, include:

1. The development of a comprehensive collaborative decision-making system that not only recommends the optimal solution but also analyses the agreement degree of each team member, discloses how the solutions are linked with the criteria. This may involve the application of further aspects of fuzzy logic

theory, such as many-valued first-order fuzzy logic, linguistic logic, and approximate reasoning.

2. Since collaborative decision-making occurs almost throughout the whole construction process but in some stages the participants from some disciplines interact more than those from other disciplines. Therefore, the development of the collaborative decision-making tools and techniques geared explicitly towards different construction stages, especially for those where more team members and conflicts are involved, is required.

7.5.3 Implementation of Concurrent Engineering in Construction

Future research in the context of concurrent engineering in construction and collaborative decision-making would include the following:

1. Development of strategies for the application of concurrent engineering in collaborative decision-making from the perspectives of both the construction process and construction participants. During construction processes, downstream participants have little or no influence at the earlier stages (Anumba and Newnham, 2000); and a typical project involving up to six or more different professional disciplines. Thus the collaborative working strategies smoothing down the construction process and also considering disciplinary needs deliver effective tools for the implementation of concurrent engineering;
2. Research should be conducted into integrating heterogeneous software tools that are being used by different disciplinary participants in a construction project. Adoption of systematic Web-based techniques could meet the needs of the construction industry in implementation of concurrent engineering.

7.6 Closing Comments

Collaborative decision-making is an important component of the implementation of concurrent engineering in construction. A review of current works has shown that none of the existing approaches to collaborative decision-making adequately addresses the needs of distributed construction project teams. This thesis has demonstrated how collaborative decision-making within virtual construction project teams can be significantly enhanced by the use of a fuzzy-based decision-making system. In particular, fuzzy logic is applied to tackle uncertainties and imprecision during the decision-making process. Making the system Web-based also ensures low-cost accessibility for the wide-range of organisations involved in the construction supply chain. The approach encapsulated in the prototype system can also be used for generic decision-making scenarios, as it represents a substantial advance over existing approaches.

REFERENCES

Adlassnig, K. P. (1982), "A Survey on Medical Diagnosis and Fuzzy Subsets", in Gupta, M. M. and Sanchez, E. (eds), *Approximate Reasoning in Decision Analysis*, North-Holland, New York.

Adlassnig, K. P. (1986), "Fuzzy Set Theory in Medical Diagnosis", IEEE Trans. On Systems, Man, and Cybernetics, SMC-16, pp. 203-217.

Ainscough, M. and Yazdani, B. (2000), "Concurrent Engineering within British Industry", Concurrent Engineering: Research and Application, vol. 8, No. 1, pp. 2-11.

Andriessen, J. H. E. (1996), "The Why, How and What to Evaluate of Interaction Technology: A Review and Proposed Integration", in Thomas, P. (ed), *CSCW Requirements and Evaluation*, Springer, London, pp. 107-124.

Andriessen, J. H. E. and Van der Velden, J. (1993), "Teamwork Supported by Interaction Technology: the Beginning of an Integrated theory", *European Work and Organizational Psychologist*, Vol.3, pp. 129-145.

Anthony, R. N. (1965), "Planning and Control systems: A Framework for Analysis", Harvard University Graduate School of Business Administration.

Anumba, C. J. and Newnham, L. (2000), "Computer-Based Collaborative Building Design – Conceptual Model", *The International Journal of Construction Information Technology*, Vol. 8, No. 1, pp. 1-14.

Anumba, C. J., Baldwin A. N., Bouchlaghem, D., Prasad, B., Cutting-Decelle, A. F., Dufau, J. and Mommessin M. (2000), "Intergrating Concurrent Engineering Concepts in a Steelwork Construction Project", *Concurrent Engineering: Research and Applications*, Vol. 8, No. 3, pp. 199-211.

Asse, A, Mangin, P. and Willaeys, D. (1987), "Assisted Diagnosis Using fuzzy Information: Method of Inverting Equations of Fuzzy Relations with Φ fuzzy Sets", in Bezdek, J. C. (ed), *Analysis of Fuzzy Information*, CRC Press, Boca Raton.

Attoh-Okine, N. O. (1997), "Rough Set Application to Data Mining Principles in Pavement Management Database", *Journal of Computing in Civil Engineering*, Vol. 11, No. 4, pp. 231-237.

Balbontin, A., Yazdani, B., Cooper, R. and Souder, W. E. (1999), "New Product Development Success Factors in American and British Firms", *International Journal of Technology Management*, Vol. 17, Issue. 3, pp. 259-280.

Bannon, L. J. (1997), "Use, Design and Evaluation: Steps Towards an Integration", in Shapiro, D., Tauber, M. J. and Traunmuller, R. (eds), *The design of computer supported Cooperative Work and Groupware Systems*, North-Holland, Amsterdam, pp. 423-442.

Barkley, J. (1993), "Applications of Concurrent Engineering", *Autotestcon 93: Enhancing Mission Effectiveness: Proceedings of the IEEE Systems Readiness Technology Conference*, pp.451-457.

Belbin, R. M. (1981), *Management Teams: Why They Succeed or Fail*, Heinemann, London.

Bennett, J., Flanagan, R., Lansley, P. Gray, C. and Atkin, B. (1988), "Building Britain 2001", *Centre for Strategic Studies in Construction*, University of Reading, UK.

Bhargava, H. K., Krishnan, R. and Muller, R. (1997), "Decision support on Demand: Emerging Electronic Markets for Decision Technologies", *Decision Support System*, Vol. 19, pp. 193-214.

Biondini, F., Bontempi, F. and Malerba, P. G. (2001), "Reliability Assessment of Concrete Structures by Using Fuzzy Theory and Genetic Algorithms", in Singh (ed), *Creative Systems in Structural and Construction Engineering*, Balkema, Rotterdam.

Bogia, D., Tolone, W., Bignoli C. and Kaplan, S. (1997), "Issues in the Design of collaborative systems: Lessons from ConversationBuilder", in Shapiro, D., Tauber, M. J. and Traunmuller, R. (eds), *The design of computer supported Cooperative Work and Groupware Systems*, North-Holland, Amsterdam, pp.401-422.

Cappetti, N. and Santoro, E. (1998), "An application of Computer Visualisation for Solving a Mechanical Design by Fuzzy Set", London.

Carter, D. E. (1994), "Concurrent Engineering", Proceedings of the 2nd International Conference on Concurrent Engineering and Electronic Design Automation (CEEDA '94), pp. 5-7.

Chak, C. K., Feng, G. and Palaniswami, M. (1998), "Implementation of Fuzzy Systems", in Leondes, C. T. (ed), *Fuzzy Logic and Expert Systems Applications*, Academic Press, New York, pp. 57-121.

Chameau, J. Guneratne, M. and Altschaeffl, A. G. (1987), "An Application of Type 2 Fuzzy Sets to Decision Making in Engineering", in Bezdek, J. C. (ed), *Analysis of Fuzzy Information, Vol. II, Artificial Intelligence and Decision Systems*, CRC Press, Boca Raton.

Chao, L. and Skibniewski, M. J. (1998), "Fuzzy Logic for Evaluating Alternative Construction Technology", *Journal of Construction Engineering and Management*, Vol. 124, No. 4, pp. 297-304.

Chen, S., (1997), "A New Model for Tool Steel Materials Selection under Fuzzy environment", *Fuzzy sets and Systems*, Vol. 92, pp.265-274.

Chen, L. and Li, S. (2000), "Modelling Concurrent Product Design: A Multifunctional Team Approach", *Concurrent Engineering: Research and Applications*, Vol. 8, no. 3, pp. 183-198.

Chicken, J. (1994), *Managing Risks and Decision in Major Projects*, Chapman & Hall, London.

Clausing, D. P. (1991), "Concurrent Engineering", *Proceedings of the Design and Productivity International Conference*, Honolulu, Hawai, 6-8 February, 1991.

Cohen, M. E. and Hudson, D. L. (1992), "Medical Decision-Making Using Multidimensional Polynomials", in Kandel, A. (ed), *Fuzzy Expert Systems*, CRC Press, Boca Raton.

Cointe, C. and Matta, N. (1998), "Multi-Agents System to Support Decisoin Making in Concurrent Engineering", in Horvath, I. and Taleb-Bendiab, A. (eds), *2nd International Symposium on Tools and Methods for Concurrent Engineering*, Manchester, UK, 21-23 April, pp.271-279.

Constable, G. (1994), "Concurrent Engineering – Its Procedures and Pitfalls", *Measurement and Control*, Vol. 27, No. 8, pp. 245-247.

Courtney, J. F. (2001), "Decision Making and Knowledge Management in Inquiring Organizations: Toward a New Decision-Making Paradigm for DSS", *Decision Support Systems*, Vol. 31, pp. 17-38.

de la Garza, J. M., Alcantara, P., Kapoor, M. and Ramech, P. S. (1994), "Value of Concurrent Engineering for AEC Indusrty", Journal of Management in Engineering, Vol. 10, No. 3, pp. 46-55.

Dowling, K. L. and Louis, R. D. (2000), "Asynchronous Implementation of the Nominal Group Technique: Is It Effective?", *Decision Support Systems*, Vol. 29, pp. 229-248

Dubois, D. and Prade, H. (1988), *Possibility Theory, An Approach to computerized Processing of Uncertainty*, Plenum Press, New York.

Eason, K. and Olphert, W. (1996), "Early Evaluation of the Organisational Implications of CSCW Systems", in Thomas, P. (ed), *CSCW Requirements and Evaluation*, Springer, London, pp. 75-89.

Eden, C. and Ackermann, F. (1994), "Strategy Development and Implementation", in Holtham, C. (ed), *Executive Information systems and Decision Support*, Chapman & Hall, London.

Esogbue, A. O. and Elder, R. C. (1983), "Measurement and Valuation of a Fuzzy Mathematical Model for Medical Diagnosis", *Fuzzy Sets and Systems*, No. 10, pp. 223-242.

Evbuomwan, N. F. O. and Anumba, C. J. (1996), "Towards a Concurrent Engineering Model for Design-and-Build Projects", *The Structural Engineer*, Vol. 74, No. 5, pp. 73-78.

Evbuomwan, N. F. O. and Anumba, C. J. (1998), "An Integrated Framework for Concurrent Lifecycle Design and Construction", *Advances in Engineering Software*, Vol. 29, No. 7-9, pp. 587-597.

Fayek, A. R. and Sun, Z. (2001), "A Framework for Evaluating Design Project Performance", in Singh (ed), *Creative Systems in Structural and Construction Engineering*, Balkema, Rotterdam.

Fiksel, J. and Hayes-Roth, F. (1993), "Computer-Aided Requirements Management", *Concurrent Engineering: Research and Applications*, Vol.1, pp.83-92.

Furtado, T. (1988), "Training for a Different Management Style", *Personnel Management*, March, pp. 40-43.

Ganeshan, R., Grobler, F., Wang, C. and Coimbatore, V. (2001), "CITYWORK: Application of Collaborative Technologies for Infrastructure Management", *Journal of Computing in Civil Engineering*, Vol. 15, No. 1, pp. 74-80.

Ghasemzadeh, F. and Archer, N. P. (2000), "Project Portfolio Selection through Decision Support", *Decision Support Systems*, Vol. 2, pp. 73-88.

Grabot, B., Blanc, J. and Binda, C. (1996), "A Decision Support System for Product Activity Control", *Decision Support systems*, Vol. 16, pp. 87-101.

Gupta, M. M., Martin-Clouaire, R. R. and NiKiforuk, P. N. (1984), "Fuzzy Set Theory in Medical Science", in Sanchez, E. (ed), *Fuzzy Information, Knowledge Representation and Decision Analysis*, Pergomon, Oxford.

Guzzo, R. A. (1995), "Introduction: At the intersection of Team Effectiveness and Decision Making", in Guzzo, R. A. and Salas, E. (eds), *Team Effectiveness and Decision Making in Organizations*, Jossey-Bass Publishers, San Francisco.

Hague, M. J. and Taleb-Bendiab, A. (1998), "Tool for the Management of Concurrent conceptual Engineering Design", in Horvath, I. and Taleb-Bendiab, A. (eds), *2nd International Symposium on Tools and Methods for Concurrent Engineering*, Manchester, UK, 21-23 April, pp.203-217.

Hannus, M., Huovila, P., Lahdenpera, P., Laurikka, P. ans Seren, K. (1997), "Methodologies for Systematic Improving of Construction Processes", in Anumba, C. J. and Evbuomwan, N. F. O. (eds), *Concurrent Engineering in Construction: Proceedings of the first International Conference*, Institution of Structural Engineers, London, pp.55-64.

Hague, B. U., Belecheanu, R. A., Barson, R.J. and Pawar, K. S. (2000), "Towards the Application of Case Based Reasoning to Decision-Making in Concurrent Product Development (Concurrent Engineering)", Knowledge-Based Systems, Vol. 13 (2-3), pp. 101-112.

Harding, J. A. and Popplewell, K. (1996), "Driving Concurrency in a Distributed Concurrent Engineering Project Team: a Specification for an Engineering

Moderator", *International Journal of Production Research*, Vol. 36, No. 3, pp.841-861.

Harrison, K. W., Dumas, R. D., Solano, E., Barlaz, M. A., Brill Jr., E. D. and Ranjithan, R. (2001), "Decision Support Tool for Life-Cycle-Based Solid Waste Management", *Journal of Computing in Civil Engineering*, vol. 15, No. 1, pp. 44-58.

Hickson, D. J., Bulter, K. J., Gray, D., Mallory, G. K. and Wilson, D. C. (1986), *Top Decision Making in Organizations*, Blackwell, Oxford.

Hopgood, A. A., Phillips, H. J., Picton, P. D. and Braithwaite, N. St. J. (1998), "Fuzzy Logic in a Blackboard System for Controlling Plasma Deposition Processes", *Artificial Intelligence in Engineering*, Vol. 2, pp. 253-260.

Huovila, P., Lakka, A., Laurikka, P. and Vainio, M. (1997), "Involvement of Customer Requirements in Building Design", in Alarcon, L. (ed), *Lean Construction*, A. A. Balkema, Rotterdam, pp.403-416.

ICE (1996), *Creating Value in Engineering, ICE Design and Practice Guides*, The Institution of Civil Engineers, Thomas Telford, London.

Jablonowski, M. and Standard, H. (1998), "Fuzzy Risk Analysis in Civil Engineering", in Ayyub, B. M. (ed), *Uncertainty Modeling and Analysis in Civil Engineering*, CRC Press, New York.

Janis, I. L. (1972), *Victims of Groupthink: A Psychological Study of Foreign Policy Decisions and Fiascos*, Houghton Mifflin, Boston.

Jebb, A., Sivaloganathan, S. and Evbuomwan, N. F. O. (1992), "Simultaneous Engineering", City University Engineering Design Centre, *Technical Report No. 66*, pp. 1-15.

Jeusfeld, M. A. and Bui, T. X. (1997), "Distributed Decision Support and Organizational Connectivity: a Case Study", *Decision Support Systems*, Vol. 19, pp. 215-225.

Kacprzyk, J. (1987), "On Some Fuzzy Cores and 'Soft' Consensus Measures inGroup Decision Making", in Bezdek, J. C. (ed), *Analysis of Fuzzy Information, Vol. II, Artificial Intelligence and Decision Systems*, CRC Press, Boca Raton.

Kamara, J. M., Anumba, C. J. and Evbuomwan, N. F. O. (1997), "Considerations for the Effective Implementation of Concurrent Engineering in Construction", ", in Anumba, C. J. and Evbuomwan, N. F. O. (eds), *Concurrent Engineering in Construction: Proceedings of the first International Conference*, Institution of Structural Engineers, London, pp.33-44.

Kamara, J. M., anumba, C. J. and Evbuomwan, N. F. O. (1999), "Client Requirements Processing in Construction: A New Approach Using QFD", *Journal of Architectural Engineering*, Vol. 5, No. 1, pp. 8-15.

Kandel, A. (1986), *Fuzzy Mathematical Techniques with Applications*, MA: Addison-Wesley, Reading.

Kartalopoulos, S. V. (1996), Understanding Neural Networks and Fuzzy Logic, IEEE Press, New York.

Katzenbach, J. and Smith, D. (1993), *The Wisdom of Teams: Creating the High Performance Organization*, Harvard Business School Press, Boston.

Kaufmann, A. (1975), *Introduction to the Theory of Fuzzy Subset*, Vol.1, Academic Press, London.

Klir, G. and Folger, T. (1988), *Fuzzy Sets, Uncertainty, and Information*, Prentice Hall, New Jersy.

Koskela, L. (1992), *Application of the New Production Philosophy to Construction, Technical Report No. 72*, Centre for Integrated Facility Engineering (CIFE), Stanford University, CA, USA.

Kosko, B. (1992), "Fuzzy Associate Memory Systems", in Kandel, A. (ed), *Fuzzy Expert Systems*, CRC Press, Boca Raton.

Kosko, B. (1997), *Fuzzy Engineering*, Prentice Hall, New Jersey.

Kruse, R., Gebhardt, J. and Klawonn, F. (1994), *Foundations of Fuzzy Systems*, John Wiley & Sons, Chichester, UK.

Kuo, R. J. and Xue, K. C. (1998), "A Decision support system for sales Forecasting through Fuzzy Neural Networks with Asymmetric Fuzzy Weights", *Decision Support Systems*, Vol.24, pp. 105-126.

Lakmazaheri, S. and Edwards, P. (1997), "Linguistic approach to 2D Geometric Modelling of Hierarchical Systems", *Journal of Computing in Civil Engineering*, Vol. 11, No. 3, pp. 165-174.

Lam, K. C., So, A. T. P., Hu, T., Ng, T., Yuen, R. K. K., Lo, S. M., Cheung, S. O. and Yang, H. (2001), "An Integration of the Fuzzy Reasoning Technique and the Fuzzy Optimization Method in Construction Project Management Decision-Making", *Construction Management and Economics*, Vol. 19, pp. 63-76.

Larkin, L. I. (1985), "A Fuzzy Logic Controller for Aircraft Flight Control", in Sugeno, M. (ed), *Industry Applications of Fuzzy Control*, North-Holland, New York.

Laudon, K. C. and Laudon, P. L. (2000), *Management Information Systems*, 6th Edition, Prentice-Hall, New Jersey, USA.

Lawler, E. E. and Moreman, S. A. (1985), "Quality Circles after the Fad", *Harward Business Review*, Jan-Feb, pp. 65-71.

Lin, S. (1998), "Fuzzy Modelling of Risky Investment Decision In Engineering Projects", in Ayyub, B. M. (ed), *Uncertainty Modelling and Analysis in Civil Engineering*, CRC Press, New York.

Lindblom, C. E. (1995), "The Science of Muddling Through", *Public Administration Review*, XIX (2), pp. 79-88.

Lorterapong, P. and Moselhi, O. (1996), "Project-Network Analysis Using Fuzzy Set Theory", *Journal of Construction Engineering and Management*, Vol. 122, No. 4, pp.308-318.

Love, P. E. D. and Gunasekaran, A. (1997), "Concurrent Engineering in the Construction Industry", *Concurrent Engineering: Research and Applications*, Vol. 5, No. 2, pp. 155-162.

Madan, P. (1993), "Concurrent Engineering and Its Application in Turnkey Projects Management", *IEEE International Management Conference*, pp. 7-17.

Maeda, M, Murakami, S. and Onoue, T. (1987), "Fuzzy Multiattribute Decision Analysis on the Choice of Clinical Tests and /or Treatments for Anovulatory Women", in Bezdek, J. C. (ed), *Analysis of Fuzzy Information*, CRC Press, Boca Raton.

March, J. G. and Olsen, J. P. (1976), *Ambiguity and choice in Organizations*, Universitetsforlaget, Bergen.

Marimin, Umano, M., Hatono, I. and Tamura, H. (1997), "Non-Numeric Method for Pairwise fuzzy Group Decision Analysis", *Journal of Intelligent and Fuzzy Systems*, Vol. 5, pp. 257-269.

Marir, F., Rezgui, Y. and Benhadj-Djilali, R. (2000), "A Case-Based Expert System for Construction Project Process Activity Specifications", *The International Journal of Construction Information Technology*, Vol. 8, No. 1, pp.53-73.

McGrath, J. E. (1990), "Time Matters in Group", in Galegher, J., Kraut, R. E. and Egido, C. (eds), *Intellectual Teamwork, Social and Technologycal Foundations of Cooperative*, Lawrense Erlbaum, Hillsdale, NJ.

McIntyre, R. M. and Salas, E. (1995), "Measuring and Managing for Team Performance: Lessons from Complex Environments", in Goldstein, I. L. (ed), *Team Effectiveness and Decision Making in Organizations*, Jossey-Bass Publishers, San Francisco.

Miles, J. C., Moore, C. J., Kotb, A. S. M. and Jaberian-Hamedani, A. (1998), "End User Evaluation of Engineering Knowledge Based Systems", *Civil Engineering and Environmental Systems*, Vol. 17(4), pp. 293-317.

Molina, A., Al-Ashaab, A, H., Ellis, T. I. A., Young, R. I. M. and Bell, R. (1995), "A Review of Computeer-Aided Simultaneous Engineering Systems", *Research in Engineering Design*, Vol. 7, No. 1, pp. 38-63.

Monk, A., McCarthy, Watts, L. and Daly-Jones, O. (1996), "Measures of Process", in Thomas, P. (ed), *CSCW Requirements and Evaluation*, Springer, London, pp. 125-139.

Monroy, J. (1992), "Concurrent Engineering", *APEC 92: Seventh Annual Applied Power Electronics Conference and Exposition*, pp. 311-314.

Moore, C. J., Miles, J. C. and Rees, D. W. G. (1997), "Decision Support for Conceptual Bridge Design", *AI in Engineering*, Vol. 11, pp. 259-272.

Morgen, B. B. Jr., Glickman, A. S. Woodard, E. A., Blaiwes, A. and Salas, E. (1986), *Management of Team Behaviours in a Navy Environment*, (NTSC Report, No. 86-014), Orlando.

Morris, J., Rogerson, J. and Jared, G. (1998), "a Tool for Modelling the Briefing and Design Decision Making Processes in Construction", *Proceedings of the 14th Annual Conference of the Association of Researchers in Construction Management (ARCOM)*, 9-11 September, University of Reading, UK, pp. 320-329.

Murlidharan, T. L. (1999), "Handling Uncertainties in Knowledge Modelling and Acquisition for the Development of a Knowledge-Based System", *Computer-Aided Civil and Infrastructure Engineering*, Vol.14, pp. 141-154.

Murnighan, J. K. (1982), "Game Theory and the Structure of Decision-Making Groups", in Guzzo, R. A. (ed), *Improving Group Decision Making in Organizations*, Academic Press, London.

Nakatsuyama, M., Nagahashi, H. and Nishizuka, N. (1984), "Fuzzy Logic Phase Controller for Traffic Functions in the One-way Arterial Road", *Proceedings of IFAC 9th Triennial World Confress*, Pergamon, Oxford, pp. 2865-2870.

Nguyen, H. T. and Walker, E. A. (1997), *A First Course in Fuzzy Logic*, CRC Press, Boca Raton.

Ngwenyama, O. K., Bryson, N. and Mobolurin, A. (1996), "Supporting Facilitation in Group Support Systems: Techniques for Analysing Consensus Relevant Data", *Decision Support Systems*, Vol. 16, pp. 155-168.

Nicholas, J. M. (1994), "Concurrent Engineering: Overcoming Obstacles to Teamwork", *Production and Inventory Management*, vol. 3, No. 2, pp. 18-22.

Novak, V. (1989), *Fuzzy Sets and Their Applications*, Adam Hilger, Bristol.

Ohkubo, S. and Dissanayake, P. B. R. (1998), "An Intelligent Optimum Design Method for a Structural System Dealing with Multiple Objects and Fuzziness", in Horvath, I. and Taleb-Bendiab, A. (eds), *2nd International Symposium on Tools and Methods for Concurrent Engineering*, Manchester, UK, 21-23 April, pp.287-297.

Osborn, A. F. (1963), *Applied Imagination: Principles and Procedures of Creative Thinking*, Scibner's, New York.

Pacini, P. J. and Kosko B. (1997), "Fuzzy Signal Detection in Impulsive Noise", in Kosko, B. (ed), *Fuzzy Engineering*, Prentice Hall, New Jersey.

Pedrycz, W. and Goide, F. (1998), *An Application to Fuzzy Sets: Analysis and Design*, The MIT Press, London.

Pena-Mora, F., Sriram, D. and Logcher, R. (1995), "Design Rationale for computer-Supported Conflict Mitigation", *Journal of Computing in Civil Engineering*, Vol. 9, No. 1, pp.57-72.

Perkinson, G, M., Sandivo, V. E. and Grobler, F. (1994), "A Facility Programming Information Framework", *Engineering, Construction and Architectural Management*, Vol. 1, No. 1, pp.69-84.

Poh, K. L. (1998), "A Knowledge-Based Guidance System for Multi-Attribute Decision Making", *Artificial Intelligence in Engineering*, Vol. 12, pp. 315-326.

Poh, K. L. (2000), "An Intelligent Decision Support for Investment Analysis", Knowledge and Information Systems, Vol. 2, No. 3, pp. 340-358.

Prasad, B., Morenc, R. S. and Rangan, R. M. (1993), "Information Management for Concurrent Engineering: Research Issues", *Concurrent engineering: Research and Applications*, Vol. 1, No. 1, pp. 3-20.

Prasad, B. (1995), "On Influencing Agents of CE", Editorial, Concurrent Engineering: Research and Applications, Vol. 3, No. 2, pp. 78-80.

Prasad, B. (1996), *Concurrent Engineering fundamentals, Volume 1: Integrated Products and Process Organisation*, Prentice Hall PTR, New Jersey.

Ranky, P. G. (1994), *Concurrent/Simultaneous Engineering (Method, Tools and Case Studies)*, CIMware Limited, England.

Rees, J. and Koehler, G. J. (2000), "Leadership and Group Search in Group Support Systems", *Decision Support Systems*, Vol. 30, pp. 73-82.

Rezgui, Y. Cooper, G. and Brandon P. (1998), "Information Management in a Collaborative Multiactor Environment: The COMMIT Approach", *Journal of Computing in Civil Engineering*, Vol. 12, No. 3, pp. 136-144.

Ritchie I., (1995), "Synthetic Thinking Between Engineers, Architects and Designers", in Spence R., (ed), *Proceedings of A Discussion Meeting at the Royal Academy of Arts*, Oct. 16, 1995, London, pp. 3-7.

Romano, N. C., Nunamaker, J. F., Briggs R. O. and Vogel, D. R. (1998), "Architecture, Design, and Development of an HTML/JavaScript Web-based Group

Support System", *Journal of American Social Information Science*, Vol. 49, No. 7, pp. 649-667.

Ross, T. J. (1988), "Approximate Reasoning in Structural Damage Assessment", in Hojjat, A. (ed), *Expert systems in Construction and Structural Engineering*, Chapman and Hall, London.

Sage, A. P. (1992), "On the Processing of imperfect Information Using Structured Frameworks", in Kandel A. (ed), *Fuzzy Expert Systems*, CRC Press, Boca Raton, pp. 99-112.

Sanvido, V. E. and Medeiros, D. J. (1990), "Applying Computer-Integrated Manufacturing Concepts to Construction", *Journal of Construction Engineering and Management*, Vol. 116, No. 2, pp. 365-379.

Sarkodie-Gyan, T., Lam, C. W., Hong, D. and Campbell, a. W. (1997), "an Efficient Object Recognition Scheme for a Prototype Component Inspection", *Mechatronics*, Vol. 7, No. 2, pp. 185-197.

Schneider, M., Perl, J. M. and Kandel, A. (1992), "COMEX-An Autonomous Fuzzy Expert System for Tactical Communications", in *Fuzzy Expert Systems*, CRC Press, Boca Raton.

Sellen, A. (1994), "The Effects of Video-Mediation on Human Interaction", *Workshop 'Video-Mediated Communication' at ACM Conference on CSCW-94*, Chapel Hill, NC, Nov. 1994.

Shen, Y. and Grivas, D. A. (1996), "Decision-Support system for Infrastructure Preservation", *Journal of Computing in Civil Engineering*, Vol. 10, No. 1, pp. 40-49.

Shieh H. and Ku, H. (2001), "A hierarchy Fuzzy MCDM Method for Studying Taipei Rapid Transit System Contracting Model", in Singh (ed), *Creative Systems in Structural and Construction Engineering*, Balkema, Rotterdam.

Shrestha,B. and Duckstein, L. (1998), "A Fuzzy Reliability Measure for Engineering Applications", in Ayyub, B. M. (ed), *Uncertainty Modeling and Analysis in Civil Engineering*, CRC Press, New York.

Simon, H. A. (1960), *The New Science of Management Decision*, Harper & Row, New York.

Sivaloganathan, S. and Evbuomwan, N. F. O. (1997), "Quality Function Deployment-The Technique: State of the Art and Future Directions", *Concurrent Engineering: Research and Applications*, Vol.5, No. 2, pp. 171-181.

Soh, C. K. and Yang, J. (1995), "Fuzzy Controlled Genetic Algorithm Search for Shape Optimization", *Journal of Computing in Civil Engineering*, Vol. 10, No. 2, pp. 143-150.

Spillman, R. and Spillman, B. (1987), "A survey of Some Contributions of Fuzzy Sets to Decision Theory", in Bezdek, J. C. (ed), *Analysis of Fuzzy Information, Vol. II, Artificial Intelligence and Decision Systems*, CRC Press, Boca Raton.

Tang, J. C. and Isaacs E. (1993), "Why Does Users Like Video?", *Computer Supported Cooperative Work* Vol. 1, pp. 163-196.

Thamhain, H. J. (1994), "Concurrent Engineering: Criteria for Effective Implementation", Industrial Management, vol. 36, No. 6, pp. 29-32.

Tong, R. M. and Bonissone, P. P. (1980), "A Linguistic Approach to Decision Making with Fuzzy Sets", *IEEE Transaction on Systems, Man, Cybernetics*, Vol. 10, pp. 716-723.

Treu, S., (1994), *User Interface Design: A structured Approach*, Plenum, New York.

Van de Ven, A. H. and Delbecq, A. (1974), "The Effectiveness of Nominal, Dephi and Interaction Group Decision Making Processes", *Academy of Management Journal*, Vol. 17, pp. 605-632.

Ven der Velden, J. M. (1992), "Delft WIT-lab, Research Issues and Methods for Analysing Group Behaviour", *ACM Siggraph Video Review*, Issue 87, CSCW'92, Toronto.

Vlacic, L., Amagasa, M., Ishikawa, A. Williams, T. and Tomizawa, G. (1997), "Applying Multiattribute-Based Group Decision Making Techniques in Complex Equipment Selection Tasks", *Group Decision and Negotiation*, Vol. 6, pp. 529-556.

Wanous, M., Boussabaine, A. H. and Lewis, J. (2001), "A Fuzzy Logic Decision Support System for Competitive Tendering", in Singh (ed), *Creative Systems in Structural and Construction Engineering*, Balkema, Rotterdam.

Watanabe, K. and Tzafestas, S. G. (1998), "Mean-Value-Based Functional Reasoning Techniques in the Development of Fuzzy Neural Network Control Systems", in Leondes, C. T. (ed), *Fuzzy Logic and Expert Systems Applications*, Academic Press, San Diego.

Wilson, D. C. and Rosenfeld, R. H. (1990), *Managing Organizations, Text, readings and Cases*, McGraw-Hill book company, London.

Winner, R. I. Pennell, J. P., Bertrand, H. E. and Slusarczuk, M. M. G. (1988), "The Role of Concurrent Engineering in Weapons System Acquisition", *IDA Report R-338, Institute of Defence Analysis*, Alexandria.

Wong, F. S., Ross, T. J. and Boissonnade, A. C. (1987), "Fuzzy Sets and Survivability Analysis of Protective Structures", in Bezdek, J. C. (ed), *The Analysis of Fuzzy Information*, CRC Press, Boca Raton, Florida.

Zadeh, L. A. (1965), "Fuzzy Sets", *Information and control*, No. 8, pp. 338-353.

Zadeh, L. A. (1975), "The Concepts of a Linguistic Variable and its Application to Approximate Reasoning I II III", *Information Science*, No. 8, pp. 199-257.

LIST OF PUBLICATIONS ARISING FROM THE RESEARCH

1. Yang, H. M. and Anumba, C. J. (2000), "Collaborative Decision Making in Construction - A Potential Application Area for Fuzzy Systems?", in John, R. and Birkenhead, R. (eds), *Soft Computing Techniques and Applications, Advances in Soft Computing Series*, Physica-Verlag, Heidelberg, pp. 258-267.

2. Yang, H. M., Anumba, C. J., Kamara, J. M. and Carrillo, P. M. (in press), "A Fuzzy-Based Analytic Approach to Collaborative Decision Making for Construction Teams", *Journal of Logistics Information Management.*

3. Yang, H. M. and Anumba, C. J. (2001), "Application of Fuzzy Systems to Collaborative Decision Making in Construction", *International Journal of Knowledge-Based Intelligent Engineering Systems,* Vol. 5, No. 1, pp.52-60.

4. Yang, H. M., Anumba, C. J. and Kamara, J. M. (2000), "Development of a Fuzzy-Based Decision Making Tool for Construction Project Teams", *Implementing IT to Obtain a Competitive Advantage in the 21st Century, Proceedings of the International Conference on Construction Information Technology (INCITE),* Hong Kong, 17-18th January 2000, pp. 726-743.

5. Yang, H. M. and Anumba, C. J. (1999), "An Approach to a Fuzzy-Based Decision Support System for Construction Project Teams", in Kumar, B and Topping, B.H.V (eds), *Proceedings of 5th International Conference on Artificial Intelligence in Civil and Structural Engineering Computing (AI Civil-Comp '99),* Civil-Comp Press, Edinburgh. Oxford University, 13-15 September 1999, pp. 53-60.

INDUSTRY SURVEY— COLLABORATIVE DECISION MAKING IN CONSTRUCTION PROJECT TEAMS

As mentioned in the accompanying letter, this questionnaire is concerned with collaborative decision making in construction project teams. Most of the questions have tick boxes, but please use additional sheets of paper if you wish to expand on your answer. Thank you.

A. Background Details

1. Which of the following best describes your role on construction projects?
   ☐ Client ☐ Architect ☐ Structural Engineer ☐ Contractor ☐ Quantity Surveyor
   ☐ Mechanical/Electrical Service Engineer ☐ Material Supplier

2. Are you chartered? | Yes | No | Professional Bodies ____________

3. What is your experience of being involved in construction projects? _____ years

B. Group Decision Making

1. Which disciplines do you collaborate with at the various stages of a construction project? (please tick all that apply)

	Briefing	Preliminary Design	Detailed Design	construction Planning	Actual Construction
Client					
Architect					
Structural Engineer					
Quantity Surveyor					
Mechanical/ Electrical Engineer					
Contractor					
Material Supplier					
Others					

2. How often do you attend project team meetings solely for decision making?

Very often	Often	Occasionally	Never

3. a)How do you usually exchange information with other participants?

Physical Meeting	Telephone	Email	Post(Physical Drawings)	Post(Drawings on disk)

   b)How often do you use Inter-net for information / communication?

Very often	Often	Occasionally	Never

4. a) Are there any Information Technology (IT) tool/techniques that are used to support

your decision making process? | Yes | No |

b) If yes, please state what they are and how they facilitate group decision making?

Tool/Technique	Role

5. To what extent do you think the participants' personalities (e.g. position, experience,etc.) affect the outcomes of decision-makings? | Always | Often | Occasionally | Never |

6. a) How often are you asked to contribute to collaborative decision making?

| Always | Often | Occasionally | Never |

b) When asked, are your contribution accepted ? | Always | Often | Occasionally | Never |

7.a) In project team decision making, are the contributions from all disciplines equally weighted? | Always | Often | Occasionally | Never |

b) When unequally weighted, are there any criteria used to rank the contributions? If yes, please specify:______________________________________

c) Could you please rank the weightings of the contributions from the following disciplines quantitatively:

Client ☐ Architect ☐ Structural Engineer ☐ Quantity Surveyor ☐

Mechanical/Electrical Service Engineer ☐ Contractor ☐ Material Supplier ☐

8. Do you consider Collaborative Decision Making (CDM) better than individual disciplines acting on their own? | Always | Often | Occasionally | Never |

Advantages of CDM______________________________________

Disadvantages of CDM______________________________________

9. When there is deadlock in decision making with other participants on a project, how do you usually resolve them? By:

| Discussion | Voting | Client Veto | Project Manager's Veto | Other: |

Apart from the above method, are you aware of any efficient tools from which generate a solution that satisfies all participants?

If yes, please state______________________________________

____

10. Please state what aspects of your current group decision-making practice you

consider worthy of emulation ______________________________

____

C. Handling of Uncertainties

1. Are there any vague views / information that you find very difficult to handle with existing methods during your decision-making process? [Yes | No]

   If yes, please describe ______________________________

2. How do you cope with group decision-making when the information supplied is not adequate quantitatively?

   ____

   ____

3. Are you aware of any tools and techniques to assist you when there is a lack of data in the information available, which means you can only have qualitative analysis, for group decision-making? [Yes | No]

   If yes, please specify ______________________________

   ____

3. Are there any vague views / information that you find very difficult to handle with existing methods during your decision-making process? [Yes | No]

   If yes, please describe ______________________________

   ____

D. Potential Improvements

1. In what ways do you think collaborative decision making on construction projects can be improved? ______________________________

   ____

2. How do you think the views of all appropriate team members can be objectively considered in group decision-making?

   ____

   ____

3.Any other comments? ______________________________

____

APPENDIX 3

A Fuzzy-Based Decision Making System for Construction Project Teams

Evaluation Questionnaire

This evaluation questionnaire should be completed following a demonstration of the operation of the prototype system.

A. Information about Respondents

Specify role carried out or position held (e.g. project manager, design consultant, engineer)

____

Area of experience (e.g. civil engineering, building, etc)________________
Experience in/with construction industry (years)______

B. Evaluation of the Prototype System
(*Please put a tick in the box that best represents your assessment of a question*)

		Ranking *1 is poor & 5 is excellent*				
	TEAM WORK	1	2	3	4	5
1	How well does the system facilitate group decision making by geographically distributed project team members?					
2	How well does the system encourage objectivity in group decision-making?					
3	How well does it eliminate unhealthy and antisocial behavior in group decision-making?					
4	How appropriate is the role of the decision-making team leader as implemented in the system?					
	APPLICABILITY TO PRACTICAL DECISION-MAKING CASE					
5	How appropriate are the linguistic terms for ranking decision criteria/options?					
6	How well does the system deal with fuzzy linguistic expressions during the practical decision-making process?					
7	How accurately does the system structure actual decision-making procedure (any major aspects/steps missed or unnecessary)?					
8	How appropriate are the limitations on numbers of team members, criteria and solution options in the system?					
9	How accurate was the final decision suggested by the system?					
	MANAGEMENT OF SYSTEM INTERACTION					
10	How attractive is the graphical user interface of the system?					
11	How easy is the use of the system?					
12	How easy/clear are the instructions for completing the forms?					
13	To what extent does the system allow the choice of the optimum decision option?					
14	How easily can the system's output be understood?					
	EFFICIENCY					
15	How convinced are you that the system can be used easily within a project team, particularly in a concurrent engineering environment?					
16	How efficient is the overall method for decision-making within a construction project team?					
17	To what extent does the fuzzy-based approach adopted in the system benefit collaborative decision-making within a construction project team?					
	GENERAL					
18	Rate how confident you are with computers (generally)					

19	How generic do you consider the system to be?					
20	What is your overall rating of the system?					

C. General Comments

1. In what ways can the system be improved?

____

____

2. Further comments:

____

____

____