ECO-DESIGN DECISION MAKING: TOWARDS SUSTAINABLE ENGINEERING DESIGN OF LARGE MADE-TO-ORDER PRODUCTS

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ABSTRACT

Sustainable design provides an holistic, life-cycle approach by which design engineers can minimise negative impacts and maximise positive impacts, thus ensuring that current industrial progress is not achieved at the expense of future generations. In the context of sustainable design, large made-to-order (LMTO) product sectors must address some unique issues:

- The design process may be in the order of years, involving the client, the design contractors, co-venturers, suppliers and regulators.
- The one-off nature of the design may limit the opportunity for reuse of design knowledge.
- The existence of the possibility of catastrophic out-of-envelope events leading to large scale safety and environmental impacts.
- There is potential for high energy and resource consumption.
- Some LMTO products may cause local and transboundary environmental impacts.
- There may be long term, post-decommissioning impacts.
- Some aspects of the product life-cycle may give rise to impacts on social welfare.

Engineering design is a process of decision making both during option synthesis and option selection. The first part of this research examined the current integration of environmental objectives and attributes with industrial design decision making processes using qualitative research methods. In particular, design selection was considered as the case-study focused on the activities of two case-study design contractors. The second part of the research proposed a framework to assist the consideration of environmental and societal impacts using transparent, systematic methodologies based on Multiple Attribute Decision Making (MADM) approaches. Two MADM methods were compared in relation to a case-study regarding the selection of an option for a produced water treatment system; Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) and Concordance and Discordance Analyses by Similarity to Ideal Solution (CODASID). Due to the subjectivity and uncertainty associated with information relating to sustainable design, a fuzzy set-based methodology was also investigated. In order to simulate the intuitive processes of human decision makers, the application of linguistic terms to evaluate sustainable design attributes was explored. This method was applied to a group decision making case-study to determine the best option for replacing a heat exchanger situated in a pond water cooling system. Comparisons were made between the fuzzy MADM method and the decision obtained from a group-based discussion.

Finally, the third part of the research specifically addressed *perceived risk* attributed by the public to proposed large made-to-order products or processes, accommodating the societal element of sustainable design. Public risk perception was decomposed into measurable indices which were suitable for application to the fuzzy MADM method. The final aggregated evaluation, representing the overall perceived risk associated with the product in question, was then examined under different tolerance scenarios in order to make an informed judgement with respect to product viability. These three core research elements provide the foundation for managing the environmental and societal aspects of sustainable engineering design of large made-to-order products, thus providing an important addition to the wider concept of integrated product design.

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1 INTRODUCTION

1.1 Introduction

This Chapter explains the fundamental concept of sustainability, its importance to industry and its application to the engineering design process. Sustainable engineering design demands the consideration of product function in terms of environmental and societal impacts within an integrated design process, supported by standardised performance measurement. High level research aims are discussed and the organisation of the thesis is presented.

1.2 Sustainable Development Within Industry

Sustainable Development is a concept that is challenging those industries that recognise the importance of sustainable business practices. A widely accepted definition was introduced in the World Commission on Environment and Development's report (World Commission on Environment and Development, 1987);

'development that meets the needs of the present without compromising the ability of future generations to meet their own needs.'

The majority of definitions of sustainable development stress the environmental considerations and limitations traditionally associated with economic growth. An alternative definition provided by Forum for the Future emphasises the dynamic nature and social equity aspects of sustainable development (Forum for the Future, 2001).

'Sustainable development is a dynamic process which enables all people to realise their potential and to improve their quality of life in ways which simultaneously protect and enhance the Earth's life support systems.'

Indicators of sustainable development provide a measure of a system's sustainability, including industrial processes and products. The concept of sustainability has been adopted by many businesses and a wide range of companies now publish their corporate strategies on sustainability (Procter & Gamble Sustainability Full Report 2000; Yasuda Fire & Marine Sustainability Report 2000; Norsk Hydro 2000; The Shell Report: People, Planet and Profits, 2000). Efforts have been made to standardise sustainability reporting by the Global Reporting Initiative (GRI, 2000).

1.3 Sustainable Engineering Design

Historically in the LMTO product sector, the focus of the engineering designer's attention has been directed towards capital expenditure. However, the move towards non-prescriptive and consultative regulation and increased environmental awareness is driving the LMTO sector to consider of a wider range of design objectives. In doing so, the competing demands of potentially conflicting criteria or attributes must be reconciled, including the environmental and social implications of the product life-cycle. It is also becoming apparent that the minimisation of a product's life-cycle cost is often synergistic with the optimisation of the product's environmental performance. The recognition that life-cycle costs are strongly linked to the product's consumption of environmental resources, (Hendrickson et al., 1994), endorses that life-cycle costing offers a more sustainable economic evaluation method. As product design represents the key stage at which total product life-cycle costs are committed, (Blanchard and Fabrycky, 1981; Fabryky, 1987), there is a need to consider the entire life-cycle of the product during design, including the product's societal and environmental performance (Keoleian et al., 1994). Failure to do so has led to highly publicised events, such as the rejection of deep sea disposal of the Brent Spar by the public (Rice and Owen, 1999).

As industry recognises the potential impact on business which could result from unsustainable products and processes, significant budgets are spent on minimising these risks. In 1997, UK industries spent an estimated £4270 million on environmental protection. From this total, £830 million were being invested in end-of-pipe pollution abatement technology (DETR, 1997). In 2000, UK industry spent an estimated £4.2

billion on environmental protection (DEFRA, 2002). This indicates that the minimisation of environmental impact is becoming increasingly important to industries and that the environment should be considered as an important factor during product design to avoid costly end-of-pipe solutions.

Sustainable engineering design incorporates the established goals of eco-design and clean technology (Tischner and Charter, 2001). However, this principle goes beyond the environmental optimisation of products and their associated processes by challenging the industrialised world's patterns of resource consumption, economic growth and societal impact.

1.4 Large Made-to-Order (LMTO) Products and Processes

The consideration of environmental issues is increasingly important to the LMTO product sector in the context of design (Takerada, 1996; Fet, 1997) There are several reasons why the design of LMTO products deserves special consideration in terms of environmental and societal impacts:

- These products often consume large amounts of energy and resources during their life-cycle.
- Their associated environmental discharges can be numerous and complex (Scholten et al., 2000).
- Many LMTO products have the potential for out-of-envelope failures which could lead to catastrophic environmental and societal impacts (Reason, 1990). Examples include loss of containment from marine vessels, explosions on board offshore platforms or a leakage of radioactivity from a nuclear reprocessing plant.
- LMTO products, such as offshore platforms, aircraft, marine vessels and process plant usually have long life-cycles which affect future generations. Examples

include the storage of radionuclides with long half-lives, abandoned offshore structures or land contaminated with heavy metals.

- The potential for significant out-of-envelope consequences and the inter-generational nature of their environmental legacies can lead to high levels of public risk perception and intolerance (Walker et al., 1998; Rice and Owen, 1999).

- The design process often involves a complex interaction between the client and contractor and may span years (Halman and Braks, 1996). This represents an organisational and cultural challenge with respect to achieving sustainable engineering design.

Although many sustainable design principles will be shared between mass-produced and LMTO products, this list of factors suggest there will be some key differences regarding how these principles may be applied to achieve sustainable engineering design.

1.5 High-level Research Aims of the Thesis

Specific research aims are detailed in each of the following research chapters. However, the overall aims of this thesis are to:

- Test the hypothesis that the environment is inadequately integrated during the early stages of the LMTO design process using qualitative research investigations within two case-study organisations.

- Identify opportunities for improving the integration of environmental considerations into design based on the qualitative research.

- Apply multiple attribute decision making (MADM) methods to engineering design decisions gathered from the case-study companies and establish their potential to optimise life-cycle environmental attributes along with traditional design attributes.

- Apply fuzzy MADM methods to a case-study decision and determine if any advantages are yielded by using qualitative evaluations during subjective, uncertain decision making processes.

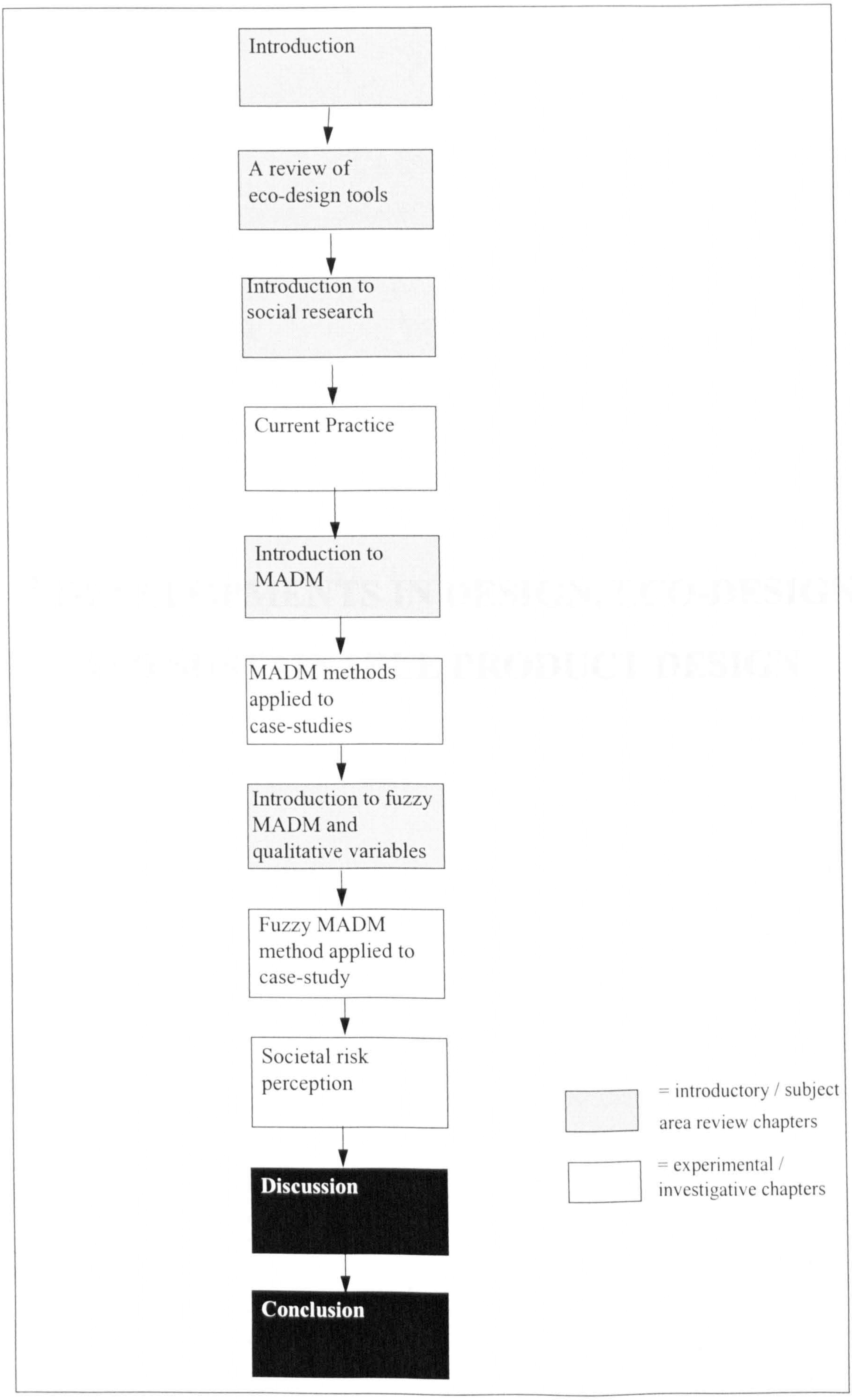
- Develop societal risk perception indicators which can be integrated with environmental and traditional decision attributes in order to achieve a sustainable design decision making framework.

It is believed that this framework will make progress towards integrating environmental and societal aspects of product design in an explicit and transparent manner, enabling monitoring of corporate sustainability objectives. The emphasis on the case-study approach enables the acquisition of rich contextual data, the purpose of which is to develop a framework that would truly integrate with the current LMTO design process and to capitalise on the sustainable design practices that are already in place. Examples are the determination of safety and environmental consequences by Hazard and Operability studies (HAZOPs), design optimisation through Value Engineering and the embodiment of environmental objectives set by the Client.

1.5.1 Organisation of the Thesis

The thesis is organised into introductory chapters which provide a review of the key literature and background to the subject areas, in conjunction with research chapters which document the experimental and investigative aspects of the work (Figure 1-1).

Figure 1-1: Layout of Thesis



2 DEVELOPMENTS IN DESIGN, ECO-DESIGN AND SUSTAINABLE PRODUCT DESIGN

2.1 Introduction

This Chapter presents an introductory literature review of the core research areas that underpin sustainable product design: engineering design, eco-design and public risk perception. Firstly, design is discussed in relation to prescriptive and descriptive viewpoints. In addition, the philosophy of concurrent design is explored along with the supporting concept of life-cycle engineering and organisational aspects of the LMTO design process. Secondly, approaches to eco-design are explained in terms of analysis and improvement methods. Consideration is also given to how these methods may be managed within the design team. Finally, the environmental focus of sustainable engineering design is extended to consider perceived risks attributed to certain products by society. Although this area is comparatively under-researched, it is of critical importance to achieving acceptance of LMTO projects by the public, and therefore the understanding of risk perception is key to the sustainability of the LMTO industries.

2.2 Engineering Design

Engineering design has foundations in both science and art, involving the organisation of information, decision making, problem synthesis, analysis and creativity. The design process is part of the product development process, along with other company disciplines, such as Marketing and Research and Development. These other disciplines are very important with regard to the achievement of sustainable products as they will help determine the product need. However, this thesis concentrates on the design process which identifies how the product need can be met in a sustainable fashion, taking into account the potential environmental, economic and societal impacts.

Attempts to understand and improve the design process have led to a range of design philosophies, methodologies, tools and aids, the distinction between which is not well-defined. However Todd (1998) provided the following set of terminology to enable consistency:

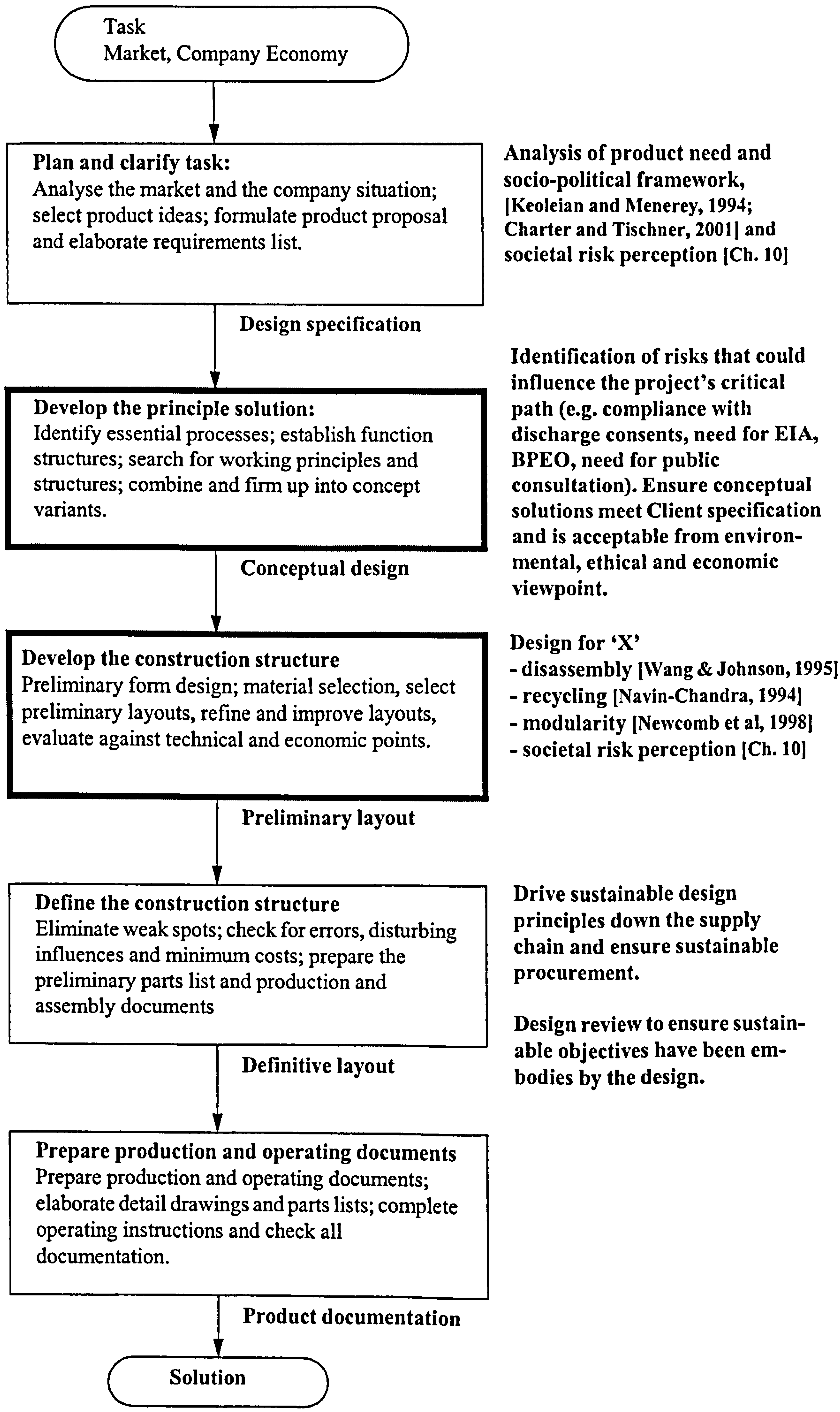
- Design method - the procedure by which designers conduct projects which includes tools, aids and techniques.
- Design tool - a procedure which generates and structures information to assist a designer in making a decision (such as Quality Function Deployment).
- Design aid - a procedure which improves the creativity of the designer (such as brainstorming or CAD).
- Design strategy - "The chosen path formulated to achieve business and design objectives supported by an indication of how resources will be committed" (British Standard for design management systems, BS7000, cited by Todd).

Prescriptive design models attempt to provide an improved way of conducting the design process (Cross, 2000; Suh, 1990). Descriptive design models describe how people conduct their design activities using the designer's experience, typically placing much significance on generating a solution concept early in the design process (Todd, 1998). A review of prescriptive and descriptive methods was produced by Finger and Dixon (1989). However, recent work by Todd found current design models to be inadequate as many models focused on the design process in isolation from the business background in which it was taking place. This weakness would have serious implications for the success of a sustainable engineering design model. Therefore, this thesis has taken the project management structure and business drivers into account.

2.2.1 The Contribution of Prescriptive Design Models Towards Sustainability

A systematic design model was proposed by Pahl and Beitz (1996), presenting the path from task identification to solution generation in a number of steps (Figure 2-1). This approach is very similar to the German standard guidelines on design method, VDI-Guidelines 221 (Cross, 2000). French also produced a systematic model which includes a feedback loop to ensure that requirements are met by the solution (French, 1985). Systematic models tend to reduce the problem into sub-functions which are then systematically recombined to maximise the number of design possibilities (Todd, 1998). Research into prescriptive design implicitly or explicitly assumes that a systematic methodology will culminate in optimal design. However, few research groups have tested this assumption (Finger and Dixon, 1989). Whether this assumption holds true or not, it is indisputable that key requirements for engineering design decision making are transparency, auditability and consistency. These requirements play an essential part in obtaining discharge authorisations or planning permission. In addition, prescriptive models assist the identification of appropriate stages for the integration of eco-design and sustainable product design tools and techniques.

Figure 2-1: Design Process Steps and Sustainable Design Milestones



(Adapted from Pahl and Beitz, 1996)

Figure 2-1 shows Pahl and Beitz's schematic of the engineering design process which has been adapted to indicate how key sustainable design activities could be integrated with the traditional steps of the design process. The diagram is simplified and it should be noted that many of these stages are iterative. For example, it is often necessary to revisit some of these activities more than once during the design process, as more detailed information becomes available.

The focus of this thesis is on the introduction of sustainable design considerations during conceptual and preliminary layout design, as indicated in Figure 2-1. These boundaries were set as a result of the investigative work discussed in Chapter 4 and in order to ensure the scope of the thesis was manageable. However, Figure 2-1 also indicates that important sustainable design activities that precede and follow these targeted design steps.

Early conceptual design establishes product function which refers to the purpose of the design without reference to how it is accomplished (Keoleian and Menerey, 1994). This is a very important stage for the early integration of sustainable engineering design principles, ensuring that all concept variants are acceptable in terms of economics, the environment and society. However, it was found that this stage in particular lacked methods and tools to support the integration of environmental and societal considerations.

Subsequently, the concept variants or the preferred variant may be further developed using 'Design for X' (DFX) heuristics shown in Figure 2-1. 'X' represents various constraints on the design space, such as design for assembly, design for disassembly and design for recycling (McAloone and Holloway, 1996; Spath, 1996). DFX techniques focus on one particular product aspect or one stage of the life-cycle (de Caluwe, 1997). However, the effectiveness of these DFX tools is dependent on the inclusion of related supporting principles at the definition and conceptual stages (Todd, 1998).

Pahl and Beitz (1996) and Newcomb et al., (1998) assert that Design for Safety, Recycling, Maintenance, Modularity and Ergonomics are largely applicable at the embodiment or detailed stages of design. However, it is increasingly recognised that this reduces scope for better engineering solutions. For example, passive 'fail-safe' control measures included early in design are generally more effective than protective safety measures added late in design or after the design process has been completed. For instance, the height of a drum storage facility can be designed in line with the integrity limits of hazardous waste containers, preventing any loss of containment that may occur if a container was dropped. Furthermore, legislative requirements drive environmental constraints to the front end of design as there are often requirements placed on industry to present documentation and discharge estimates to the regulators prior to detailed design.

2.2.2 The Contribution of Descriptive Design Models Towards Sustainabilty

Descriptive design studies examine how the design process is carried out in reality. For instance, the humanistic aspects of design are examined in a collection of experiments using protocol analysis (an empirical method based upon verbalised thought processes) to examine the cognitive and social aspects of design (Cross et al.,1996). For example, one study examined the differences between the design strategies of individuals compared with a design team (Dwarakanath and Blessing, 1996). Another example is provided by Kennedy (1999), who gathered descriptive data to examine the use of design tools within an Australian industrial design company.

As descriptive studies can be used to gain an understanding of the humanistic aspects of design, this approach has potential for exploring the humanistic aspects of sustainable engineering design which is dependent on individuals' mindsets, motivations and educational background. Andreason (1991) identified the following key factors that influence the design process which all contain descriptive aspects:

- The design engineer or design team;
- The supporting facilities available;
- The methods, tools or procedures for structuring the task and performing design activities;
- The knowledge and ability to model the product during its life-cycle;
- Management of the design process including strategies and targets;
- The physical, social and psychological conditions of the working environment.

These factors could affect a product's sustainability in a multitude of ways. For example, unsustainable designs may be a result of poor environmental awareness within the design team, an inability to obtain life-cycle data from suppliers, a lack of suitable tools and techniques to assist the integration of environmental and societal aspects of product design or the presence of a management culture which focuses on capital expenditure to the exclusion of non-economic factors. An example of a such a descriptive investigation was provided by the UK's Design for Environment Decision Support (DEEDS) group, who analysed questionnaires from 18 electronics / electrical manufacturing companies (targeting designers, management and EH&S personnel) to identify factors which influence the success of environmentally conscious design. The following underlying influences were identified (McAloone and Evans, 1997):

- Motivation; legislation, eco-labelling, customer requirements for the manufacturer to 'take-back' products and the degree of integration between design and EH&S.
- Information flow; the presence of a multi-functional team culture, communication

of corporate environmental vision to design teams, informing designers of recycling processes and creating awareness of design tools, alternative materials and legislation.

• Whole-life thinking; understanding of economic advantages of eco-design and selling services rather than products.

• Provision of environmental decision support tools; including environmental commitment at early product definition and throughout the design process, enabling environmental assessment and prioritisation of options.

Although this study was based on the mass produced market sector, it gives a clear indication that most of these influences could be applied to the LMTO sector. It was considered that much could be gained from undertaking prescriptive design studies to see how effective these influences are in the case of more complex product systems.

2.3 Concurrent Engineering and Life-Cycle Design

Concurrent engineering is a design philosophy which aims to improve the design of complex product systems by emphasising the need for innovation and by using an integrated, team-based approach (Todd, 1998). Life-cycle design is a key part of this philosophy which encourages designers to consider all phases of the product, from the procurement of materials and equipment, through to decommissioning and site restoration.

Concurrent design aims to consider all product requirements, functions and design disciplines simultaneously, driving designers to consider all stages of the product life-cycle from the outset in an integrated manner. The approach encompasses the following central themes; identification of customer requirements, encouragement of innovation and product ownership, motivational management, utilisation of multi-disciplined teams to consider all product life-cycle aspects, creation of good supplier relations and establishing a defined information infrastructure (Willaert, et al. 1998). This should result in increased product quality, reduced life-cycle costs and reduced time-to-market. In summary, concurrent engineering aims to maximise the effectiveness of the design process to deliver a competitive, quality product. Therefore, if the principles of sustainable design are captured within the definition of 'quality' it would be possible to achieve commercial advantage without compromising the needs of future generations.

Although the concurrent engineering philosophy is a collection of simple ideas, the implementation of these ideas within a large scale design project could provide a difficult challenge. Cote et al. (1998) provides an example of a concurrent engineering framework for ship design, construction and operation in the US Navy's ERAM (Engine Room Arrangement Modeling) Team. Quality function deployment (QFD) was used to identify the top 8 to 10 customer requirements. Core skills were then identified in line with these requirements, which were used as the foundation for design team selection. After participating in a team building and training programme, multi-disciplined team members were given tasks appropriate to allocated sub-systems, such as Hull/Structural, Piping Systems and Machinery. This study demonstrates how Concurrent Engineering may be applied to the complex design process of LMTO product systems.

As discussed previously in this Section, life-cycle engineering is part of the concurrent engineering philosophy. A key driver for life-cycle design is improved economic feasibility as 85% of the product system's life-cycle costs are committed by the conceptual design stage (Blanchard and Fabrycky, 1991). Therefore front-end focused design is the first step towards cost leadership in the marketplace (Todd, 1998).

As the majority of the product's economic footprint is determined during the initial phases of design, it follows that the environmental and societal footprint will also be set to a large extent during early design. Life-cycle design is discussed specifically in the context of integrating environmental and societal aspects into the design process by Keoleian and Menerey, (1994). The parallel between Total Quality Management and the minimisation of undesirable environmental impacts is explored, whereby the environment is seen as a 'customer' and environmental impacts are described as quality defects. Notably, the fundamental need for the product itself is challenged.

"Life cycle development projects properly focus on fulfilling significant customer and societal needs in a sustainable manner. Avoiding confusion between trivial desires and actual needs is a major challenge of life cycle design".

(Keoleian and Menerey, 1994)

Keoleian and Menerey discussed the following key stages of life-cycle design:

- Requirements should be stated and objectives defined in order to help the design team translate the customers' needs (where the environment is viewed as a customer) into a solution space for design. These requirements are assembled into a requirements matrix where columns represent life-cycle stages and rows represent components of the product system.

- Conceptual design - innovative ways to meet requirements are proposed, avoiding too much reliance on past designs. Concepts are then screened to determine their feasibility.

- Preliminary design - the design is decomposed into sub-systems and life cycle sub-stages. Detailed design synthesis and design selection proceeds, returning to the concept and requirements stages where the acquisition of detailed knowledge reveals problems.

• Detailed design - the final details of the best design alternative are obtained through drawings, engineering specifications and final process design. Design reviews, including representatives from the life-cycle chain (for example, operators and manufacturers), ensure that design objectives have been translated successfully into the design.

A similar approach to Keoleian and Menerey's design matrices is the adapted QFD methodology, Green QFD-II (Zhang et al., 1998). Requirements of the customer, the product's environmental life-cycle and total product costs are balanced during three stages; technical requirement identification, product concept selection and product and process design. Green QFD is underpinned by the simple additive weighting method (see Section 5.3 of Chapter 5), where design options are evaluated using relative subjective scoring of the design against broad environmental performance categories. However, adaptation of this method is likely to be necessary on a case specific basis. For example, to account for the out-of-envelope risks associated with LMTO products and the uncertainty surrounding design data during early design.

This Section has explained the aims of the concurrent engineering philosophy and how they are relevant in terms of their potential to support the principle of sustainable engineering design. If this approach were to be adopted, progress towards sustainable engineering design would be achieved through a clearly stated customer requirement and supporting objectives which take the product life-cycle into account. This life-cycle viewpoint is necessary for sustainable engineering design, as all phases of an LMTO product or process could affect the environment and the human population in a local and global sense (e.g. the large-scale extraction of materials during procurement and the potential for contaminated land legacies that remain after decommissioning).

2.4 Management of the LMTO Design Process

LMTO design in the engineering and construction industries was undertaken by a contract designer for the client operator. However, the issue of individual contracts to separate product disciplines (design, fabrication, installation and pipelines) suffered from conflicting interests and inefficient project interfacing. Project Alliancing is a recent answer to these problems, where all parties work together closely and economic benefits are shared out according to each party's risk exposure. For example, BP's Andrew Field Project Alliance resulted in a 21% reduction in capital expenditure through reduced numbers of personnel, improved supplier relationships, reduced interfaces and design innovation (Halman and Braks, 1999).

This co-interest helps lead to openness regarding objectives and a better understanding of business drivers between parties of the alliance. Risk and Reward incentives may be built into agreements which can include various targets for cost, schedule and availability. Incentives are dependent upon performance measurement and it is asserted that subjective performance measures, such as client satisfaction or response time to requests for information, may be particularly appropriate for alliance projects (Smith, 1999).

A successful project alliance contains both organisational systems and team building elements. It has been a criticism that too little effort is spent on unifying the workforce within the newly formed group which may negatively influence communications, attitudes, behaviours, commitment and involvement (Crane and Richmond, 1999). However, if this obstacle can be overcome, the alliance-management of design projects offers scope for sustainable engineering design at the contractual and cultural level if the client company has genuine environmental, societal and long-term economic commitments.

2.5 Developments in Eco-design and Design for Environment

The terms eco-design and Design for Environment (DfE) are used interchangeably in this thesis in accordance with the following definitions:

"Eco-design or DfE refers to the systematic incorporation of environmental factors into product design and development. Eco-design being the European definition and DfE being the US definition."

Charter (1996)

In order to understand how eco-design may be achieved, it is necessary to introduce some of the methods, metrics and eco-design practices that have been developed. Fiksel (1996) stated that the following key elements are required for integrated eco-design:

- Eco-efficiency metrics, driven by fundamental customer needs or corporate goals to support environmental performance measurement. Examples are percentage recovery of materials, energy consumption and wastewater volumes. ISO14001 may provide a vehicle for performance measurement if design is considered to have significant environmental effects.

- Eco-efficient design practices, based on in-depth understanding of relevant technologies and supported by engineering guidelines. Examples are material substitution, waste minimisation and energy efficiency.

- Eco-efficient analysis methods to assess proposed designs with respect to the above metrics and to analyse cost and quality trade-offs. Examples are screening methods, assessment methods and decision making methods.

Sweatman and Simon (1996) organised a number of eco-design methods into two categories in their concise review of analysis and improvement methods. Analysis methods include Life-cycle Analysis (ISO/TC 207, 1998; United Nations Environmental Programme, 1996) and abridged Life-Cycle Analysis (Kane et al., 2000). Improvement methods include checklists (Simon et al., 1998; CIRIA, 2000), workshops and DFX approaches; design for recycling, design for disassembly and design for the removal of hazardous substances.

The following parts of this Section discuss a variety of eco-design methods based on the following sub-headings:

- Specific eco-design methods for analysis
- Specific eco-design methods for improvement
- Regulatory frameworks for environmental analysis and improvement
- The use of ISO14000 to support eco-design
- Integrated methods for design analysis and improvement

More comprehensive reviews of eco-design methods were published by (de Caluwe, 1997; Fiksel, 1996).

2.5.1 Specific Eco-design Methods for Analysis

Charter and Balmane (1999) asserted that eco-design or Design for Environment practices tend to be managed by the organisation's environmental function rather than integrated throughout the design functions. One example of a method which specifically addresses environmental performance is Life-Cycle Analysis (LCA), a formalised methodology comprising four main stages:

- **Goal Definition and Scope:** The goal of an LCA study maybe to compare two products or to understand which life-cycle stage of a single product confers the most environmental burden using gravity analysis (ISO/TC 207, 1998). The goals of the study must be clearly defined along with a strategy for achieving those goals. LCA is unlikely to be used for benchmarking against competitive products in the LMTO product sector (Hindle, et al. 1993; Saur et al., 1996). However, it may assist the initial eco-design target setting phase for LMTO products. Abridged LCA methodologies which can be undertaken on an iterative basis could increase the feasibility of applying LCA to LMTO products as it reduces the enormous data requirement (Kane et al, 2000).

• **Life-cycle Inventory:** Data quality is critical to the validity of LCA results (de Smet and Stalmans, 1996) and data collection can be extremely time consuming and expensive. Life-cycle inventory data can be obtained from published sources, such as the Boustead database or SimaPro (Sweatman and Simon, 1996). However, some of the more unusual materials used in LMTO products are not listed as the commercially available databases are geared towards packaging, automotive and other high volume manufacturing industries. For instance, life-cycle data on super-duplex steel and anti-foulant paints is not generally available.

• **Life-Cycle Impact Assessment:** Life cycle impact assessment is subdivided into three steps; classification, characterisation and valuation. The valuation step, which includes impact weighting, has a great influence on the final outcome. Several weighting approaches exist, for example; authoritative panel methods (Landbank, 1994), monetarisation methods (Tellus Institute, 1992; Steen, 1994) and distance-from-target methods (Goedkoop, 1995).

• **Improvement Assessment and Interpretation:** The LCA results may be used to identify the best product within a comparative study. Alternatively, the LCI data may be used to uncover product life-cycle stages that present significant environmental burdens. The interpreted LCA results lead to the improvement analysis stage of LCA where 'environmental hotspots' are addressed using more problem-specific methods (Sweatman and Simon, 1996) discussed later in Section 2.5.2.

An important criticism levelled at LCA is that it tends to lead to the identification of incremental improvements which are applied to the next generation of products (Sherwin and Bhamra, 1999). Furthermore, methods that aggregate the impact data into a single index reduce the transparency of the decision process and frequently contain error (Boustead, 2000). Finally, the assembly of the life-cycle inventory data is very time intensive and is best suited to product sectors that can frequently re-use this resource, such as Fast Moving Consumer Goods (FMCG). Therefore, it is not ideally suited for LMTO products where a single project can take years to develop.

Another example of eco-design analysis methods are group discussion-based 'what-if' type methodologies which are more conducive to innovative design. However, these types of methods often require well-developed diagrammatic representations as a basis for the discussion which removes focus from the front-end of design. One such example is ENVOP, an adaptation of the established Hazard and Operability method discussed which identifies opportunities for waste reduction (Potter and Isalski, 1993).

At early conceptual design, where measurements are mostly qualitative or relative (ordinal), comparative analysis tools are more appropriate. For example, the eco-fitness spiderweb diagram developed by Dow (ENDS, 1996). Eco-fitness is measured on a subjective scale of 0-5 against 6 performance attributes; use intensity, material efficiency, energy efficiency, environmental and health risk potential, resource conservation and waste reduction. Where product comparisons reveal a clear winner, as shown by Dow's 'Blue House' case-study, this tool conveys a useful visual indication of the best design alternative. However, the spread of fitness between alternatives may not reveal a clear winner, resulting in an incomplete decision. In addition, the user is not explicitly asked to consider each alternative in the context of each life-cycle stage, as is the case with Keoleian and Menerey's life-cycle requirements matrix (1994).

2.5.2 Specific Eco-design Methods for Improvement

Improvement methods are generally concerned with optimising a certain environmental aspect or collection of environmental aspects relevant to the product in question. They are usually conducted after eco-design analysis has identified a need in the specific improvement area.

As design progresses and more quantitative data becomes available, scope for mathematical optimisation increases. Pistikopoulos et al. (1994) proposed an improvement tool to optimise the environmental and cost performance of process designs based on the environmental impacts identified within the system boundary. Environmental impacts were quantified and combined into a Global Environmental Impact indicator which was inserted into a multiobjective optimisation problem along with operating costs.

Design for Recovery methods search for the design configuration which optimises the process of disassembly. Restar is an example, developed by Navin-Chandra (1994), which detects the break-even points and points of maximum profit of a disassembly sequence. Profit in this instance can relate to cost, time, energy and waste minimisation, as determined by the user. A similar tool was described by Wang and Johnson, however, energy consumption was not treated as an explicit parameter during optimisation (1995).

2.5.3 Regulatory Frameworks for Environmental Analysis and Improvement

Best Practicable Environmental Option (BPEO) and Environmental Impact Assessment (EIA) provide frameworks for analysis and improvement stages (Pearce et al., 1999). BPEO is a regulatory requirement in the UK for industrial processes that are authorised under IPC (Integrated Pollution Control). The Environment Agency adapted The Royal Commission on Environmental Pollution's definition of BPEO, resulting in the accepted (IPC) BPEO definition (Environment Agency, 1997b):

"the option which in the context of releases from a prescribed process, provides the most benefit or least damage to the environment as a whole, at acceptable cost, in the long term as well as the short term."

The plant operator must demonstrate that the design or plant modification represents the BPEO in order to obtain IPC authorisation. The BPEO assessment represents an analysis stage, requiring an evaluation of all feasible process options in terms of:

- Long term effects in air, water and land
- Short term effects in air, water and land
- Global Warming
- Ozone Creation and Depletion
- Waste Arisings
- Other Environmental Effects (odour, visible plumes, critical loads)

If significant environmental effects are identified, releases are prioritised to assist option selection, representing the improvement stage of the framework. This often takes the form of a multiple attribute decision making problem.

The focus of a BPEO study is to minimise emissions to air, water and land in an holistic sense. It provides methodologies for environmental impact assessment, economic assessment and sensitivity analysis so that the future or current operator may make an objective judgement with regard to selecting the best *practicable* option. The selection process embodies the principle of BATNEEC, Best Available Technology Not Entailing Excessive Cost, which recognises the need for a cost-benefit approach. Processes that fall within the scope of the more recent IPPC Regulations (EA, 2001) undertake a very similar assessment process. However, the principle of BATNEEC has been replaced by BAT (Best Available Technology) which places slightly more pressure on the operator to invest more in environmental technology, so long as the technology yields a significant environmental benefit. In addition, there is more emphasis on clean technology rather than end-of-pipe solutions. For both IPC and IPPC assessments, the relative harm of each proposed option is estimated, as quantitatively as possible, based on the magnitude of the release, ambient pollution concentration and the characteristics of the receiving environment. Although it is recognised that significant qualitative assessment will also be necessary.

Similarly, EIA is a formal requirement within the UK for all projects categorised under Annex I, and certain development projects categorised under Annex II, of the EIA Regulations (ODPM, 2003). This places a requirement on the developer to submit an Environmental Statement with the planning application, both of which become public documents. The Environmental Statement reports on significant environmental impacts associated with various stages of the project life-cycle (e.g. the analysis stage). Suitable measures must then be presented which will eliminate or reduce the significant environmental impacts (e.g. the improvement stage). Ideally, several project alternatives should be considered and discussions should commence with the local planning authority and relevant statutory consultees (English Nature and the Countryside Commission are examples of statutory consultees) as early as possible in the development process.

The following sections should be included in the Environmental Statement:

- Information describing the project

- Information describing the site and its environment
- Assessment of effects
- Mitigating Measures
- Risks of accidents and hazardous development (this is not included in the EIA Directive but is advised in the DETR's guidance when the proposed development involves harmful materials).

The requirement for EIA also applies to the offshore oil and gas industry through EC Directive 97/11 (Lummis, 1998) which asks that certain categories of offshore developments to prepare an Environmental Statement. As a potential critical path in project progression, this increases the need to address environmental impacts at the early stages of design and establish a well-structured system for environmental decision making (Robertson-Rintoul, 1998).

Robust decision making with a visible audit trail is central to these regulatory environmental frameworks. Therefore, a decision making process that demonstrates full consideration of a project's environmental aspects during engineering design is essential for gaining regulatory approval for LMTO projects.

2.5.4 The Use of ISO14000 to Support Eco-Design

In addition to the regulatory frameworks presented in Section 2.5.3, international standards may also be used by design organisations to structure their approach to eco-design. Fet (1998) demonstrated how ISO14000 could be applied in the ship-building industry to reduce environmental impact. Targets and procedures can be developed in relation to design activities so that continuous improvement of this aspect of the business becomes part of the certification process. For example, Fet's study presented Environmental Performance Indicators (EPIs) and showed how the environmental performance evaluation standard (ISO 14031) can be applied to design. EPIs were developed in relation to a ship's sub-systems, alongside relevant reporting parameters, e.g Material Utilisation measured as the % of excess material. The indices of each subsystem were combined using the ISO 14040 LCA method to measure contributions to global warming, acidification, eutrophication, smog formation and material efficiency. In addition, environmental performance indicators were developed for management areas; financial performance, safety performance, policy and programme implementation, and compliance with regulations.

Therefore, in addition to the regulatory requirement for transparent and robust decision making, ISO14000 introduces voluntary standards for the timely implementation of environmental actions and targets to ensure that improvements regarding environmental performance are monitored, communicated and reviewed (Cascio, 1996)..

2.5.5 Integrated Methods for Design Analysis and Improvement

Integrated design methods utilise a set of carefully chosen environmental and non-environmental attributes in order to select or synthesise the most robust design overall. Therefore, the goal of integrated design activities is not exclusively environmental, but represents a trade-off between competing design criteria. Well-established integrated techniques exist which may be used as a means of analysing or improving a design's environmental performance, such as Value Engineering studies and Hazard and Operability Studies (HAZOP).

Value Engineering, or Value Analysis, is an optioneering process developed in the second World War in the United States (Kelly and Male, 1993). It is now a globally practiced method which aims to improve a product's value in relation to cost, using the following stages:

- Team selection
- Information gathering
- Brainstorming
- Evaluate the alternatives
- Develop the alternatives
- Make recommendations for design
- Implement recommendations

Value Engineering can include any attributes perceived to confer value to the client or customer. In some cases, 'environmental performance' would be considered to impart value. Functional analysis is conducted in order to determine how successfully environmental performance and other value attributes are captured by the design options. Group members score each option against each attribute in a similar fashion to the optioneering stage of BPEO assessment.

HAZOP analysis was developed by ICI and is widely used throughout the process industries (ICI Engineering Technology 1996; Swann and Preston, 1997). Originally intended to systematically identify safety hazards and operability issues, HAZOPs are often extended to identify environmental hazards.

HAZOP studies are based around authorised process flow diagrams or process and instrumentation diagrams. Specific parts of the diagram will be subjected to a series of 'what if?' questions which relate to a set of keywords and deviations. Examples of keywords are flow, temperature and pressure. Deviations include words or phrases, such as more of, less or none. This can be a useful tool for identifying environmental hazards as a precursor to risk assessment and risk management. However, the method is focussed on hazard identification, and therefore long term cumulative and chronic effect, eco-scarcity issues and environmental nuisance will not be identified. Furthermore, due to its relatively detailed nature, HAZOP is less likely to bring about innovative changes to the early design concept.

2.6 Multiple Attribute Decision Making Methods (MADM); Improvement or Analysis, Specific or Integrated?

Section 2.5 has provided information on methods and frameworks that are available to support the principles of eco-design. This Section discusses MADM which commonly provides the underlying foundation of these methods and frameworks. For example, Value Engineering and the Dow eco-design fitness compass are both based on the Simple Additive Weighting method; see Section 5.3 of Chapter 5 for a full description. In addition, the use of MADM in the optioneering phases of BPEO and EIA is widely supported by the Regulators.

MADM enables the selection of a preferred option from a number of alternatives, based on the options' performance against a number of selected criteria or attributes. The use of MADM has the advantage of being able to manipulate qualitative or quantitative data, enabling application throughout design as the data quality improves.

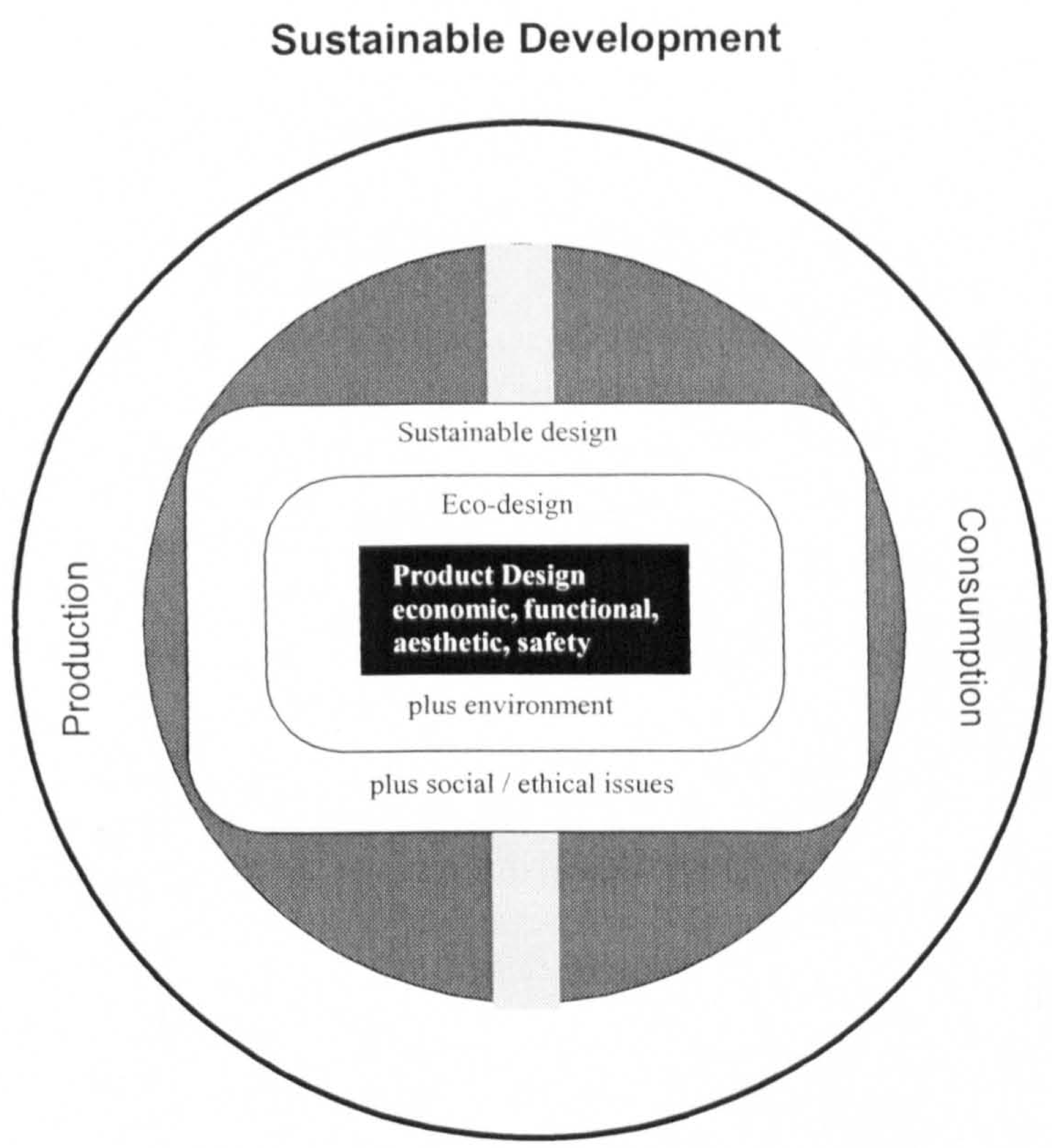
Product design is often considered as a rational decision making process, where a problem can be decomposed into a set of options and associated criteria. A mathematical operation is then applied to find the optimal decision, or specifically in this case, the best design option. Frequently, there is conflict between sustainable design criteria. For example, redundant or duplicated components will ensure the safe functioning and durability of critical systems on an offshore platform, reducing the risks of out-of-envelope incidents and potential loss of containment. However, the extra material and weight associated with the duplicated plant conflicts with the eco-design principle of dematerialisation (ENDS, Report 252, 1996; Fiksel, 1996).

MADM is a common denominator for many of the methods, tools and techniques developed for eco-design, which is due to its flexibility. This is an important characteristic, as a sustainable engineering design technique must be adaptable on a case-by-case basis if it is to be widely used. Techniques developed to support the selection of sustainable designs are introduced in Chapters 6 and 8 which are founded on this rational multiple attribute decision making approach.

2.7 Societal and Ethical Product Design

Whereas Sections 2.5 and 2.6 have concentrated on the achievement of better environmental performance, this Section discusses available methods that may help to attain societal acceptance of industrial development. Sustainable Development is often described as the triple bottom line owing to it's integration of economic, environmental and societal considerations. The social and ethical component of the triple bottom line is by far the least developed. In terms of engineering design it is an emerging concept, yet it can have considerable impact on the viability of an LMTO project (Cramer, 1999). Considerable work has been done within academia to examine eco-design. However, the focus of academic research often include the adoption of long-term goals, such as the consideration of inter-generational environmental effects, which are not the key concern of industry which tend to be focussed on the short-term implications of a project (Argument et al., 1998). Tischner illustrated the relationship between design, eco-design and sustainable product design in Figure 2-2 (cited by Tischner and Charter, 2001). All three activities can contribute to building a more sustainable relationship between production and consumption whilst maintaining quality of life.

Figure 2-2: The Relationship Between Design, Eco-Design and Sustainable Product Design, (Tischner and Charter, 2001).

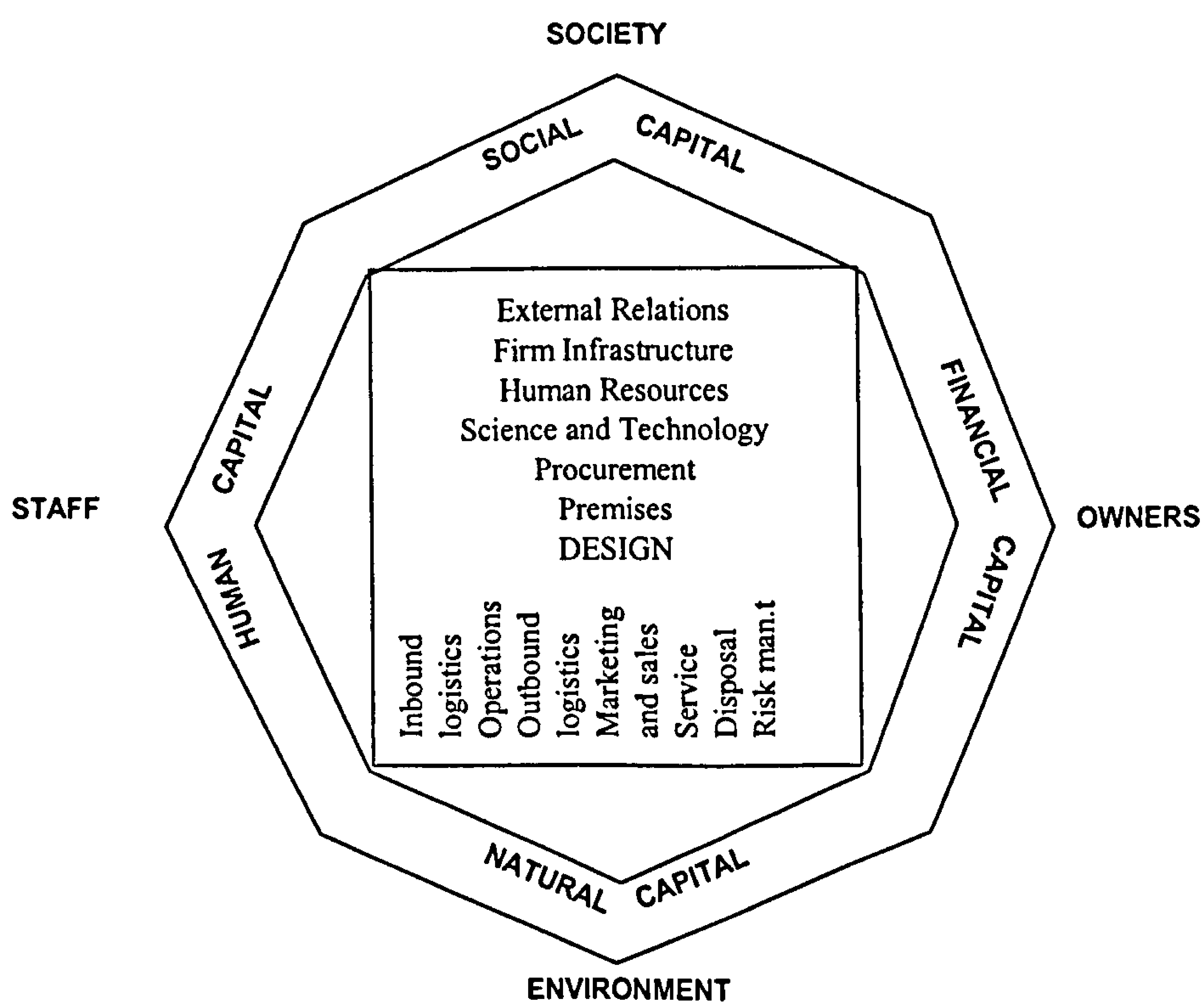


Typical social or ethical issues commonly associated with sustainable product design are; fair trade, equitable policy, human resources, conditions of work, investment in the community and participation of stakeholders. Accounting for the public's perception of risk is rarely explicitly mentioned. However, it is often the goal of stakeholder consultation and is necessary for obtaining equitable engineering decisions at a community level.

Societal impacts associated with the life-cycle of products and services are considered to be key indicators for sustainability reporting by the voluntary Global Reporting Initiative (GRI, 2000). Examples of social aspects that could be considered by LMTO businesses are; community involvement, skills transfer, technology transfer, site selection, complaints, community reinvestment, activities in developing countries, altruism and taxes.

Business has sometimes ignored society as a stakeholder during safety and environmental decision making at great cost to their credibility and profitability. For instance ABB's proposed construction of the Bakun Dam in Malaysia was thwarted by opposition from indigenous people, NGOs and the media (The Antidote, 1996). The importance of product design with regard to sustainability is illustrated by James' sustainability octagon, based on Porter's model of value creation (James, 2001). Design is placed at the centre of the octagon as it represents the primary function that determines a product's impacts.

Figure 2-3: The Importance of Product Design with respect to Sustainability (James, 2001).



Eekels (1994) describes multiple product functioning where the business, societal and ecological requirements must be met by the design engineer. Eekels explores the amalgamation of these functions and asserts that societal requirements are usually multiple and conflicting in themselves. For example, society demands a supply of energy but also place value on an environment free from man-made radiation or the intrusive visual and noise impacts of wind farms.

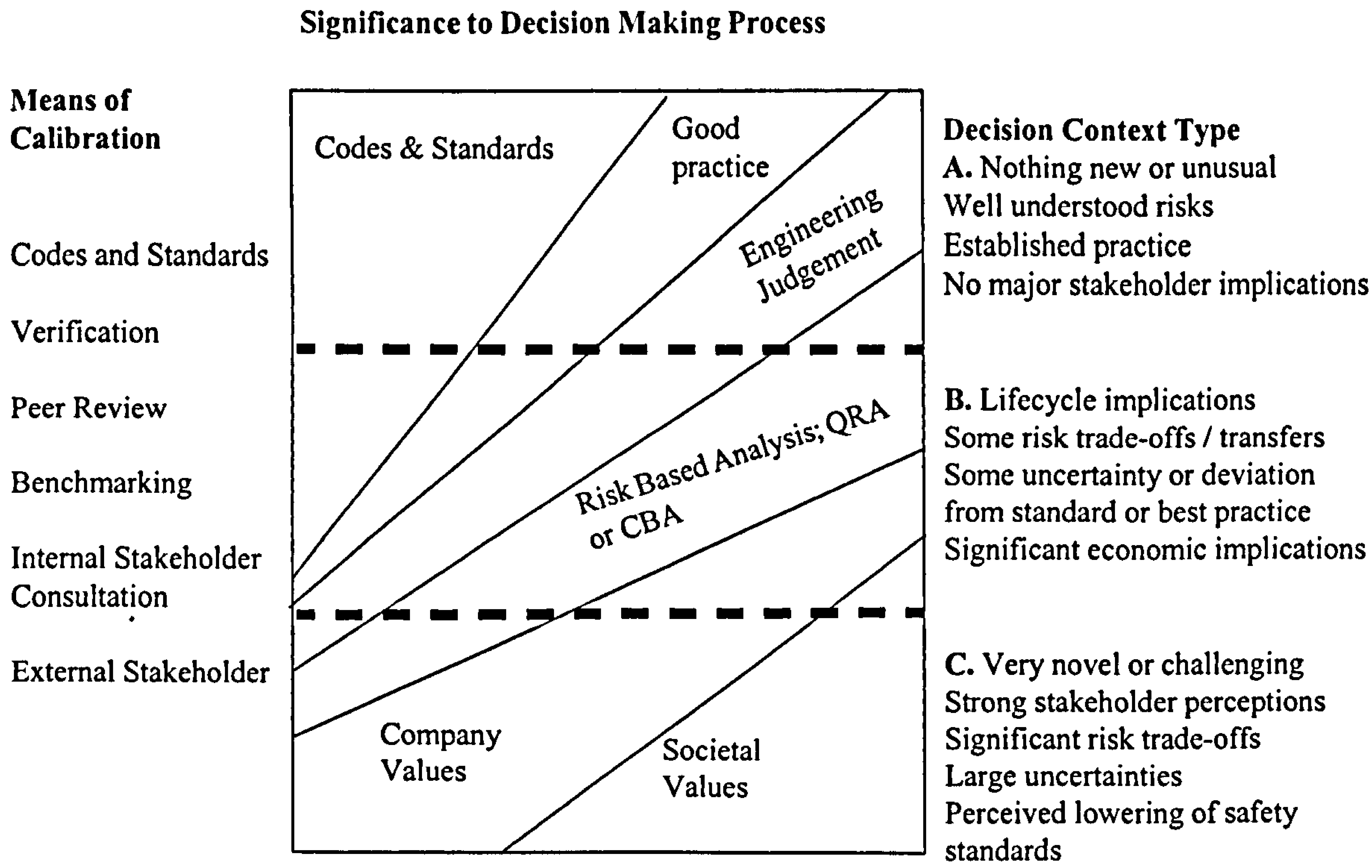
'One of the most serious [ethical implications of design] is that the formidable scientific and engineering input into technical action may lead to one forgetting that its roots lie in value statements'.

(Eekles, 1994)

This is an important statement which exemplifies the danger of developing narrow or exclusively scientific models of engineering design. This is supported the application of the Precautionary Principle to risk management which accounts for adverse consequences that have not yet been established or that remain unproven (UK Interdepartmental Liaison Group on Risk Assessment, 2002).

Shell UK Expro have developed a chart (see Figure 2-4) which illustrates how risk evaluation tools are selected in relation to engineering decisions and includes societal values (Carne, 2001). The skewed lines suggest the comparative contribution of decision making mechanisms for various types of engineering decision. Type C decisions would therefore be dominated by internal and external stakeholder consultation with little or no influence from Design codes and Standards or Good Practice verification activities. Figure 2-4 shows that QRA has relevance to all decision types but that it should be used *in conjunction* with other means. In the case of Type C decisions, it will have a relatively small contribution in comparison with corporate and societal values.

Figure 2-4: Shell UK Expro's Risk Evaluation Chart for Engineering Decisions



Whilst this risk evaluation chart may be useful, it does not fully answer the important questions; what are societal values and what factors lead to the public's intolerance of risk? Public opinion was taken into account in the Green QFD-II methodology (Zhang et al., 1998). However, the approach was over-simplified and a full explanation regarding how a designer should rate the public opinion weighting factor was not provided. In order to develop methodologies in this area, it is important to understand the nature of public risk perception.

2.7.1 The Relationship Between Risk Perception and Sustainable Development

Perceived risk has been defined as;

"The belief or fear that the harmful potential of a hazard will be realised" (Kirkwood, 1993)

The link between sustainable development and perceived risk has been discussed in terms of temporal, spatial and social dilemmas. This describes how individuals are called upon to compromise their local security, comfort or wealth in order to reduce risks for future generations or communities that live far from the individual. In some cases risks may be discounted due to their delayed or distal effects, and an over-weighting of benefits 'now, here and for me', (Vlek and Keren, 1992). This postulated inability of people to make altruistic decisions in the context of future generations or globalised impacts may lead to conflict with key objectives of sustainable development. For example, that of intergenerational equity where development during this generation does not compromise the resources of future generations. Furthermore, people from different cultures and political regimes have different interpretations of their relationships to the world and obligations to others on the planet (Jasanoff, 1999).

The public's perception of risk is often different in relation to scientific risk assessment and this attitude has often been attributed to a lack of technical or scientific understanding. Research has suggested that this may be caused by the'unscientific' coverage of major incidents by the popular press (Cohen, 1998), and poor awareness of the causes and effects associated with environmental impacts, (McDaniels et al., 1996).

The adoption of the Precautionary Principle (UK Interdepartmental Liaison Group on Risk Assessment, 2002) could serve as a protection mechanism which counters the limited ability that individuals have with regard to judging risks that are distant in terms of space or time. This Principle is intended to prevent or limit the possible harm caused by agents or activities before it has been established that the activity or exposure condition constitutes a harm to health.

From an epistemological point of view, risk perception may represent additional information which can contribute to the decision model, to the benefit of all. Risk aversion and precautionary approaches to risk taking are influential in human decision making to varying degrees, subject to culture, education and personality. These underlying decision strategies are survival mechanisms used when decisions need to be made in an uncertain environment. (Kahneman *et al.* 1982, Slovic 1987). In addition, Fischoff *et al* (1978) suggested that safety risk assessments, such as ALARP (Melchers, 2001) overlook causes and effects that are not included in the system model. Models of environmental risk are similarly vulnerable to incompleteness, necessary assumptions and value judgements. Thus a purely rational, aleatory approach could generate business decisions that are unacceptable to society.

2.7.2 Accounting for Risk Perception in Business Decision Making

Risk perception can be considered actively within business decision making process or as a guide for organisations when communicating risks to the public (Wilkinson, 1997).

Public opinion is sometimes taken into account during voluntary public consultation or as part of a regulatory requirement. For example, when it is necessary for a business to comply with the Control of Major Accident Hazards Regulations 1999 (COMAH). These Regulations place a statutory requirement upon the operator to inform the public of its off-site emergency plans within a defined *public information zone*. Some attempts have been made to incorporate a risk aversion factor, α, to account for safety-related risk aversion when defining safety levels. For example, an α factor of 1.2 was applied to safety criteria for nuclear reactor design (Griesmeyer and Okrent, 1981). However, the determination of these α factors has been disputed by different research groups and evidence attributed to risk aversion may be more a consequence of imprecision with regard to the number of lives under threat (Slovic, 1984).

Frequently, risk communication messages are imparted by experts (company representatives, independent scientists or academics) to the lay public in order to educate people, build trust and raise awareness. However, this usually occurs after the decision making process has taken place with no opportunity for the public to contribute. Risk implications of the decision are communicated in order to increase the public's acceptance by accounting for age, sex, ethnic group, educational background and other factors which have been postulated to influence how risks are perceived (Bier, 2001). Public consultations are notoriously difficult to manage and can be susceptible to strong opinion polarisation which reduces the opportunity for increased awareness on both sides and the attainment of acceptance. However, research conducted for the Health and Safety Executive (HSE) found that the consultees' views were often provisional and negotiated during the discussion (Walker et al., 1998).

So why should commercial organisations take the public's perception of risk into account during engineering design decision making? This question can be addressed under two headings. Firstly, the normative argument recognises the ethical reasons for including risk perception. Secondly, the epistemological argument suggests that risk perception represents additional knowledge that is inadequately represented by probabilistic risk assessment (Pidgeon, 1998). Thirdly, there is a risk of being unable to proceed with a preferred option due to public opposition, leading to the refusal for planning permission for example.

Traditionally in the UK, decisions have been made on the basis of expert opinion and evaluation from design engineers, project management and external regulatory and advisory authorities, such as the United Kingdom's Environment Agency or Health and Safety Executive. On normative grounds, risks taken by industry may affect society's health and safety, civil liberty and social welfare in the short term and in terms of future generations. A decision model should include societal risk perception where the presence of factual uncertainty and value judgements render a purely technocratic approach inadequate.

Lessons can be learned with respect to the initial decision in favour of deep-sea disposal of the Brent Spar caused public outcry in spite of the decision being the result of an approved BPEO process (Rice and Owen, 1999). In addition, decisions made within the nuclear fuel industry have led to the rejection of decisions based solely on robust technology and economic viability (Sohn et al, 2001).

Therefore, the consideration of society as a stakeholder in engineering design is essential to secure the long term future of LMTO industries in an increasingly risk intolerant society.

2.8 Academic Research and Relevance to Industry

This Chapter has provided an introduction to engineering design, management of the design process, eco-design and social and ethical issues that may affect the viability of a design. An understanding of these areas is necessary to enable an informed investigation of how sustainable engineering design may be achieved within the LMTO product sector.

3 SOCIAL RESEARCH METHODS IN THE CONTEXT OF CASE-STUDIES

3.1 Introduction

Quantitative approaches, such as questionnaires, will enable the researcher to generalise from a studied sample to a wider population, depending on the sampling method employed. Even in the absence of random sampling, the sample covered by a survey is likely to be much larger than is feasible for qualitative studies, such as interviews or focus groups. However, qualitative research may be required to investigate phenomena in a deep and narrow sense using methods that will provide richer, contextual data.

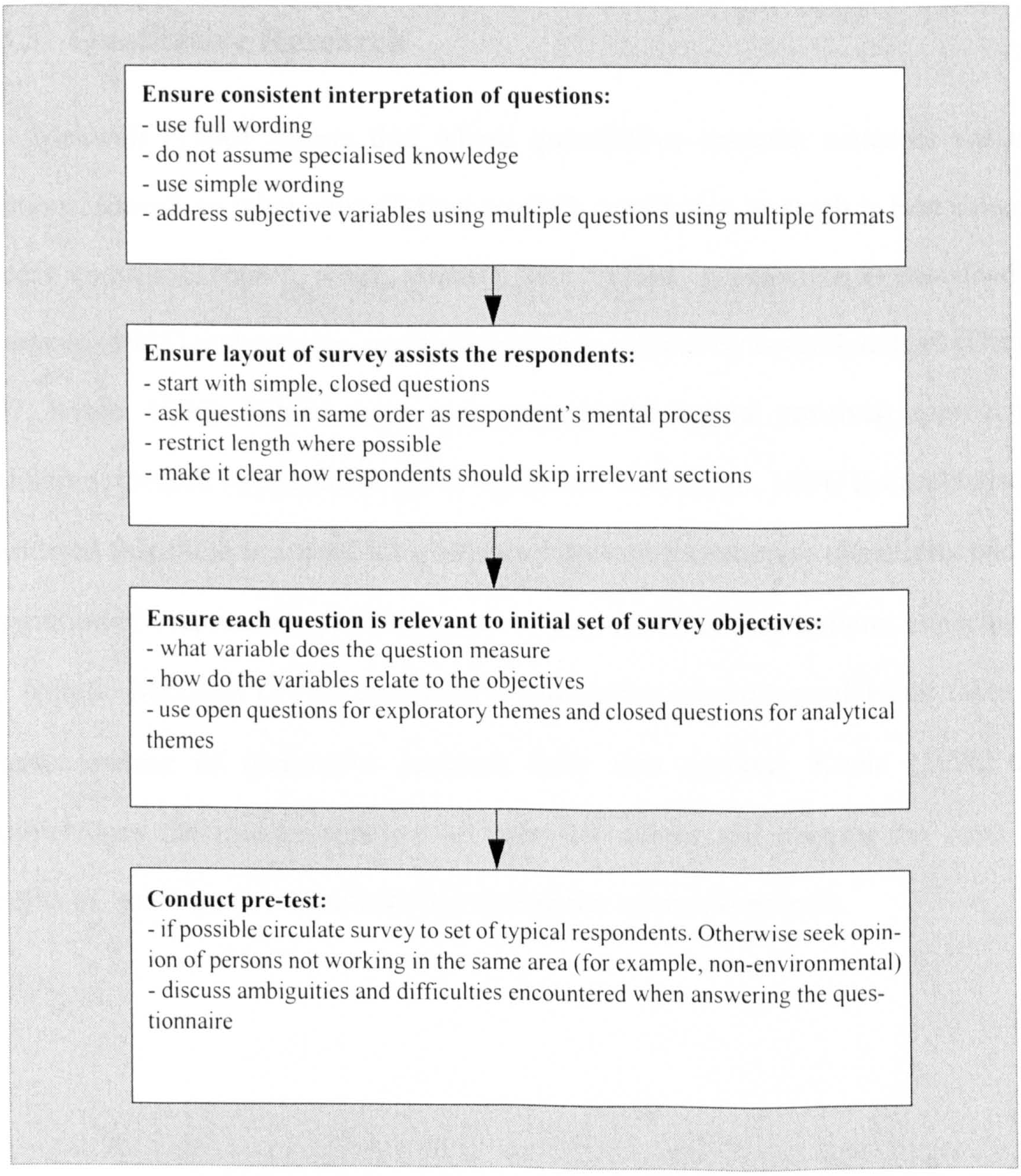
The opinions of well-established social research authors on questionnaire and interview design, data analysis and interpretation are discussed. Various attributes of qualitative research are investigated along with the limitations of case-study research in terms of generalisability.

3.2 Questionnaires

A wealth of texts are available on how to conduct a survey or questionnaire Oppenheim (1992), Fowler (1988) and de Vaus (1993) provide clear, practical advice on scoping the study, sampling, questionnaire design, collecting data, data analysis and ethical issues. Most texts are aimed at extensive sampling frames in order to identify characteristics associated with a population or to enable causal analysis by looking at the variation obtained in response to a variable or linked variables (de Vaus, 1993). However, the goal of some surveys is not to generate statistics but to measure a range of ideas or opinions in the context of a pilot survey (Fowler, 1988).

Guidelines for question design, questionnaire design and validity remain important regardless of the type of survey in question. Low response rates may affect the validity of results and non-respondents may represent a specific sub-group (Fowler, 1988). For example, in the context of sustainable design, engineers very much opposed to the consideration of environmental issues may not respond. Although Fowler argues that the mode of data collection does not affect response rate, he succinctly outlines the advantages and disadvantages of telephone surveys, self-administered surveys and questionnaires conducted in an interview situation. Figure 3-1 outlines some steps that will assist validation of exploratory surveys.

Figure 3-1: Achieving Validity Through Questionnaire Design

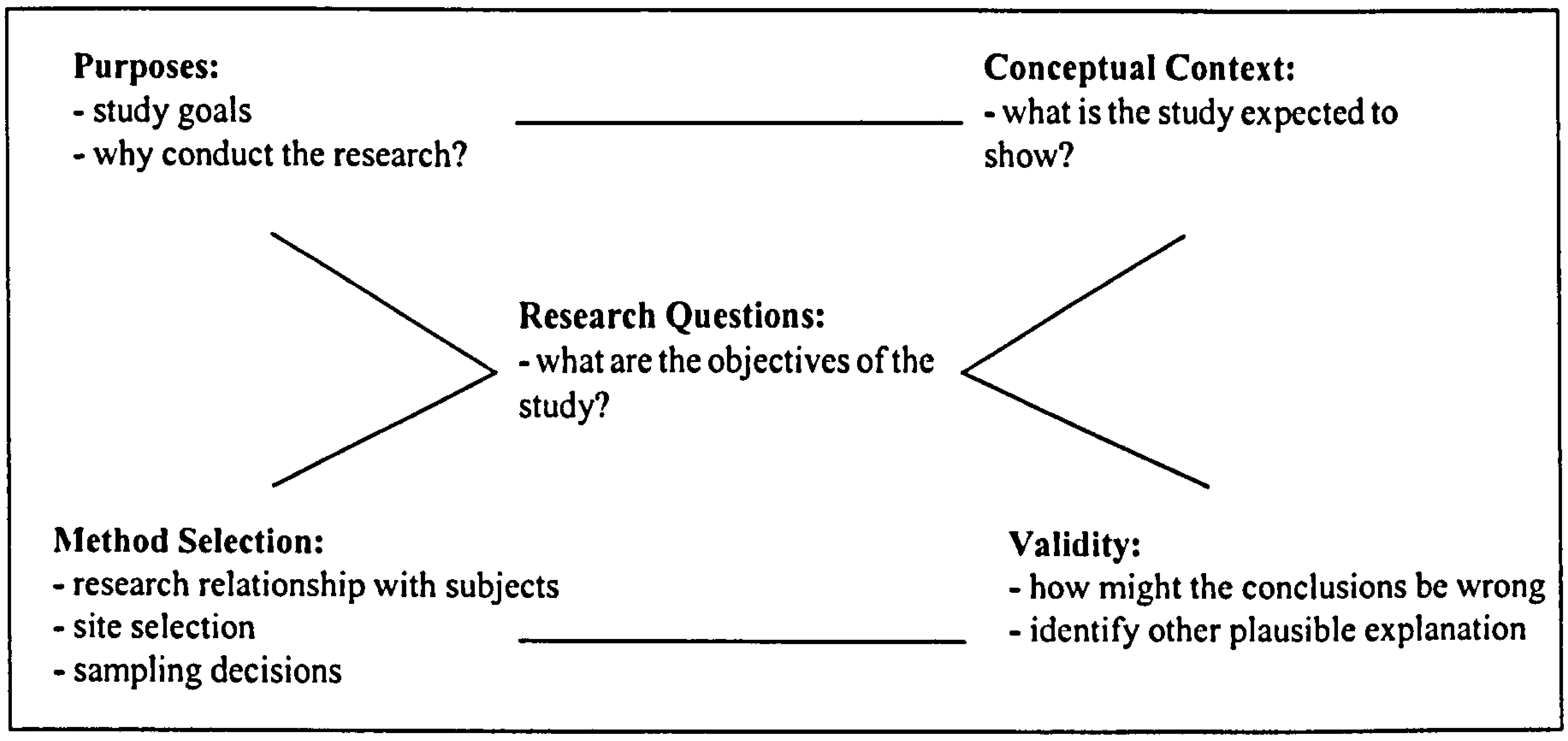


Data analysis of exploratory, pilot surveys is often restricted to descriptive statistics where conclusions will only apply to the sample of respondents involved (excluding the non-respondents). Frequency distributions are derived from the number of respondents that gave each answer. These are generally expressed as percentages, where *n* usually represents the number of respondents that gave an answer (de Vaus, 1993). Histograms may be used to illustrate the results and give a pictoral indication of skew, spread and most common answer. Further analysis can be conducted by calculating the mode (nominal data), median (ordinal data) or mean (interval variables).

3.3 Qualitative Research

Maxwell (1996) asserts that where quantitative research concerns variance questions, (does?, to what extent?, how much?), qualitative research is best suited to process questions, (how?, why?, when?). The 'realist' perspective is described by Silverman (1985) and concise, practical advice is offered by several authors (Drever, 1997; Kvale, 1996). Whilst many texts support the logical positivist approach to qualitative research (Oppenheim 1992; Miles and Huberman, 1984) it should also be considered that there is a need for a balance between maintaining objectivity and the recognition of irrepressible problems, such as preconceived assumptions, expectations and beliefs. Maxwell (1996) presented a qualitative research model that takes the dynamic nature of qualitative research fully into account. Kvale (1996) also acknowledges the interdependence of interview stages and debates the costs and benefits of 'getting wiser' (inductivity) during the interview process.

Figure 3-2: Interactive Model of Qualitative Research (Maxwell 1996)



The following discourse refers specifically to qualitative research interviews. Other qualitative research methods exist, for example stakeholder analysis (focus group meetings), analyses of company documentation, 20 statements test, tracer studies and observational studies (Cassell and Symon, 1994) which were not considered the best approaches in this case.

For case-study research in organisations Hartley (1994) recommends that the researcher undertakes some preliminary studies on organisational structure and gives some useful advice on gaining and maintaining access during the course of the investigation. For example, identifying critical 'gate keepers' (influential contacts) and involving multiple contacts to ensure that the research continues should the main contact leave the organisation or change role.

3.4 Research Interviews

Interviewing is a well established method of gathering qualitative data about a real world system. However, it is a controversial area amongst the scientific community. Kvale, (1994) discusses the controversy in accepting qualitative research interviews as a scientific method. From the positivist outlook, conclusions should be observable through the data and drawn objectively. Qualitative interview techniques violate this positivist concept of science as the data is qualitative and involves interpersonal interaction which goes against the notion of objectivity. Interview data is unlikely to be repeatable and reliability cannot be measured in the way of quantitative analysis (the amount of measurable agreement between data sets). However, some proponents of qualitative research techniques believe that interviewing can be undertaken in an objective, unbiased manner (Oppenheim, 1992). Whereas other advocates of the area feel that subjectivity is a strength of the method as long as the researcher recognises the influence of his or her experiential knowledge (the researcher's expectations, assumptions and beliefs), and ensures that any influence upon the conclusions is transparent (Maxwell, 1996). It is also argued by Kvale (1994) that interpretation and theoretical presuppositions feature in accepted positivist methods where meanings are translated into data, for example in content analysis.

Indeed, qualitative interviewing does not violate all definitions of science. Many well recognised scientific disciplines employ qualitative techniques. For instance cell biologists will use electron micrographs to convey visual information on cell structure or the location of cell constituents. The question of whether this method is a science is less important than the utility of the knowledge that the research represents.

3.4.1 Methodologies for qualitative research interviews

Kvale (1996) presents variations on a semi-structured interview approach which is based on seven stages; thematizing, designing, interviewing, transcribing, analysing, verifying and reporting.

Thematizing is a conceptual clarification and theoretical analysis of the theme to be investigated; the what, why and how of the interview (Kvale, 1996). This leads to the formulation of the interview questions and whether the purpose is to gain information, opinion or attitudes. Maxwell (1996) illustrates this stage within the *Purposes*, *Conceptual Context* and *Research Questions* categories shown in Figure 3-

2. The interactive and evolutionary nature of the qualitative study is particularly emphasised by Maxwell who argues that models placing the development of research questions at the start do not account for the inductive nature of qualitative research, where question formulation continues as the study proceeds. In addition, the concept may evolve as data is gathered. Concept mapping, or similarly conceptual framework diagrams, may need frequent redrawing as understanding develops (Miles and Huberman 1994; Maxwell, 1996). 'No risk' concept frameworks should be avoided where only global-level variables are included and relationships are mainly denoted by two way arrows. These pictorial concept diagrams can then be used to help generate relevant research questions. Miles and Huberman (1994) demonstrate this technique using a school improvement field study as an example.

Research questions can be organised into nine categories; Introducing Questions, Follow-up Questions; Probing Questions; Specifying Questions, Direct Questions, Indirect Questions, Structuring Questions, Silence and Interpreting Questions (Kvale, 1996).

Methods (Figure 3-2) are developed in accordance with site selection, data collection, data analysis, research relationships and sampling decisions. During research design the sample size must be established which will usually be a compromise between the availability of interviewees; the time available to conduct, analyse and process the interview; and financial resources. Kvale (1996) reasons that if the number of interviews is small it will not be possible to make statistical generalisations. If the number is too large, the depth of interview will be reduced and profound interpretations will not be possible. Oppenheim (1992) discusses the use of exploratory interviews in qualitative research and advises that, if only 30 or 40 interviews are conducted, it is not advisable to quantify such studies as the sample is unlikely to be representative. He adds that in this type of research, representativeness should not be the aim. It is more important to obtain a good spread of respondent characteristics. Maxwell (1996) clarifies that sampling for the purposes of qualitative research has different aims compared with a quantitative study. The notion of *purposeful* or *criterion-based* sampling is introduced where the optimal strategy is selected which will provide the desired information. For instance, if the research question concerns the activities and attitudes of a design team a sample should include representatives from each discipline.

Research design should always take into account the ultimate purpose of the research and how the study may be published or presented. For example, are we conducting a case-study analysis or do we wish to represent the broader outlook of LMTO industry? A case-study approach will provide rich, contextual data which is useful for organisational research (Hartley, 1997). Two case-studies provide sufficient knowledge for a compare and contrast study but only suggestive generalisations can be made (Maxwell, 1996). Kvale (1996) suggests that the number of interviews generally conducted tends to be between 5 and 25. In the field of qualitative research interviewing, quality is preferred over quantity.

3.4.2 The Interview

The interview stage is an interpersonal exercise, as opposed to questionnaires which are anonymous. In an interview situation it is important to note that knowledge is created between the interviewer and the interviewee. It is also recognised that the human nature of this interaction will lead to the development of feelings on the part of the researcher and interviewee. Rather than discard this response as a failure of objectivity, Hartley (1997) suggests that emotional responses (to an individual or topic raised during discourse) should be noted and used to enrich and further understand the data. Although the results are an interactive result obtained from the interviewee and interviewer, the input of the interviewer should be minimised (Oppenheim, 1992). The interviewer's role is to listen carefully and without prejudice, limiting their input to encouraging the interviewee's response (Kvale, 1996).

The initial briefing stage of the interview is the stage at which trust between the interviewer and interviewee is generated. If the subject is assured of confidentiality and the research ethics of the interviewer, the subject's responses will be open and expansive. The briefing will also describe the interview requirements, such as whether interviews will be recorded and the purpose of the research to the subject. In some cases, a complete explanation of the research aims is not desirable and this part of the brief is kept vague (Drever, 1997).

The interviewer may prepare an interview guide (Kvale, 1996; King, 1997; Drever, 1997) prior to the interview if structured or semi-structured interviews are involved. Kvale suggests that the interviewer evaluates each question thematically (the relevance of the question with respect to the research theme) and dynamically (do the questions promote interviewee response, are questions easy to understand in terms of language and length).

The type of interview method selected for the research task will affect the insights of the subject's 'lived world' that the interviewer will obtain. Interview methods range from specific questions delivered in a specific sequence, to interviews which only pre-organise the theme in advance; the questions are developed spontaneously during the interview based on interaction with the subject.

Kvale (1996) introduces a set of interview quality criteria:

- The extent of spontaneous, rich, specific, and relevant answers from the interviewee.
- The shorter the interviewer's questions and the longer the subject's answers, the better.

- The degree to which the interviewer follows up and clarifies the meanings of the relevant aspects of the answers.

- The ideal interview is to a large extent interpreted throughout the interview.

- The interviewer attempts to verify his or her own interpretations of the subject's answers during the course of the interview.

- The interview is "self-communicating" - it is a story contained in itself that hardly requires much extra descriptions and explanations.

3.4.3 Structured Interviews

Structured interviews are sets of verbal questions in conjunction with pre-determined response categories. This simplifies the problem of data analysis and will increase the reputability of results. This method is unlikely to yield results on the cultural aspects of the system (for example, the organisation, the design process etc.) or uncover aspects of the problem which were unforeseen by the researcher. A common problem is that interviewees may find parts of the interview irrelevant which may reduce the credibility of the interviewer.

3.4.4 Unstructured Interviews

In this case, there are no preset topics or questions. The interviews will vary, (sometimes entirely) between interviewees, making the data very difficult to analyse and compare. This method is more likely to draw out complex issues but there is a danger that the data may be impressionistic and may describe artefacts of a particular interview, rather than give a representative view of the system. Unstructured interviewing is appropriate for the collection of ideas and impressions, rather than hard data (Oppenheim, 1992; McCracken, 1988).

3.4.5 Semi-structured Interviews

Semi-structured interviewing represents a hybrid of the previous methods. The interview guide will outline the topics to be covered and suggested questions. In practice some questions may not be used due to irrelevance or the ordering of questions and themes may be changed due to the responses received from the subject. Interviewees have the freedom to expand and diverge from the agenda where they feel it is required. Semi-structured interviewing will not yield hard, representative data. However, the qualitative data will be more comparable than unstructured interview data as the same topics will have been addressed in approximately the same order.

During structured and semi-structured interviews, there may be several prescribed answer categories which the interviewee is expected to choose from. When the alternative answers are read out as a list along with the question, this is known as a prompt. If the alternatives are written as a show card, the answer categories are on display to the interviewee so they can keep these options in mind whilst answering the question (Oppenheim, 1992).

3.4.6 Closing the Interview

After the interview it will be necessary to debrief. There may be tension towards the close of an interview due to the subject reflecting on the information that he or she has divulged and they may have concerns about potential consequences. They may question what they have gained from participation in the exercise, whereas some may be enthusiastic and will request a copy of the final report. It is important to include time at the end of an interview for all queries to be raised.

3.4.7 Transcription, Processing and Analysis

The raw data acquired from interviews must be processed. The initial stage of data processing usually involves transcription of the verbal interview to a textual format. Transcription is far from straight forward and time consuming (Drever, 1997). Often the transcribed text is misguidedly thought of as the core data. However, it is important to remember that the text is a decontextualised account and frequent references should be made to the original audio or video recording for clarification of the richer meaning (Kvale, 1996). Kvale also exhorts that if more than one person is involved in the transcription process, the primary researcher produces some initial examples for guidance and issues clear instructions with respect to transcription style.

King (1997) provides a succinct account of data analysis methods; quasi-statistical, template or codebook approaches, editing and immersion. Miles and Huberman (1994) give a fuller account of thirteen approaches. Kvale (1994) discusses the common 'ad hoc' approach where researchers synthesis their own analysis protocols. For example, using visualisation techniques to illustrate connections and structures implicit within the studied phenomenon.

In many cases, the data is organised using a code-based classification system. A specific example of this method type is content analysis (Krippendorf, 1981). Numerical codes are applied to linguistic information with the assistance of a code book. The code book includes the text of the original question, probes and details of the numerical classification system. Positive and negative signs are often used to denote the presence or absence of the coded theme or category in question (Kvale, 1996). Krippendorf (1981) maintains that content analysis is an instrument of science and must therefore be reliable and repeatable. Miles and Huberman (1994) warn researchers against relying too heavily on numerical data as richer meaning of the original text can frequently be overlooked. Data triangulation is suggested as a way of overcoming this problem.

3.4.8 Verification; Generalisability, Reliability and Validity

Kvale (1996) regards the issue of verification (a process of ensuring appropriate generalisations, reliability and validity) from a moderately postmodern outlook. That is to say, their meaning which was originally derived from quantitative studies must be reconceptualised in order to be relevant to interview research.

Generalisability refers to the inferences that may be drawn from a study. From a scientific perspective, statistics are applied to the results obtained via a random sample and generalised to the wider population. However, where random samples are not used, analytical generalisations are possible through theoretical proposition. In this case, reasoned judgement is used to make explicit assertions in conjunction with supporting evidence so readers can ascertain the actuality of the generalisation (Kvale, 1996; Hartley, 1997). Indeed, the rich contextual nature of case-study research enables a researcher to specify the conditions under which certain behavioural phenomena will occur (Hartley, 1997).

Reliability concerns the consistency of the research findings and, where relevant, the repeatability. This is particularly important during transcription processing, such as coding. Key phenomena should be identified from the outset and analysed in a uniform manner throughout the data interpretation. Quasi-statistics may help make the conclusions more robust by providing an indication of how many respondents shared a specific viewpoint or mentioned a specific theme. Care must be taken when specifying the theme or viewpoint in question as they may be expressed variably but synonymously amongst respondents.

Validity regards the quality inherent within the research process. Applied to research interviews, this translates as the extent to which each stage of the interview process supports the original research aims. It is critical to examine the validity threats to a qualitative research study and to build in validity protection during research design. At the interview stage for example, reactivity is the phenomenon by which the researcher influences the individuals or setting. There is also opportunity for bias to enter the qualitative data processing stage. The researcher may interpret information within his or her own framework of expectations or assumptions. Furthermore, bias can enter at the interview stage if the interviewer asks leading or short answer questions that can lead to artefactual conclusions which support the researcher's initial expectations. However, leading questions or leading body language can be used to verify answers in a beneficial way (Kvale, 1996). Maxwell (1996) argues that reactivity and bias cannot be eliminated but the researcher must understand it and try to use it productively. Maxwell also relates that a common flaw in qualitative research is the lack of consideration given by researchers to alternative explanations or understanding of phenomena during the data interpretation phase.

Certain validity precautions exist which should minimise the risk of conducting a flawed study. Rich data gathering refers to the recording and verbatim transcription of interview data. Researchers that record and transcribe selectively may only gather the evidence that supports their preconceptions (Maxwell, 1996).

Triangulation is the process whereby a phenomenon is investigated using more than one method or data source (Fielding and Fielding, 1986). Harvey et al. (submitted for publication 2004) presents a triangulated method approach applied to the measurement of safety performance in a processing plant, involving content analysis of relevant reports, attributional coding of interview data and statistical analysis of questionnaires. Thus conclusions drawn from each method can be examined in terms of data support or conflict, reducing the influence of systematic bias or limitations associated with a specific method (Maxwell, 1996). Fielding and Fielding (1986) discuss the integration of qualitative and quantitative methods, for example where survey data is used in conjunction with interviews to guard against over-emphasis of exotic or unusual data. However, Fielding and Fielding caution that tiangulation may not ensure validity if the selected methods have the same inherent biases.

Finally, giving interviewees the opportunity to verify or dispute final conclusions is a method of validation known as member checks (Maxwell, 1996). It will also provide important feedback to the subjects who assisted with the study and maintain their interest.

4 Current Practice in LMTO Design Teams

4.1 Introduction

This stage of the research featured two companies specialising in LMTO product design. Company A and Company B are representatives of the offshore and nuclear power industries. Both companies bid for engineering design contracts. Company A was engaged as the contractor in an alliance system and worked to a project specific environmental policy as well as their own corporate environmental policy. Company B was a wholly owned subsidiary and therefore worked to the parent company's environmental policy along with having a separate policy statement. Both Company A and B were preparing for ISO 14001 standardisation during the period that this research was conducted and have since gained accreditation.

The aims of this Chapter are to:

- Provide a comprehensive account of current eco-design practice within two case-study companies from the LMTO product sector.
- Gather evidence in relation to the tools and methodologies currently used and awareness of available tools and methodologies.
- Identify organisational and cultural problems relating to the integration of environmental objectives with design activities. Provide recommendations for improving the design process for better product life-cycle environmental performance and design tool development.

Primarily, a semi-structured interviewing technique (Drever, 1997; Foddy, 1993; Oppenheim, 1992) was used to gather information about the systems currently in place to facilitate eco-design within two LMTO companies. The study was designed in accordance with Maxwell's interactive model (see Figure 3-2 of Chapter 3).

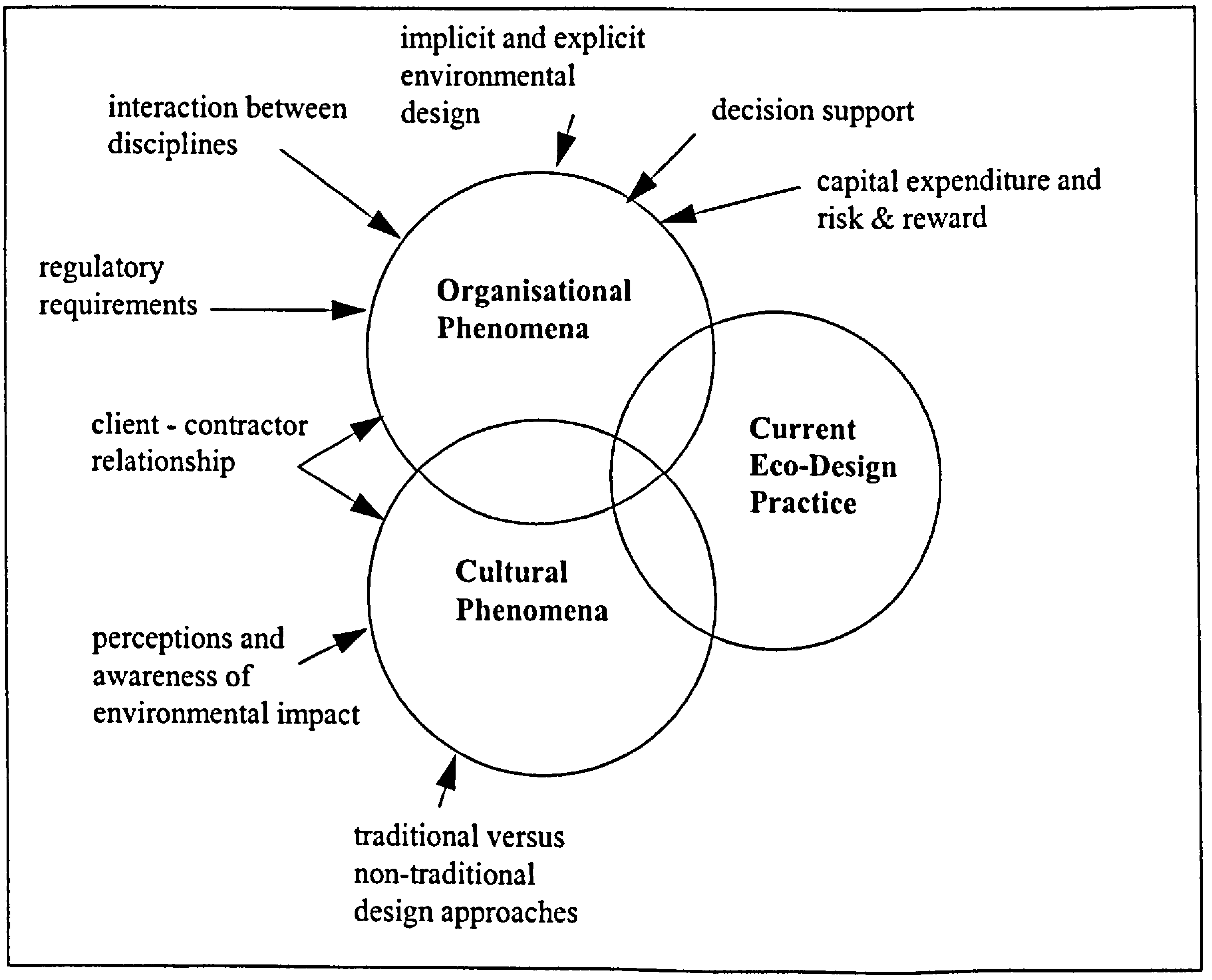
In addition, fifty questionnaires were distributed amongst the design teams of each company as shown in Appendix V. Questionnaire design took key factors into account, such as unambiguity, question order, question type and brevity (Wilson and McClean, 1994). The use of multiple methods to investigate an area of research is known as triangulation.

4.2 Method of Research

4.2.1 Conceptual Context

The study was expected to identify areas for improvement of the current eco-design process and was based upon the assumption that there was a need for improvement. This assumption was derived from evidence documenting the problems faced during decommissioning of LMTO products, increasing concern with respect to operational and accidental emissions and increasing legislation that aim to protect the environment. An initial concept map was produced to focus the research (see Figure 4-1).

Figure 4-1: Initial Concept Map



4.2.2 Interviews

Sixteen semi-structured interviews were conducted with selected personnel from the design teams of each Company (Appendix I). Each interview began with an introduction to remind the interviewee of the aims of the exercise and a list of key-words were presented on a flip-chart to define environmental information as follows:

'Any information related in any way to environmental performance and environmental impacts; pollution, waste production and waste minimisation, energy loss/efficiency, materials reduction, loss of containment, safety incidents that could have environmental consequences etc.

Information format:

Legislation, data, guidelines, drawings, advice, specification, informal conversations, events and conferences.'

The purpose of the keywords was to prevent the interviewees losing direction after they had expanded on a single topic, reminding them of the variety of other relevant topics at a glance. Duration of the interviews varied between 15 and 60 minutes which were recorded on audio cassette and transcribed (Appendix II).

The questions were formulated to cover 4 main categories in order to test the hypothesis that the environment is inadequately integrated during the early stages of the current LMTO design process:

- General design activities - in order to understand where the individual fits into the design process, his or her general opinions on their work requirements and to establish the presence of any indirect environmental design activities that the respondent had overlooked.
- Decision making activities - to identify decision support and the current integration or potential for future integration of environmental attributes.

- Environmental information flow - the sources and format of environmental information along with the respondents' opinion with respect to the efficiency of any systems in place.

- Environmental inputs and outputs - respondents were asked to describe any specific environmental inputs or deliverables, such as company initiatives, client requirements or environmental legislation.

4.2.3 Development of Textual Analysis Methods for Interviews

Firstly, the textual data was analysed using the template (coding) method (Crabtree and Miller, 1992). Data relating to the engineer's activities was categorised in order to produce activity models which show possible influences on environmental performance in a functional sense. Secondly, the audio recordings of the interviews were used to construct summaries of each interview shown in Appendix III. Important research themes were identified during the preliminary coding analysis and their frequency was quantified to indicate the commonality of the theme. The overall method consisted of eight steps:

- Initial coding of 5 transcripts
- Initial coding system (data / information, outputs, agent, activity)
- Adaptation to IDEF0 categories (input, control, mechanism, output)
- Transcription of remaining interviews
- Transcription processing
- Activity modelling
- Transcription summaries
- Theme counting (phrases, concepts)

4.2.4 Theme Counting

Themes relating to the objectives of the research were identified and the number of times that interviewees referred to these themes, or closely related sub-themes, was recorded. Figure 4-2 shows an example where the mention of an interviewee's contribution to an Environmental Statement was considered to be a clear indication of the interviewee's involvement with the EIA process, and captured in the recorded theme frequency.

Figure 4-2: Determination of Phenomenological Themes

Theme:
Involvement in environmental
impact assessment

Sub-themes:
Any mention of:
contribution to Environmental
Statement

Supply of data specifically
destined for Environmental
Statement

4.2.5 Transcript Processing for IDEF0 Representation

Each interview was recorded and transcribed. Five transcripts were analysed to define the preliminary coding and counting units. Initially, information was condensed from the transcripts into four high level categories; Activities, Data / Information, Agent (e.g. who from; who to), Outputs / Documentation. Each interviewee's discourse was examined under these categories along with additional information, such as quotes and details of specific eco-design decisions (Appendix III).

It became apparent that there was a close match between the initial coding categories and the categories of a formal approach, IDEF0. The transcripts were re-examined under the IDEF0 categories developed by SofTech for the US Air Forces'

Integrated Computer Aided Manufacturing programme (Mayer, 1990). A hierachical series of diagrammatic representations of the interviewees' design activities were modelled. The arrows between functions represent constraints as opposed to order or time dependency. Information was sorted into IDEF0 categories; INPUT, OUTPUT, CONTROL and MECHANISM (Figure 4-3).

IDEF0 (Mayer, 1990) begins with a non-detailed representation of the process being studied. The initial A0 diagram is shown in Figure 4-4 which outlines the high-level inputs, controls, mechanisms and outputs of the current eco-design process. This top level diagram was then successively decomposed into sets of more detailed diagrams representing key engineering disciplines and then specific individuals. IDEF0 diagrams should comprise three to six elements (boxes). However, as eight engineering disciplines were interviewed from Company A, this restriction was relaxed.

Figure 4-3: Basic IDEF0 Element

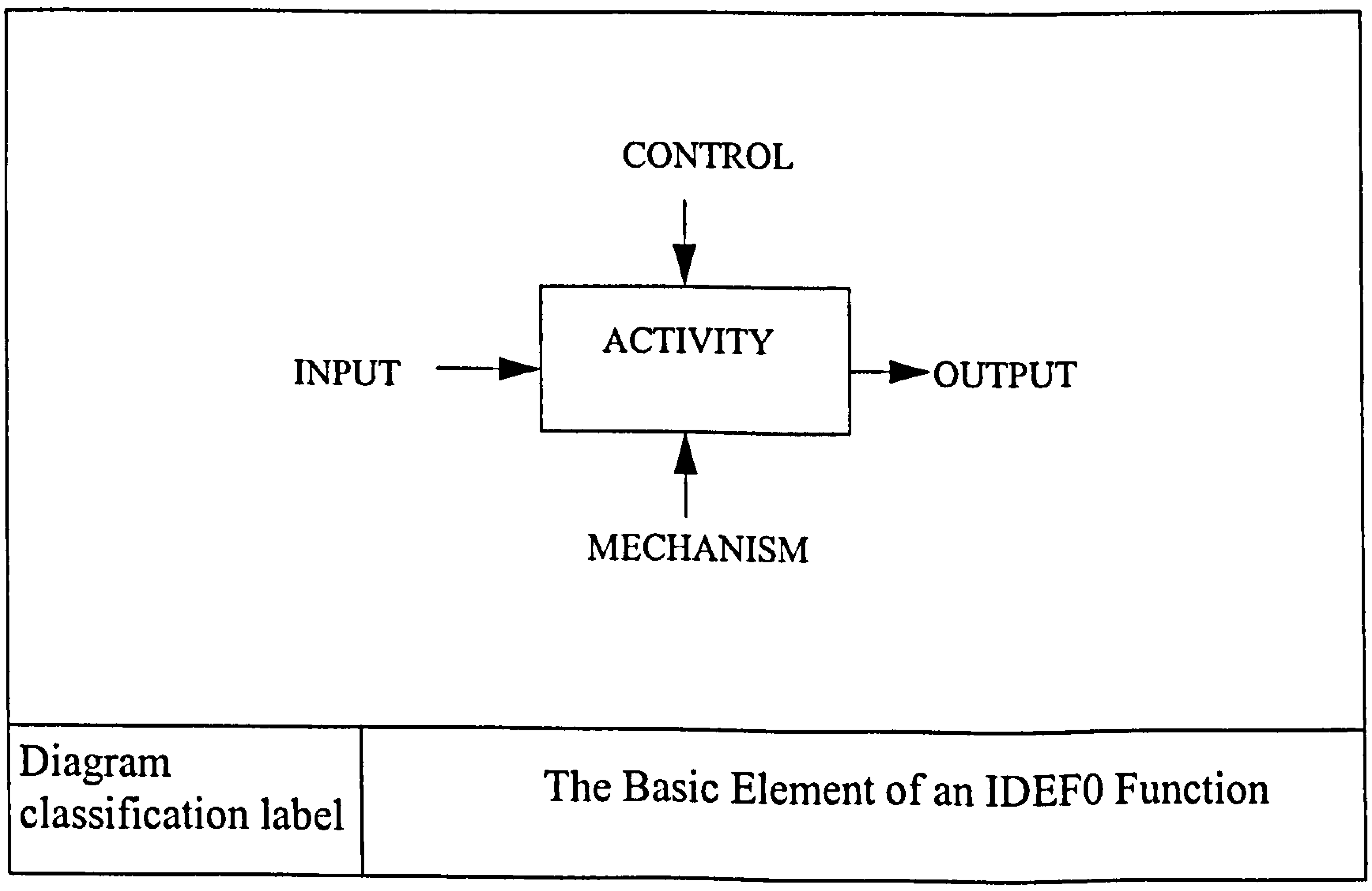
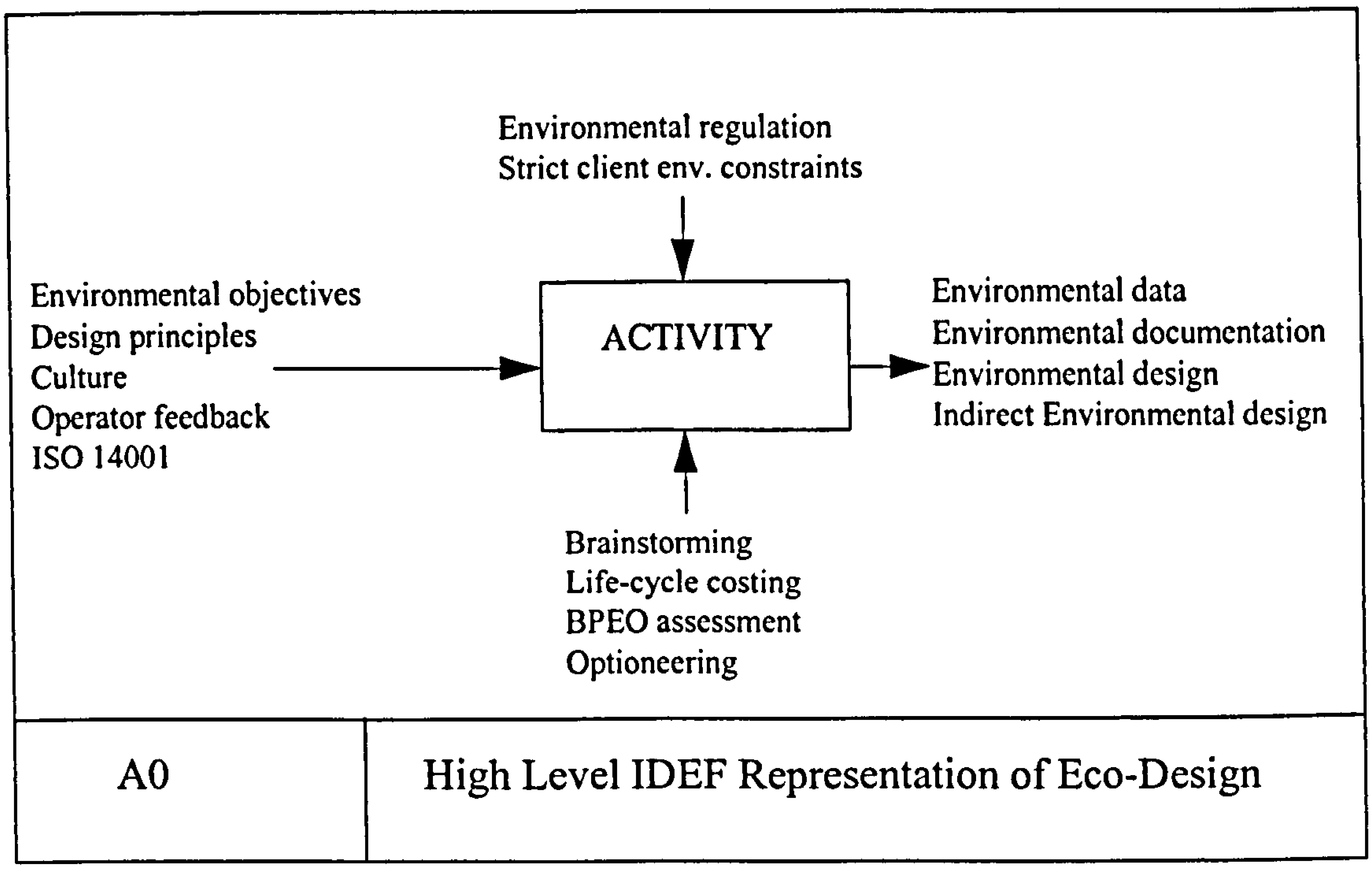


Figure 4-4: A0 IDEF Representation of Eco-Design



4.2.6 Questionnaires

A questionnaire investigation was also carried out as described in Appendix V. Respondents were asked for their names but assured that their responses would remain anonymous. This provided an opportunity for future contact in case there was a need for clarification during data interpretation.

The total number of respondents from both organisations is denoted as n. The percentage values are calculated for each question based on the total number of responses given (Σ), which may be more than n for questions which allowed more than one answer to be given per respondent, or less than n where respondents chose not to answer.The results of the questionnaire study given in Appendix V are integrated where relevant with the evidence drawn from the semi-structured interviews to support or challenge the main points. Emphasis is placed on the rich data gathered from the interviews. A full report on the questionnaire study is available (Stoyell et al., 1999). From one hundred questionnaires issued to the two design teams, the return rate for Company A and B was 74% and 56% respectively.

4.2.7 Validation

Results and conclusions were validated using data triangulation and method triangulation. Interview data was validated through the use of multiple data analysis methods. For example, IDEF0 diagrams were supported by theme counting to prevent over-emphasis of exotic themes. This was supported in turn by the inclusion of quotes and summaries derived from the audio recording in order to provide a more contextual approach. However, the selective nature of quotation was balanced by the provision of theme frequency data and alternative explanations.

Method triangulation was also undertaken through the use of questionnaires to further support the results and conclusions drawn from the interviews. Questionnaires introduced a quantitative examination of the same research themes, using a different sample of respondents based within the same Companies.

4.3 Findings

Examining the two companies' design processes at the IDEF0 A0 level, (Appendix IV: (A)A0, (B)A0), one can construct an overview of the inputs, controls, mechanisms and outputs which could potentially influence the environmental performance of the product during its life-cycle. The following results are presented in terms of IDEF0 terminology and in the following order:

- Inputs - objectives, targets, information from the client or from other design disciplines. Includes less tangible inputs, such as a mindset or corporate culture.
- Controls - hard constraints, such as legislation, design standards, strict company targets and client specification.
- Mechanisms - tools and techniques used to support the design activity and outputs include design deliverables, information and documentation which result from the design activity.

• Outputs - deliverables resulting from the activity in question, such as data, reports, diagrams or decisions.

As each IDEF0 category is addressed in the results, evidence to support important themes is drawn from the full transcripts (Appendix II), text summaries (Appendix III, Interviewee A15) and questionnaires (Appendix V).

The occurrence of a particular theme is quantified to indicate whether it applies broadly to the design team or whether it is an artefact of a single individual. Theme counting is represented as superscript, for example $^{(10/16A)}$ denotes ten out of sixteen interviewees from Company A mentioned this theme in the interview. These themes are summarised in Table 4-1.

Table 4-1: Frequency (*f*) of Specified Themes

IDEF category	Counted Theme	*f*[a]
CONTROL	Strict environmental constraints from client	4/16A 8/15B
CONTROL	External environmental regulations a major consideration	4/16A 7/15B
INPUT	Influence of ISO 14001 on engineers' activity	2/16A 2/15B
INPUT	Need to design beyond compliance	4/16A 5/15B
INPUT	Presence of formal environmental objectives	10/16A 3/15B
INPUT	Zero emissions mindset	1/16A
INPUT	Lack of environmental culture	1/16A
INPUT	Client's strong environmental culture	1/16A
INPUT	Feedback from operators to improve design	3/16A 5/15B
INPUT	Environmental champions	1/16A
INPUT	Involvement with EDPs / Breakthrough Tasks	3/15B
INPUT	Importance of non-radiological environmental impact	7/15B
INPUT	Strong focus on radiological environmental impact	3/15B
INPUT	Safety case / ALARP	3/15B
MECHANISM	Supplier assessment for environmental performance	6/16A 3/15B
MECHANISM	Involvement in Environmental Impact Assessment	2/16A 4/15B
MECHANISM	Use of HAZOP with environmental context	7/16A 9/15B
MECHANISM	Use of life-cycle costing	5/16A 3/15B
MECHANISM	Cost benefit analysis	1/16A 1/15B
MECHANISM	Participation in environmental brainstorming	5/16A
MECHANISM	Value engineering studies including env. criteria	7/15B
MECHANISM	Kepner Tregoe studies including env. criteria	5/15B
MECHANISM	Consideration of environmental aspects at design review	5/15B
MECHANISM	Life-cycle Analysis of materials	1/15B
MECHANISM	Environmental criteria weighted comparatively low	4/16A 3/15B
MECHANISM	BPEO assessment	2/15B
OUTPUT	Environmental data sheets	2/16A
OUTPUT	Safety case	3/15B

a. *f* represents the number of respondents that engage in the theme in question / total number of respondents.

4.3.1 Inputs: Top Level

Environmental inputs to the design process were identified and are shown in Table 4-2. Parent diagrams (Appendix IV: (A)A0, (B)A0) summarise the inputs flowing into each discipline's design activities as described by the interviewees. The design activities of each individual were aggregated with others from the same discipline to obtain a top level IDEF0 representation.

Table 4-2: Eco-Design Inputs Illustrated by IDEF0 A0 Models

Main Inputs: Company A	Main Inputs: Company B
Input from other disciplines	Input from other disciplines
Information from Safety	Information from Safety
ISO14001	ISO14001
Information from operators	Information from operators
Life-cycle costing	Life-cycle costing
Info. on available technology	(future) Engineering Design Principles
Zero emissions mindset	Output from waste minimisation forum
Publicised environmental targets	Design procedures and manuals
Design data from Process engineers	Design data from Process engineers
Product data from vendors	Safety Case
COSHH datasheets	Environmental monitoring document
Risk reviews	Pipeline information
Emissions estimates	Radioactivity estimates
HAZOP actions	Decommissioning philosophy
	Consultancy studies
	Client design requirement flow sheets

The A0 parent diagrams for company A and B (Appendix IV: (A)A0, (B)A0) show the inputs common to both case-study companies. For instance, input from other design disciplines, information from operators, information from the Safety department, ISO14001 and life-cycle costing figures are shown. There were also a large number of company-specific inputs in various forms; environmental objectives, data, emissions estimates, documentation, design philosophies, reviews, actions, principles and procedures. Possibly the most important inputs in terms of attaining an eco-design culture amongst the design team are those which are applied to all disciplines. For example, this could be a set of procedures defined by ISO14001 or a set of client-defined environmental objectives, as employed by Company A. However, Table 4-1indicates the lack of a universal approach as few eco-design inputs are shared by the majority of interviewees. Although both organisations have an Environmental

Policy which should apply to the whole workforce, only some discussed this as an input to their design activities. One explanation is that the existence of a policy in itself is too passive to influence a specific activity, such as design, without further interpretation. For example, if an Environmental Policy states that an organisation 'is committed to the protection of our environment', further inputs may be necessary to explain how this commitment should be demonstrated during design activities.

4.3.2 Inputs: Discipline Specific

A second strategy is the integration of discipline-specific inputs. These are powerful drivers towards eco-design if applied to those disciplines which have the strongest influence at conceptual design. In both case-studies, Process and Mechanical design engineers were most heavily involved with generating the design concept. Their activities set out the basis of design against which other disciplines must design, purchase or fit their equipment or systems.

A detailed analysis of discipline-specific activities, including their inputs, is illustrated for the Process discipline (Appendix IV: (A)A2-1, A2-2; (B)A1-1, A1-2). Similarly, for the Mechanical discipline (Appendix IV: (A)A3-1; (B)A2-1, A2-2, A2-3). Process activities will have a great effect on environmental performance, for instance during process selection, equipment and material specification, economic review and emissions estimates. Environmental criteria, such as efficiency, dematerialisation, reduced eco-toxicity and design for disassembly should ideally be considered during decisions made within this discipline. Mechanical engineers also have a large influence on product environmental performance through the development of equipment specifications, material selection, design for reliability and fail-safe mechanisms.

Within Company A the process design engineers are responsible for writing efficiency targets and material requirements into the specifications of other disciplines, such as Control and Instrumentation. Interviewee A4 provides an example (Appendix III; A4):

"- certainly [err] in specifying the machinery we need for processing that plant... processing the oil... yes because we have to be aware of what the most efficient driver is. For example... should we use electrical drives... turbine drives and low NOx applications [err] also we have to optimise the plant thermally against fuel usage. For example we may feel that we should spend money to make an exchanger twice as big... we can then run our turbines at a much lower load and save fuel. Those are constraints that we impose on ourselves within our simulations."

The design outputs of these key conceptual design disciplines become inputs to the procurement and design activities of other design disciplines.

4.3.3 Inputs: Environmental Champions

The use of environmental champions was specific to Company A. An environmental champion is a member of the design team who ensures the integration of client environmental objectives with the design process. There is one for each major design discipline. For instance, a lead process engineer may be given this additional title. Company A received formal environmental objectives[(10/16A)] from the client at the early conceptual design phase which became the responsibility of the 'environmental champions'. An interviewee (Appendix IV: (A)A1-1) discussed the impact of the environmental champions on design:

"The Process environmental champion and the Mechanical environmental champion did some specific environmental studies but the concept of environmental champions was not taken much further."

This was the only subject who mentioned environmental champions which indicates that this strategy did not have a prevalent impact on the design process. An alternative explanation could be that the role of environmental champions happened very early in the design process and was no longer salient in the interviewees' minds. The effectiveness of environmental champions may be improved by:

- Assigning more environmental champions within the engineering disciplines.
- Ensuring that they take an active role in delivering eco-design inputs, continuously refreshing the messages throughout the development of design.
- Linking successful delivery of eco-design inputs with performance assessment, career progression and bonuses.

4.3.4 Inputs: Environmental Objectives and Targets

Client engineers had developed some initial environmental design concepts prior to awarding the contract to Company A. Therefore, the contract engineers were expected to develop these environmentally conscious concepts into feasible alternative designs. In addition the alliance engineers were issued with quantitative environmental discharge objectives based on the goal of zero emissions. These were publicised throughout the project's design phase and were frequently discussed[(7/16A)]. One subject (Appendix III: A3) commented on the success of this approach"

"... if you give environmental discharge objectives and so forth such a wide sort of [err] publicity as they have done on this project you're likely to that the system becomes less formalised which in a way I think is good because everybody thinks about it [set of environmental discharge objectives] all the time.".

Another example concerns a target oil in water emission concentration of 12 ppm set by the client. In contrast, Company B lacks specified eco-design targets and objectives (Appendix IV: (B) A1-1, A1-2, A2-1, A2-2, A2-3). However, at the time of the interview study, Company B was in the process of developing qualitative design principles for energy efficiency and waste minimisation[(3/15B)] for application to the design process.

Some interviewees from Company B only talked about client environmental objectives in the context of radiological impacts(3/15B). This minority gave no consideration to non-radiological environmental impact during the course of their interview, highlighting the importance of radiological impacts to this design environment. Three individuals(3/15B) stated that non-radiological environmental impacts would be weighted low compared with other design constraints. However, nearly half the respondents opposed this view during their discourse and mentioned the importance of non-radiological environmental impact(7/15B).

In the absence of clear objectives and targets, any improvement on product environmental performance relies more heavily on the enthusiasm and competence of the individual. Fiksel (2001) presents a series of steps to enable the selection of appropriate targets:

- Consider stakeholder needs.
- Identify major product aspects.
- Establish objectives based around the identified aspects.
- Select indicators and metrics.
- Determine measurable targets.

4.3.5 Inputs: Operator Feedback to Design

Appendix IV: (A)A0, (B)A0), shows that the engineering disciplines within Company B liaise closely with operators of existing plant(5/15B) forming an important feedback loop. There was a new initiative under development where the operators were asked for feedback on existing designs in order to improve current designs on non-regulated aspects, including environmental aspects. Operator feedback was achieved in Company A by employing operators within the design team. They were also in the process of formalising the link between operational platform verification and the design phase, (Appendix III: A15):

> *"What we are looking at is if as a result of their* [client company's external verification team who work on the operating platform] *verification task on our various platforms... they see concerns arising, they will cross feed those to other platforms and hopefully progress their way back through the design phases...".*

For Company B, information exchange between operators and designers is also essential to ensure that the newly designed plant will meet site discharge authorisations as most designs will eventually be installed to support existing plant. This is a less important consideration for Company A as their projects are located offshore, more or less independent from existing plant.

4.3.6 Inputs: Environmental Management Systems

An Environmental Management System (EMS) should help to monitor progress and drive continuous improvement as part of the 'plan, do, check, act' cycle (Brezet and Rocha, 2001). IBM have integrated ISO14001 with their Environmental Conscious Products (ECP) Programme and the Dutch have developed the POEMS approach (Product-oriented Environmental Management Systems), (Charter, 2000). ISO 14001 requires that targets and objectives are set for activities within the whole organisation, including design.

Table 4-1 shows that ISO 14001 was only mentioned by a relative minority of interviewees from both companies; Company A(2/16A) and Company B(2/15B). The lack of EMS-related inputs discussed by interviewees may indicate that supporting inputs do not exist, or that there is ineffective communication of the procedures and targets of the EMS. It may also be a result of a more general issue, where EMSs focus on processes and site-specific production attributes, rather than the environmental performance of the product (Sweatman et al., 1997; Brezet and Rocha, 2001).

Brezet and Rocha (2001) suggest that eco-design should be seen as a continuous improvement process in line with the EMS and that actions are being taken to establish a closer relationship between EMSs and eco-design at the EMAS committee level and within the International Standards Organisation.

4.3.7 Inputs: Zero Emissions Mindset

One interviewee from Company A directly mentioned the existence of a positive zero emissions 'mindset'[(1/16A)], which originated from the client's corporate culture. This has been supported by various mechanisms, helping this mindset to permeate the design team culture. However, barriers to environmental design were raised during the interviews. For example, there were views expressed both for and against environmental design amongst individual members of the team and disparity between the client and contractor cultures was discernible. This point was illustrated by an interviewee (Appendix III: A6) who was employed by the contracting organisation. In his opinion, an environmental mindset has not been achieved within the alliance and feels that the alliance approach presented a hindrance to design decision making. He went further to say that most instances of eco-design led to cost penalties. Therefore, the cultivation of an environmental mindset has proved difficult within this alliance and is often challenged by the CAPEX-driven culture. One subject described the transfer of environmental design objectives from pre-bid work done by client engineers to the alliance design team;

> *"Yes... I think from my vision all decisions related to environmental... certainly the main outlines* [design concepts] *were taken before the design competition. And I think that the only reason they survived.... If they would have been taken here in the alliance they would have all been taken out as CAPEX saving which would have been a pity."*

This conflict of cultures with respect to eco-design is not referred to during the interviews from Company B. This alliance was a more stable, long-term arrangement. In Company A the conflict was discussed by a minority[(3/16A)]. However, the depth with which this issue was discussed demonstrated that this conflict presented a significant hindrance to eco-design in some cases.

4.3.8 Controls

Controls are less varied than the extensive range of inputs. The A0 parent diagrams (Appendix IV: (A)A0, (B)A0) show that the main controls include the regulatory framework for each industry, the client demands (client specifications, basis of design documents and client brief) and design codes and standards. The latter apply particularly to Company B where radiological environmental impact is minimised through this type of control.

4.3.9 Controls: Regulatory Framework

Company B designs facilities for the reprocessing and treatment of radioactive waste and is therefore tightly regulated (Murray, 1993, Murley, 2000). The main control imposed on Company B's design activities was the client's requirement to satisfy regulations[(7/15B)]. In many instances, regulations for the protection of human safety from radiation will act in synergy with the goals of environmental protection. In spite of the introduction given to interviewees explaining the possible forms of environmental impact, the majority of interviewees from Company B discussed environmental impact purely in the context of radiological environmental impact[(3/15 B)]. However, the consideration of non-radiological environmental impact was becoming a client requirement and the company was in the process of developing mechanisms to support the consideration of energy efficiency and waste minimisation. A principal control for Company B is the meeting of site discharge authorisations. This was mentioned specifically by Systems Monitoring and Process Design (Appendix III: B6). A third of the interviewees expressed the importance of designing beyond compliance(5/15B).

Many of Company A's controls have been generated from international conventions, such as the Oslo and Paris Convention (Gavounelli, 1995). European legislation is having an increasing influence on this industry (see Appendix VI). One of the most significant developments was the Offshore Petroleum Production and Pipelines (Assessment of Environmental Effects) 1998 Regulations (Lummis, 1998). Intended as a project planning and decision making tool, the UK offshore EIA process is overseen by the Department of Trade and Industry and could provide a mechanism for eco-design although the decision making methodologies need development. This study was conducted prior to the ratification of the European Directive 85/337/EEC which requires offshore oil and gas projects over the whole of the UK Continental Shelf to produce an Environmental Statement for projects that fall within its scope. However, Company A included EIA requirements as a proactive step.

EIA is a regulatory decision making process and could therefore be categorised as both a control and a mechanism. A limited number of engineers mentioned the Environmental Statement during their interview(2/16A) which indicated that only a small sub-group of the design team participated in the process.

An interesting comment relating to regulatory control mechanisms (Appendix III: A15) indicated that conformance with non-prescriptive regulations is more difficult:

"*People were very happy when it was prescriptive. You know... you can show what you've done. You've usually had to because prescription usually means correspondence between two people.*"

It is apparent that the increase in non-prescriptive regulation will demand an increase in support mechanisms to ensure that they are demonstrably satisfied.

Therefore, for Company A, client set targets are probably more of a consideration. In particular, there are strict targets for some environmental aspects set out in the specification or Basis of Design document(4/16A).The following excerpt demonstrates that client requirements impose hard constraints which are not included in the regulatory framework:

> *"there is no legislation that says you have to flare x% or y%.... we know what our [Company] target was which was 0.3% boe [barrel of oil equivalent]."*

The results of the questionnaires indicate that Company A and Company B consider external regulation to be the most important driving factor towards considering environmental issues during design (Appendix V; Question 1), supporting the evidence drawn from the interviews.

4.3.10 Controls: Client Specification and Internal Policy

Client environmental objectives are categorised as controls if they are treated as hard constraints. That is to say, they are factors what must not be violated during decision making. If these objectives are soft constraints and can be compromised to an extent, then they are considered as inputs. The two key internal controls identified in this study were environmental limits imposed by the customer and internal Company Policy.

Offshore design contractors will often be asked to go beyond compliance by their Customer(4/16A). For instance, the legal concentration of dissolved and dispersed oil released to the environment at the time of writing is 40 parts per. million. However, the Client of Company A imposed an internal limit of 12ppm for the concentration of oil in produced water. In addition, respondents from Company B discussed Company Policy as an important control. Therefore, both Companies have shown evidence that internal controls are in place.

The questionnaires also indicated that the customer was a key driver for Company A with respect to considering environmental factors during design. Company B respondents indicated that Company Policy was second only to external regulation (Appendix V).

4.3.11 Mechanisms

Mechanisms are essential to achieving eco-design goals. They are the tools and techniques that support design decisions. Table 4-3 shows the variety of mechanisms perceived by the interviewees to have an effect on the product's environmental performance.

Table 4-3: Mechanisms Illustrated by IDEF0 A0 Diagrams

Company A: Mechanisms	Company B: Mechanisms
HAZOP	Optioneering studies (VE, Kepner Tregoe)
Design review	Design review
Electronic process simulation	Energy minimisation task force (new)
ENVID	Brainstorming
Green supplier audit	
Equipment testing	
Computer Aided Design (CAD)	
Technical evaluation	
Cost evaluation	
Life-cycle costing	
Availability modelling	
Application of COSHH	

These broadly fall into four categories; group decision making, modelling, evaluation and application of guidelines.

4.3.12 Mechanisms: Environmental Brainstorming

The questionnaires intimated that a structured HAZOP-based approach was the preferred format for any future eco-design tool (Appendix V; Questions 3 and 6). When the use of this approach was investigated during the interviews it was found that Company A had applied an environmental brainstorming technique (ENVID) to specific product sub-systems in order to generate options at conceptual design(5/16A). One subject discussed this mechanism but did not think it was an activity which had much influence on his work:

> *"I don't remember much about the ENVID so... in terms of information flows if you look at it generically the fact that I don't remember much about it possibly suggests to me that I didn't consider it to be that important a step in what actually has happened here so that's one thing."*

The same subject recalls the ENVID activity as follows:

> *"I'm trying to remember... there was something about start-up as well at the ENVID... at the ENVID the one thing that I remember from that day [err] at that time we didn't have a concept of how we were going to start-up so a lot of people talking about a lot of stuff and there was a lot of numbers being bandied about that we'd be flaring a lot of gas and so on."*

Participation in the environmental brainstorming activity was restricted to a select number of individuals from key disciplines at the very beginning of conceptual design. Therefore, this mechanisms will have supported a limited number of people. The interviewee from the Safety and Environmental department described the ENVID as follows:

> *"Well... the first thing we did was... as we discussed before was the ENVIDs. We called various disciplines [err] Instruments, Mechanical and Process... the major disciplines. And then sat around the table... the brainstorming. We had some guide words or checklist and then [err] identified all the environmental issues there and then."*

Although none of the respondents commented favourably on the ENVID mechanism, this does not necessarily mean that the mechanism was ineffective. For example, the interviews were carried out approximately nine months after the ENVID studies took place and their positive impact may have been forgotten.

Similarly in Company A, 'environment' was added to Hazard and Operability studies (HAZOP) as a keyword (7/16A). Actions resulting from HAZOPs were then allocated to specific individuals for further investigation and the outcome was recorded on a database.

As many of Company B's environmental impacts present radiological hazards the preparation of the Safety Case(3/15B) and HAZOP(9/15B) can be considered as a primary mechanism. Company B was considering the implementation of a HAZOP based mechanism specifically for environmental aspects. One interviewee (Appendix III: B6) was asked if environmental keywords were generally included in current HAZOP studies;

> *"I think they are investigating doing that because it's a hazard and operability assessment....one of the things they've been looking at is that there are similar sorts of reviews or assessments that can be done just for environmental. Again there will be... you'll have to look at the practicalities of doing that."*

HAZOP actions are entered onto a database depending on the size of the project in a similar way to Company A.

Although HAZOP is a useful mechanism, it should be recognised that the design detail required for a HAZOP study limits how early these studies can take place. However, the best time for improving product environmental performance is at early conceptual design (Fabrycky, et al., 1987, Hendrickson, et al., 1994), prior to process flow diagrams or P&IDs.

4.3.13 Mechanisms: Green Supplier Assessment

Green supplier assessment provides a mechanism to drive eco-design objectives down the supply chain (James, 2001). The supplier audit will provide a new mechanism once results affect supplier selection. A minority of individuals mentioned assessment of suppliers for environmental performance[(6/16A, 3/15B)]. However, a formal procedure does not exist whereby suppliers are rated, assessed and awarded contracts subject to meeting an environmental standard. Company A did have documentation in place for such assessment but supplier performance did not affect supplier selection at the time of the study. This will be a complex task for an LMTO organisation and will be a major achievement once it is established within purchasing activities. This is an important addition if one is to take a life-cycle perspective. However, this mechanism had not been fully established and one subject commented that little importance was attributed to the outcome of the green supplier assessment, especially if the supplier was a small concern:

> *"I mean... when you are going out to a tinpot fabricators just for a couple of things, then they are asked to fill this thing out, that's the last thing they want to know about... so obviously, you know, there's a bit of discretion. You have to take an objective view and take each one* [green supplier assessment] *as it comes."*

Another subject commented that his discipline 'goes through the motions' of the supplier assessment and ask suppliers who have high environmental standards, such as those from Germany, to drop their standards to save on cost. Conversely, another interviewee supported the introduction of the green supplier assessment. However, he felt that if the effort was made to gather data from the suppliers with regard to their environmental performance, it should decisively affect requisition.

> *"But if you get this data then you should give it teeth and tell them from the*

outset this is what we're interested in. If you [the supplier] answer wrong we won't consider you or if they are wrong we will penalise you in the bid analysis."

Company B's green supplier assessment was only mentioned by three individuals, all from architecture (Appendix III: B10-12). One architect had the following environmentally-conscious view:

"I am hoping to get to a position where we look at a material and say we are not having it if it's not green, energy efficient or needs a high amount of maintenance"

This practice appears to be restricted to architectural design activities of the companies where the focus is on commercial buildings. Formal green audit procedures had not yet been established. Following the comments made with respect to supplier assessment, one interviewee (Appendix III: B11) was asked if suppliers were generally able to supply life-cycle data on their products:

"Not really... You have to push them for that sort of information".

[He adds later] *"My personal feeling is that it* [product assessment for environmental impact during purchasing activities] *is not done early enough in the design process to have any real impact. By the time we do it we are sort of back fitting it to justify the decisions we have made rather than using it to actually assist us."*

4.3.14 Mechanisms: Optioneering Studies

Company B used optioneering studies to integrate environmental controls and inputs with product design. This includes Value Engineering[7/15B] and Kepner Tregoe analysis[5/15B]. Optioneering studies feature a brainstorming phase to identify the design options and the set of criteria (or attributes) against which they should be judged. Options are then rated on a 1 to 10 scale for each criterion. Decision criteria are weighted according to their importance and interviewees indicated that environmental performance was sometimes included as a decision criterion.

One weakness of this method is that the allocation of numerical scores can lead to a false sense of confidence in the decision outcome, even when it has been achieved using uncertain and incomplete data. It may be beneficial to adapt this approach to use linguistic terms for evaluation, which will help convey the imprecision that is often inherent with early design. In addition, an accurate record of information gaps and assumptions should be made and used to generate a list of actions to gather improved data.

4.3.15 Mechanisms: Engineering Design Principles

Company B was in the early stages of implementing a series of 'Breakthrough Tasks'[(3/15B)] aimed at waste minimisation and energy efficiency amongst others. These tasks aim to identify improvements in the design process through a process of problem identification, problem analysis, generation of solutions based on generic Engineering Design Principles (EDPs) and their implementation. The breakthrough tasks may provide an overall mechanism for eco-design, introducing EDPs as an additional input to design activities.

4.3.16 Mechanisms: Checklists

One interviewee discussed the use of checklists. Checklist could be developed in line with existing design for environment (DFE) guidelines (Fiksel, 1996, Keoleian et al., 1993) with some adaptation for LMTO products; the potential for catastrophic out-of-envelope events, complex decommissioning and end-of-life problems, a life-cycle duration of decades, large volume inventories and large quantities of materials.

4.3.17 Mechanisms: Life-cycle Costing

Life-cycle costing could be used as a mechanism to drive design towards higher energy and resource efficiency and to enable the tentative costing of less tangible costs. Interviewees from both companies mentioned life-cycle costing[5/16A, 3/15B]. An excerpt follows from an interviewee from Company B who described the general design constraints that he took into account;

> *"Whole-life cost is what we're supposed to look at... it's very difficult looking at the whole life cost. You tend to focus on capital costs. What we generally do is design things to last the life of the plant and minimise maintenance...when it's active you don't want personnel to have to touch it."*

Another interviewee from Company B discussed life-cycle costing in terms of reducing non-radiological environmental impacts:

> *"Reduction in energy actually gives you a cost saving which is good... for instance on ventilation systems you can get a big saving using variable speed drives. There has been a shift over the last two or three years to think in terms of their life-time cost rather than their initial cost and I can get acceptance for some increase in capital cost where it's justified."*

4.3.18 Mechanisms: Design Review

In Company B, design reviews present another mechanism for improving environmental performance[5/15B]. The designer submits his or her design deliverables (engineering flow diagrams etc.) to design management personnel (Principle Engineer or Project Manager), including a representative from the client organisation. The work is reviewed against a set of keywords; waste minimisation, construction, contamination, decommissioning, environment, functionality, health and safety, maintenance, operability, process and research and development. Cost is not assessed at this stage.

The use of the design review as a mechanism for eco-design would be successful if demonstrable targets were included. However, it is a retrospective process and should follow a prospective mechanism which encourages eco-design from the outset, thus avoiding re-design. Interviewees within Company A mentioned economic and technical reviews (Appendix IV: (A)A0). Eco-design objectives could be included during the technical review and assessed by the environmental champion of the relevant discipline.

4.3.19 Mechanisms: Risk and Reward Contracts

Until recently, contract design organisations were mainly interested in completing the project at lowest cost and on schedule if cost penalties were associated with falling behind deadlines. Alliance systems then emerged where the contractor and the client design teams work together. This has increased the importance of non-CAPEX design criteria, including eco-design criteria in some cases.

The study has revealed that a top-level mechanism exists within Company A which drives design for energy efficiency and material use. The client had set up a 'risk and reward' based contract where the contractor will gain financial benefit from savings in operational expenditure. Therefore, energy efficient design options may be selected even when the capital expenditure is greater. This will also drive design selection towards high availability solutions which will influence the frequency of process shut-down.

4.3.20 Mechanisms: A Need for Decision Support

Three interviewees expressed a need for decision support tools to assist the integration of environmental factors into design. A lead Process Engineer indicated that a decision support mechanism that facilitated criteria trade-off would assist his activities (Appendix III: B2):

"From my point of view, what I find the most difficult with environmental safety... is actually when you get down to the nitty gritty.... when you start

mixing things up like energy efficiency with waste minimisation and waste management [subject is referring to active waste] *they don't balance. What we do with our discharges and our authorisation is such a big thing which is integrated with the site management and then you get down into the really detailed design specification of what kind of pumps you will use and what light bulbs.... it's very difficult to manage that all the way through unless you have a set of basic standards you have to work to that says you must use this kind of bulb and you must use this kind of pump and pump motor. You can't make judgements like that on a day to day basis during the design process.... it would drive you mad. That's where I think we probably need the most help."*

One subject (Appendix III: B10) regarded environmental aspects of his design activities as important. He made the following comment at the end of his interview:

" I would certainly welcome any guiding tools to help us with these issues because quite often it's a bit of a minefield. Often the decision-making processes are complex. If you are looking at...just take material specification...if you are looking to specify on the basis of product performance, functionality and doing the job....once you start looking at all the other aspects as well it can take you in a different direction, such as costs etc."

Interviewee (Appendix III: B11) spoke of his wish for decision making tools to assist material selection:

"We have tried and tested these materials but it is deciding which one to use for which application that we need an expert system to give us guidance on it. It would give you an auditable trail as to why you came to that decision. Quite often...it shouldn't - but quite often things happen [in design] *but you do what you did last time and end up with the same materials being used."*

One interviewee from Company B refers to the trade-off between design criteria during decision making and indicates that environmental criteria would rarely be included explicitly (Appendix III: B14):

> *"I suspect many* [environmental] *issues are solved subconsciously...and it would be rare for an issue to emerge where environmental impact is the only issue that leads to the selection of one option or one alternative compared to another. Cost is always one of the issues but I guess we're always juggling with a wide range of criteria when we are looking to select the best option. So there is a whole range of evaluation criteria that we do look at when we are comparing options and developing contracts...and the environment in my view is something that is smeared across the whole lot."*

The questionnaires revealed limited use and low awareness of eco-design tools, some of which could help support decisions and answer some the respondents' concerns (Appendix V: Questions 3 and 4).

4.3.21 Stand-Alone Eco-Design Tools

Software, for example CAD and availability models, were not discussed by any interviewees as a mechanism for introducing eco-design objectives. The questionnaire study indicated that this approach may have limited support (Appendix V: Questions 5 and 6). Furthermore, there was no discussion of stand-alone algorithmic tools developed to increase recyclability or environmental efficiency (see Section 2.5.1 of Chapter 2).

4.3.22 Outputs

Key eco-design outputs are shown by the IDEF0 models (Appendix IV: (A)A0, (B)A0), a large proportion of which becomes the input to another design activity.

Table 4-4: Outputs Illustrated by IDEF0 A0 Models

Main Outputs: Company A	Main Outputs: Company B
Supplier assessment documentation	Equipment and material selection
Position papers (i.e. start-up strategy)	BPEO assessment
Environmental Statement	Environmental Statement
Scenario prediction	Bid preparation
Efficiency data	Design data and information
Technical review	Contribution to business plan
Economic review	Life cycle costs
Process data sheets	Engineering flow diagrams
Process and instrumentation diagrams	Process and instrumentation diagrams
Material and equipment specification	Acquisition of new technology
Design for maintenance	Procured equipment
Spatial layout report	CAD model
Design review for major accidents	Safety Case
Design drawings	Design drawings
Sizing reports	Systems and Monitoring design
Emissions review	Monitoring policy
Documentation of procedures	Operating instructions
Design recommendations	

One of the key concepts of environmental management is that environmental performance improvements can only be monitored if they can be measured. Design activities should produce outputs which demonstrate where environmental performance has been considered in design decisions and to what degree environmental objectives have been met (Keoleian and Menerey, 1994).

Direct eco-design outputs include BPEO assessment, documentation from the green supplier assessment, the Environmental Statement and monitoring policies. Once again, there is no cross-discipline eco-design output that requires all engineers to demonstrate that they have considered eco-design aspects during their design activities. There are numerous outputs which indirectly affect environmental performance in the form of reports, reviews, models, estimates, position papers, procedures, drawings and procurement specifications. These outputs tend not to treat eco-design as a specific consideration but it is clear that the development of process flow diagrams will determine the material and energy efficiency of a particular process.

4.3.23 Outputs: Primary and Secondary Eco-Design Disciplines

The outputs from design activities indicate the extent to which environmental performance has been considered, in a tangible, auditable manner. Design disciplines that produce deliverables directly related to improving environmental performance will be referred to as primary eco-design disciplines. One can see from the IDEF0 diagrams (Appendix IV: (A)A0) that for Company A this will include Process, Mechanical, Operations, Commissioning, Verification and HS&E. For Company B (AppV:(B)A0) all disciplines are considered as primary eco-design disciplines. Secondary eco-design disciplines affect environmental performance indirectly and are not associated with specific environmental outputs. For Company A this includes Layout and Electrical.

4.3.24 Outputs: Direct Influence on Environmental Performance

HAZOP actions, brainstorming of environmental objectives and actions resulting from Value Engineering studies produce outputs which are directly related to product environmental performance. The IDEF0 diagrams show how the outputs of one design activity become the input of another (Appendix IV:(A)A0, (B)A0) so that eco-design decisions cascade through all the design disciplines. There are numerous outputs which will affect product environmental performance directly and indirectly. An important example of this is the output of specifications by Process (Appendix IV:(A)A2-2). In Company A, client environmental energy efficiency objectives were met by concept designs produced by Process and Mechanical. These targets were then included in equipment specifications which became the input of the Electrical or Instrumentation engineers. Thus establishing a continuous flow of eco-design from concept design to procurement.

The preparation of the Environmental Statement during the EIA process requires the engineer to systematically address the possible environmental impacts of the project during the life-cycle. In response to a specific question which asked whether interviewees contributed to Environmental Statements, two interviewees from Company confirmed that they had provided a direct input to this deliverable [(2/15B)]. In the questionnaire study a large majority of respondents indicated that the design team were involved with the EIA process (Appendix V: Question 8). This conflicts with the low participation indicated by the interviewees and may be due to the use of a different sample or ambiguities in the questionnaire, which suggests the respondents had interpreted 'Environmental Impact Assessment' as a general process. This possible misinterpretation demonstrates the benefits of using a triangulated approach to examine a theme.

Disciplines in Company A, such as Process, must also meet client objectives set out in the Basis of Design by producing a design philosophy document or position paper for a specific task, such as produced water treatment. These philosophy documents were included in the Environmental Statement with details of the process options and the determination of the Best Practicable Environmental Option. Five interviewees discussed their contribution to BPEO deliverables [(1/16 A, 4/15B)]. Process design engineers also produce the P & IDs and process flow diagrams which are required for HAZOP analysis (Swan and Preston, 1997) which have a varying degree of influence on environmental performance. Emissions calculations and reviews were important environmental outputs from Company A's Operations and Commissioning disciplines.

Company B's technical engineers produced BPEO assessments. Systems engineers delivered pollution monitoring systems in order to comply with discharge authorisations together with the monitoring policy and Architecture used life-cycle analysis, environmental building guidelines from the Building Research Establishment (BRE) and life-cycle costing to deliver environmental building designs. These inputs, controls, mechanisms and outputs provide examples of direct influence upon environmental performance.

4.3.25 Outputs: Indirect Influence on Environmental Performance

General design activities produce outputs which may indirectly influence product environmental performance, such as designing for weight minimisation, safety or reliability. In Company A, the secondary eco-design disciplines produce a number of outputs which will affect product environmental performance. An example of this was described whereby a design engineer selected sheathed unarmoured cabling as opposed to galvanised steel wire braid in order to save weight and installation time. The decision was not taken in order to improve product environmental performance. Neither did the subject immediately see the synergy between this decision driven by a weight saving and the dematerialisation goal of eco-design.

Another example was a decision output from the Layout department to intensify plant spacing by reducing pipelines. This was balanced with the requirement that the plant must be easily maintainable to optimise performance and minimise production deferment during operation. The indirect eco-design consequences of these decision outcomes are numerous. Firstly, the reduction of pipe length will result in a material saving and the associated environmental impacts associated with material extraction, manufacture and disposal. In addition, reduced pipe length will reduce heat losses during the operating process. Secondly, spatial layout for easy maintenance will lead to increased process stability and efficiency. Good standards of maintenance could reduce the occurrence of out of envelope events and any associated lost containment of hazardous inventory.

4.4 Conclusions and Suggestions for Improved Eco-Design

Referring back to the research aims in Section 4.1, the interviews and questionnaires provided a comprehensive account of current eco-design practices. Organisational aspects of the case-study companies differed in ways that would affect eco-design. For example, there was a clear division between primary and secondary design disciplines in Company A. Primary disciplines were characterised by their greater input to concept design generation and their more extensive exposure to eco-design inputs, controls, mechanisms and outputs. Secondary design disciplines were largely restricted to design and procure equipment within the specifications developed by primary design disciplines. In contrast, disciplines within Company B were less differentiated with respect to their exposure to eco-design inputs, controls, mechanisms and outputs.

Company A's approach to eco-design was characterised by the client's environmental discharge objectives, supported by environmental champions and a specific group-based environmental impact identification process. Company B was developing qualitative Engineering Design Principles which were developed by various Task Forces. Environmental criteria were integrated within optioneering studies and environmental performance was assessed in some cases at the formal design review.

Culturally, Company A faced conflict between the traditional CAPEX-driven approach of the contract design business and the wider considerations demanded within a design alliance which include environmental considerations. Company B's interviewees exhibited a strong tendency to focus on safety-related environmental impacts (e.g. the control of hazardous discharges to the environment rather than environmental efficiency issues) which may be due to their established safety culture.

The study can be concluded with the following summary and suggestions for improved eco-design practice:

- Discipline-specific eco-design inputs are targeted at Process and Mechanical engineering disciplines.
- Environmental Champions were designated within Company A but the sample of interviewees reported that this approach had not influenced their work significantly.
- Environmental targets were well established within Company A. Company B were in the process of developing principles for energy efficiency and waste minimisation.
- There was evidence of learning from operating systems within both organisations.
- A small number of interviewees mentioned ISO 14001 as an input to design activities.
- Conflicting evidence was collected from Company A with regard to the success of the Client's efforts to generate an environmental mindset. One source of this conflict was the CAPEX-driven culture of the contractor.
- Regulation is a key control with respect to eco-design activities.
- The Client's environmental objectives were considered as key controls in the case of Company A as they were treated as absolute requirements.
- Company B respondents considered Company Policy to be a key control / input.
- An environmental brainstorming mechanism is in place with Company A but was undertaken as a one-off activity, very early in design. Group decision making mechanisms described in this study are unable to account for uncertainty and subjectivity and could be adapted for 'fuzzy' option evaluation.
- An environmental keyword was explicitly introduced to HAZOP studies within

Company A. HAZOPs within Company B has an implicit influence on environmental performance. Questionnaires supported the continued use of HAZOP as a method for integrating environmental factors into design, however, HAZOP is not an ideal start-point for eco-design decision making as it occurs at detailed design.

• There was evidence of green supply chain assessment in both organisations. However, three individuals commented that this had limited influence on purchasing in reality. Green supplier assessment should be undertaken during all procurement activities and the results of the evaluation should affect supplier selection.

• A significant number of interviewees from Company B took part in optioneering studies where environmental criteria were sometimes included. This use of structured discussion was supported by the questionnaire investigation.

• Company B has developed some environmental principles which are intended to support design activities. This is a recent initiative.

• Life-cycle costing was evident in both organisations which could support energy efficient design due to potential savings in operational costs. More effort is required to move away from a CAPEX driven design culture and awareness of the risk and reward strategy should be increased.

• Environmental performance is one of the assessment criteria used during design reviews by Company B.

• Company A issues a risk and reward contract to its contactor which encourages engineers to design for reduced operational cost.

• A requirement for decision support tools was expressed by three individuals, suggesting that further mechanisms would be beneficial. The questionnaires indicated that there was limited use and awareness of existing eco-design tools.

• Where novel solutions are proposed by design engineers, there should be an incentive to develop it further. Currently, the individual is expected to gather data and background to the potential solution with no reward.

• A clear plan of universal and discipline specific eco-design inputs, controls, mechanisms and outputs needs to be established and incorporated intot he Environmental Management System.

5 A REVIEW OF MULTIPLE ATTRIBUTE DECISION MAKING APPROACHES

5.1 Introduction

The investigation into current practice with respect to eco-design has shown a number of areas for improvement. This Chapter will concentrate on the need for decision support and potential methods to enable the trade-off of environmental criteria with other design factors. Multiple criteria could be traded-off using implicit judgements and group consensus. However, there is a need to make the trade-off between criteria transparent, as these decisions may be reviewed by Regulators, stakeholders and the public. Multiple Attribute Decision Making (MADM) represents a set of methods within the area of Decision Science that enables such transparency.

This Chapter introduces a range of Multiple Attribute Decision Making methods that can be applied to selection problems during engineering design and key stages of attribute selection, normalisation and preference capture are discussed. A variety of compensatory selection methods are outlined in the context of sustainable design, using academic and industrial examples.

Finally, the reasons for investigating Multiple Attribute Decision Making methods in relation to sustainable engineering design are outlined.

5.2 Multiple Criteria Decision Making: Concepts and Terminology

Multiple Criteria Decision Making (MCDM) divides into two separate areas; Multiple Objective Decision Making (MODM) and Multiple Attribute Decision Making (MADM). MODM methods direct the *synthesis* of optimal designs from an infinite number of potential alternatives, based on prioritised *objectives*, for example, when a designer creates a novel solution. MADM methods enable the selection of an optimal design from a finite set during *design selection* (Bell, et al., 1977; Hwang and Yoon, 1981; Sen and Yang, 1998), based on prioritised *attributes*. The prioritisation of objectives and attributes allow competing aspects of performance to be reconciled.

This research addresses MADM as the work of the design contractor concentrates mostly on design selection. Inter- and intra- attribute comparisons are made using implicit or explicit trade-off of conflicting decision criteria using mathematical analyses. The basic challenges associated with MADM are; the generation of relevant attributes, dealing with incommensurable units, addressing intangible units, evaluating time-dependent consequences, capturing uncertainty and ensuring social equity (Bell et al., 1977).

MADM methods have originated from a wide variety of disciplines, such as decision theory, economics, statistics and psychometrics. MADM was first implemented prescriptively by Churchman, Ackoff and Arnoff (Hwang and Yoon, 1981) to optimise the selection of business investment policies in 1957. While work has continued in the context of method development, an explosion of research has centred around the application of MADM to new areas of academia, such as resource planning and environmental management (Keeney and Nair, 1977; Bauer and Wegener, 1977; Janssen, 1992; Hokkanen and Salminen, 1994; Paruccini, 1994; Rousseau and Martel, 1994; Rogers and Bruen, 1998; Salminen et al., 1998).

A close relation of MCDM is Multiple Criteria Decision Aid (MCDA). This prescriptive approach was developed in recognition of the limitations of objectivity (Roy, 1990):

- The set of feasible alternatives is often fuzzy.
- In many real world problems, a single DM rarely exists. The decision process usually involves several people.
- The DM's preference structure is rarely well-stated due to inherent uncertainty, conflicts and contradictions.
- Numerical evaluations are often imprecise or defined arbitrarily.

- Generally, it is impossible to say whether a decision is good or bad by reference to the mathematical model alone.

Roy's paper draws a distinction between MCDA and MCDM, illustrating where MCDA attempts to address some of these limitations of objectivity. For consistency, the term MADM will be used throughout the thesis.

The hypothetical ideal solution in MADM is one whose Cartesian Product[1] is composed of the most preferable values for each of the decision attributes, (Ozernoi and Gaft, 1977; Hwang and Yoon, 1981). In MADM the process of finding the optimal design is frequently subjective, whereas it is usually objective in MODM. The subjective ideal is especially important in *distance from ideal* approaches.

Satisficing solutions are the set of acceptable alternatives. It is a subset of the feasible set that exceeds all aspiration levels of each attribute. These alternatives are said to be *non-dominated.* No single alternative outperforms another for all attributes.

5.2.1 Criteria Selection

Hwang and Yoon (1981) describe a criterion as a measure of effectiveness. Sen and Yang (1998) clarify that the criteria set in the context of MADM is comprised of *attributes*. Whereas in MODM, the criteria set contains *objectives*. Bouyssou (1990) defines a criterion as a tool that facilitates the comparison of alternatives.

Constructing the criteria set is very important in decision making and the success of a MADM method is dependent on the representativeness and manageability of the set of criteria and feasible alternatives. The generation of these sets cannot be fully formalised due to case-specificity (Ozernoi and Gaft, 1977; Saaty, 1980). Generally, the hierarchical decomposition approach is well supported, (Keeney and Raiffa, 1976;

1. Cartesian Product; the set of all ordered pairs of members of two given sets. The product A x B is the set of all pairs <a, b>. Also called a cross product.

Saaty, 1980; Belton and Vickers, 1990; Sen and Yang, 1998). Bouyssou (1990) describes some of the considerations when building criteria. For example, the importance of legibility (manageable number of criteria), operationality (the decision makers must agree that the criteria set is representative) and independence between criteria.

5.2.2 Transformation of attributes

In the context of MADM, three measurement scales are important; ratio, interval and ordinal scales (Saaty, 1980). Examples of ratio scales include weight, volumes and cost. This scale type allows precise evaluation by using a reference value. An interval scale provides equal intervals between entities and indicates the difference or distance from some arbitrary origin, for example the temperature scale (such as the arbitrary origin of absolute zero). An ordinal scale requires the least information as the scale is based on preference alone, with no information given on *how much* one option performs compared to another.

Quantitative attributes can be directly converted to ratio, interval or ordinal scales, but the transformation of qualitative attributes is less straight forward. A common way to transform qualitative attributes to an interval scale is by using the Bipolar Scale. If a 10 point bipolar scale is chosen, best value is 10, worst is 0, with midpoint signifying the breakpoint between favourable and unfavourable values. This type of scaling usually assumes that the scale value of 9 is three times as favourable as scale value 3 which may be or may not be a correct interpretation of the decision maker's mental judgements.

5.2.3 Normalisation

Normalisation is the mapping of empirical attribute values, measured on different scales, to the scale [0, 1]. Vector normalisation is a method where each row vector of the decision matrix is divided by its norm (the sum of each option's performance against attribute j). All criteria are therefore measured in dimensionless units, facilitating inter-attribute comparison but this does not lead to measurement scales of equal length as the min and max scales are not equal between criteria. This method of normalisation is used in TOPSIS, CODASID and in the ELECTRE method. Linear (or Simple) scale transformation divides the outcome of a certain attribute by its maximum value (outcome x_{ij} - min value / max - min)[1]. This scale of measurement varies precisely from 0 to 1 for each criterion (Hwang and Yoon, 1981). The choice of normalisation method has rarely been questioned. However, a recent paper has indicated that normalisation can influence the consistency of the optimal alternative (Dubravka, 2000).

5.2.4 Preference Capture

Capturing the decision makers' preferences is necessary to reconcile incompatible demands in design selection. To do this, some form of weighting must be applied to the attributes. Weighting has been a highly controversial area when assigning importance to various environmental emissions during LCA. Four main approaches are used; distance-to-target, environmental control costs, economic damage approaches and scoring techniques (Powell et al., 1997; Pearce et al., 1999). If a goal or standard has been set for the attributes in question, the distance-to-target approach allocates those attributes which are furthest from the desired point the most weight, focusing the selection on attributes that are associated with the poorest performance. However, goals and standards may not be set for certain attributes or the target may be driven by socio-political judgements which could be scientifically questionable. Environmental Control Costs derive weights from the expenditure necessary to control environmental damage. Environmental Damage Costs are based on willingness to pay to avoid the damage. Finally, scoring approaches derive weights

1. for benefit attributes. Cost attributes are normalised by:
max value - outcome x_{ij} / max value - min value

from expert judgement or cross section of interested parties, including the public (UKAEA, 2003). One such approach, commonly used to evaluate environmental impacts, is the Delphi method (Goodwin and Wright, 1998).

The discipline of decision science has developed more weighting approaches which may be usefully applied in sustainable design decision making. Entropy is an important concept in physical sciences and, later, the social sciences. In the context of information theory, entropy is an indicator of the amount of uncertainty represented by the probability distribution (Levine and Tribus, 1979). A broad probability distribution represents more uncertainty than a narrow, peaked distribution. Therefore, more importance can be allocated to those attributes that exhibit more broadly distributed performance values as these attributes convey the most information (Hwang and Yoon, 1981, Sen and Yang, 1998). Swing weighting is a similar approach which allocated weight based on the difference between the best and worst option with respect to each attribute, rather than allocating weight to convey the value or importance of an attribute. For example, Safety may warrant a high value weight within a Company due to its cultural importance. However, the difference between the best and worst option for a specific safety-related attribute may be insignificant as a discriminator between options, resulting in a low swing weight or entropy-based weight (DETR, 2001).

The Analytic Hierarchy Process (AHP) offers another value-based weighting approach which enables the explicit determination of the decision makers' tacit preferences using pairwise comparisons of alternatives or attributes (Saaty, 1980). Saaty presents an example of sustainable decision making based on the societal contribution of large energy users. A pairwise comparison matrix was constructed to ascertain the weights of three attributes; economic growth, environmental impact and national security. Relative importance values of the pairwise comparison matrix were used to determine the principal eigenvector, which upon normalisation becomes known as the vector of priorities. It should be noted that this method is subject to the phenomenon of rank reversal, where the addition of one alternative can reverse the original ranking of unrelated alternatives (DETR, 2001).

Finally, the quantifier-guided weighting approach can be applied to fuzzy variables in order to simulate human decision processes. This is discussed in detail in Chapter 8.

The application of weighting schemes is often a sensitive issue within organisations. All value-based systems, such as direct weighting, Delphi weighting, economic damage and AHP weighting only represent the preference judgements of the sample of individuals involved. Stakeholder participation in the development of weights can be used to increase the number of people involved and the range judgements. However, any value-based weighting system is subjective.

Entropy-based weights, Swing weights and distance-to-target systems are more objective as they are a function of the data. However, in the case of distance-to-target weights, the initial target setting is likely to be subjective and influenced by socio-political drivers. In addition, the data will often be incomplete or uncertain at conceptual design.

To maximise confidence in a decision outcome, it may be necessary to apply a combination of weighting approaches. In addition, rigorous sensitivity analysis to weight values should demonstrate how the result could change under foreseeable circumstances.

5.3 MADM Methods

Compensatory and non-compensatory MADM methods have been developed which allow trade-offs between attributes. This is a fundamental concept behind design selection and all models discussed in this thesis are compensatory. Compensatory models can be divided into three subgroups; scoring model, compromising model and concordance model. Scoring models present the simplest MADM approach. A widely used method is Simple Additive Weighting (SAW). Included in the compromising model category are the closest to ideal solutions, such as Technique for Order Preference By Similarity to Ideal Solution (TOPSIS). Concordance models arrange a set of preference rankings which best satisfies a given concordance measure. For example ELECTRE, PROMETHEE and Concordance and Discordance Analyses by Similarity to Ideal Designs (CODASID).

5.3.1 Multi Attribute Utility Theory (MAUT)

In MAUT, a high-level objective is hierarchically decomposed into associated low-level objectives and corresponding attributes which express measurable values and the direction of optimisation, for example, 'reduce tonnes per. annum of acid gas emissions'. The decision maker's preference with respect to each attribute is then translated into a value or utility function, a mapping of an attribute to a normalised scale so that incommensurate aspects of performance may be compared. These utility functions are subsequently aggregated to give the global utility of each option.

Popular compensatory MAUT methods are the Simple Additive Weighting (SAW) method and the analytic hierarchy process developed by Saaty (Saaty, 1980). Popular due to its simplicity, the SAW method has been widely applied (Hwang and Yoon, 1981). The performance of each alternative against each attribute is multiplied by the ascribed importance weighting. These values are added to give an alternative's overall score. The attribute values must be numerical and comparable. This is a suitable approach if there are no complementary relationships between attributes and each attribute can be justifiably considered on its own.

The AHP method organises objectives and preferences into a hierarchical system. At each node, the decision maker makes linguistic pairwise comparisons which are then converted to a numerical value. The value (relating either to option performance or attribute importance) of each node is calculated by computing the eigenvalues of the pairwise comparison matrix.

MAUT has found many environment-related applications (Keeney and Nair, 1977; Bell, 1977; Tamura et al., 1994; Dunning et al., 2000).

5.3.2 Technique for Order Preference By Similarity to Ideal Solution (TOPSIS)

TOPSIS (Hwang and Yoon, 1981) is one of the compensatory MADM methods addressed during the following research chapter where a full description is given. The method selects the alternative which is closest to the subjective ideal and furthest from the subjective negative ideal. TOPSIS is comprised of the following steps; construction of the normalised decision matrix, construction of the weighted, normalised decision matrix, determination of the positive and negative subjective ideals, calculation of the separation distance from the subjective ideals, calculation of the relative closeness to the ideal solution and determination of the preference order.

5.3.3 Outranking Methods

Three outranking relationships provide the basis for the following methods. Strict preference of *a* compared with *b* (*a Pi b*), weak preference (*a Q b*) and indifference (*a I b*).

ELECTRE was the first outranking method, from which variations were developed; ELECTRE: I, II, III and IV. All versions are based on outranking relationships (*a Pi b, a I b*) derived through pairwise comparisons; strong preference, weak preference and indifference (Roy, 1977; Roy, 1990). Type 1 ELECTRE methods (ELECTRE I, II and IV) model the decision maker's preferences using a set of crisp outranking relations. Type 2 methods (ELECTRE III and A) define preferences in terms of fuzzy outranking relations on the interval [0, 1].

The concordance index characterises the strength of the supporting evidence that $a' S a$, where S is the comprehensive outranking relation and a' is the complement of a. The discordance index measures the amount of disagreement that $a' S a$. The fundamental steps of the ELECTRE methods are; normalisation of the decision matrix, calculation of the weighted, normalised decision matrix, determination of the concordance and discordance set, calculation of the concordance matrix, calculation of the discordance matrix, determination of the concordance dominance matrix, determination of the discordance dominance matrix, determination of the aggregate dominance matrix and elimination of less favourable alternatives.

The Outranking approach is founded on simple logic and full use of the evidence provided in the decision model (Hwang and Yoon, 1981). CODASID and the PROMETHEE method are founded on ELECTRE. CODASID extends ELECTRE's concordance analysis to make full use of the input data. CODASID is explained fully in Chapter 6.

An attempt to clarify the determination of outranking relationships has been reported (Rogers and Bruen, 1998), making it more acceptable for Regulatory processes, such as EIA. The authors recommend outranking methods and concordance analysis as a suitable technique for the environmental evaluation of complex civil engineering projects.

In addition to the work done by Rogers and Bruen, various forms of ELECTRE have been applied to environmental decisions, (Salminen et al, 1998; Hokkanen, J. and Salminen, 1997; Becali et al. 1998). ELECTRE III, PROMETHEE I and the Simple Multiattribute Rating Technique were compared in a selection problem concerning the location of a waste treatment facility (Salminen et al, 1998; Hokkanen and Salminen, 1997). The large number of criteria and decision makers made the use of utility functions impracticable. The group conclude that it is best to use several MADM methods to arrive at the best alternative. However, where this is not practicable, ELECTRE III was recommended as the most robust method which allows the setting of veto thresholds.

The PROMETHEE (**P**reference **R**anking **O**rganization **Meth**od for **E**nrichment **E**valuations) methods offer an alternative outranking method (Brands et al, 1986; Brans and Mareschal, 1990). Firstly, the method requires that each attribute is associated with a generalised attribute preference structure. The generalisation is usually selected from one of six types where the preference moves from zero preference to indifference and strict preference (Brans and Mareschal, 1990). The six categories are named as the Usual attribute, the U-shaped attribute, the V-shaped attribute, Level attribute, V-shaped with Indifference and the Gaussion attribute. Secondly, for each pair of alternatives, a preference index $\pi(a, b)$ is defined and thirdly, outranking flows are determined for each alternative.

The positive outranking flow represents how each alternative outranks all other alternatives from the feasible set. The negative outranking flow conversely represents how an alternative is outranked by all the other alternative set members. PROMETHEE I uses these two indices to establish a partial preorder. PROMETHEE II uses the positive and negative outranking flows to produce a complete preorder as a balance of flow. The higher the net positive flow, the better the alternative. Sensitivity analysis showed that the PROMETHEE was more stable with respect to deviations in threshold values compared with ELECTRE III (Brans et al., 1986). However, the stability of a decision outcome is not necessarily desirable in an MADM method as it may indicate a lack of response to small changes in the decision data.

In order to select an appropriate MADM method, it is useful to consider how people make decisions in the absence of a structured method. For example, do people:

- Subconsciously break decisions down into attributes and mentally assign scores?

- Mentally assess an option in relation to hypothetical ideals and worst cases that we have mentally constructed?
- Breakdown complex problems into a series of pairwise comparisons that we then mentally process in order to reach a final preferred option?

Perhaps the most important fact to establish is whether the systems we employ when we make unstructured, personal decisions, are suitable for business decision making that must be suitable for groups of people, transparent and optimises the use of available information.

Although the Simple Additive Weighting model is transparent, simple and commonly used within business decision making, Distance from Ideal and Outranking methods may offer advantages, such as optimal use of available information. Methods from these MADM categories are investigated in Chapter 6.

5.3.4 Fuzzy MADM

Fuzzy MADM is particularly relevant to environmental design problems. As such, a separate review has been included in Chapter 7 and its application is described in Chapter 8.

5.3.5 The Benefits of a MADM Approach

MADM provides the foundation for many existing eco-design and sustainable design selection frameworks, as discussed in Chapter 2. These generic methodologies are suitable to assist design selection in any organisation, and can be used to analyse various degrees of data quality. The recognition of this flexibility, coupled with the lack of decision making mechanism identified in the case-study research (see Chapter 4), provided impetus for exploring MADM methods in the context of eco-design.

Initial inquiry showed that the SAW method was already applied within organisations in the form of Value Engineering studies and informal optioneering processes (see Chapter 2). However, current environmental and societal decision practices are insufficient from two viewpoints:

- Robust environmentally and societally acceptable decisions will rarely be achieved by inserting a single, all-encompassing attribute into an optioneering study. The meaning of the word 'environment' is far too complex (for instance, it relates to resource efficiency, biodiversity, eco-toxicity and environmental nuisance) and generally too poorly understood to justify such an approach. This argument is equally applicable to 'societal acceptance'. Rigorous societal and environmental attribute selection is essential for sustainable design and cannot be dealt with 'token' attributes.

- Where MADM is practised in industry, it is usually the SAW method that is applied. In some cases, this may be the best choice. However, many other MADM methods are available that capture more of the mental human decision processes, such as how we evaluate a set of options. For instance, does a decision maker mentally assign scores or does he base his judgements on pairwise comparisons? These concepts are explained in more detail in Chapter 6.

The following Chapter demonstrates two types of MADM method and discusses their advantages and disadvantages. In addition, a strategy for weighting eco-design attributes is proposed.

6 THE APPLICATION OF MULTI-ATTRIBUTE DECISION MAKING METHODS TO IMPROVE PRODUCT LIFE-CYCLE ENVIRONMENTAL PERFORMANCE

6.1 Introduction

This Chapter investigates the efficacy of two Multiple Attribute Decision Making (MADM) methods in terms of achieving eco-design of LMTO product systems. The application of these particular methods is appropriate once initial quantified estimates are available (e.g. from the later stages of conceptual design, onwards). MADM methods suitable for the earlier stages of design, when the quality of information imposes a more qualitative approach, are discussed in Chapter 8.

Direct and entropy derived weighting systems are compared in terms of their influence on the decision outcome. The latter is developed to provide a systematic method through which diversity of evidence, environmental expert knowledge, client targets and stakeholder opinion can be aggregated to provide a holistic weighting system.

6.1.1 Purpose and Scope of Research

This Chapter investigates the application of Multiple Attribute Decision Making (MADM) to a case-study decision which aims to minimise the environmental impact associated with the discharge of produced water. The research objectives of this Chapter are:

- To accommodate environmental requirements of the design selection process, as identified through qualitative research, within a MADM decision support system.
- To examine 2 MADM methods with regard to improving environmental decision making. Attribute selection, weighting and evaluation steps are examined in the context of the case-study decision.
- To identify the costs and benefits of using MADM to optimise this type of decision, paying regard to the use of information, the sensitivity of the results and computational requirements.

6.2 MADM: An Activity Within the Decision Process

Design decisions are subject to a combination of formal and informal decision making processes. Formal decision making often encourages the adoption of systematic decision making activities. Informal decision making may occur implicitly within design tasks or as a specific event during a moment of creativity and spontaneity on the part of the design engineer. Brainstorming or optioneering studies are systematic, but also encourage a degree of free-thinking and discussion, drawing from the more creative thought processes of a design engineer. MADM may be conducted in this type of discussion-based environment.

Decision making can be categorised as prescriptive or descriptive (Stewart, 1998; Bell et al., 1988).

- Prescriptive models attempt to assist the decision making process by providing decision support based on what we understand to be the critical stages of decision making. An example would be HAZOP or Value Engineering studies. Prescriptive decision making is usually based on a normative approach, where decision makers are assumed to be rational.

- Descriptive models attempt to capture the cognitive, affective and behavioural processes undertaken by human decision makers.

Most decision support systems have been based around the normative/ prescriptive model where the problem is conceptualised and solved mathematically, such as MADM methods. It should be noted that the development of the scope of the decision, the objectives and the synthesis and screening of options are key activities which are beyond the scope of this Chapter. These activities are as important as the optimisation method itself (Keller and Ho, 1988, Fazlollahi et al., 1997), however, the use of MADM should add confidence and transparency to the final decision outcome.

6.2.1 The Design Contractor's Role in Environmental Design Decision Making

The case-study that was used in this Chapter was supplied by Company A, one of the subjects of the earlier qualitative research chapters. Therefore, the decision support methodology is aimed at the design contractor who was predominantly involved at the later stage of conceptual design where quantified estimates were available. Prior to this stage, the client would have conducted the early conceptual work when design evaluation would have been more qualitative.

Both phases of conceptual design are important to achieving eco-design. This Chapter examines two methods that enable the quantitative analysis of the later conceptual design, whereas Chapter 8 examines a method that is able to manage qualitative assessments. Although the organisation of these Chapters is in the reverse order of the design sequence, it was considered that the methods introduced in this Chapter are simpler to understand and will help introduce the concept of MADM. This concept is then built on in Chapter 8, using the more complex idea of MADM based on fuzzy sets in a group decision making situation. It is important to implement both stages of decision analysis to ensure that the environmental objectives developed early during design synthesis reach embodiment (see Figure 2-1).

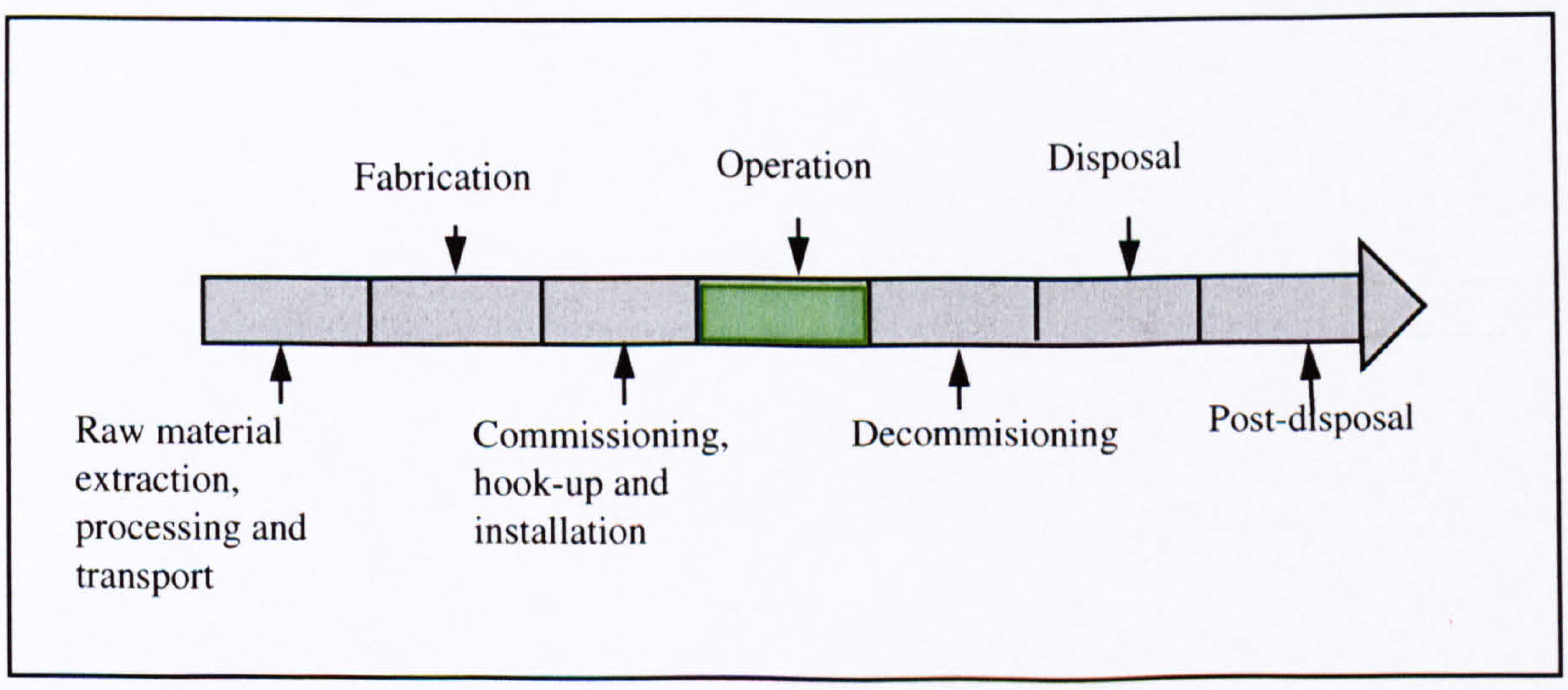
6.3 Case Study: Design Selection for Produced Water Treatment System

A full background to the project is given in Appendix VI which covers the Company's EMS, the legislative framework of the project, the Company's Environmental Policy, environmental targets and objectives and the project's Environmental Statement.

During the course of the qualitative research, examples of multiple attribute design selection problems were identified. One such problem involved the selection of design options for a produced water treatment system. The environmental impacts incurred by this sub-system are associated with the operations phase of the offshore facility and is the focus of this Chapter (Figure 6-1). The operations phase of many large made-to-order products will often be associated with significant environmental impact and in the case of LMTO products, this phase can span decades.

Produced water is a by-product of the oil and gas extraction process during the operations phase of the oil and gas facility. It comprises formation water (saline) and condensed water (non-saline) and separates into dispersed and dissolved oil fractions. In 1998, 5690 tonnes of oil was discharged to the North Sea via produced water (UKOOA, 1999). These discharges are set to increase in the future as oil and gas activities increase and the age of the North Sea reservoirs increase. Oil concentration in produced water should be less than 40 ppm in order to meet limits set out in the Prevention of Oil Pollution Act 1971. However, UKOOA have set a more stringent of 30 ppm and the Client has gone further, setting a quality level of 12 ppm.

Figure 6-1 : The Life-Cycle Focus of the Case-Study Decision



The client company requires that chemicals and heavy metals discharged to sea are compatible with the surface environment. If the discharges are not fully compatible with the surface waters, the client advises that production waters are reinjected into the sea-bed.

This case-study decision demonstrates the uncertainty typically present at conceptual design. The alliance team were principally involved at the development of solution principles and design variants. However, initial data was subject to incompleteness and low reliability. For instance prior to competition, the initial estimate of produced water production was 19,000 bpd (barrels of oil equivalent per. day). Later on in the design process, this estimate was revised to 6000 bpd and finally re-revised to 2000 bpd. In addition, the cost of reinjection increased from an initial estimate of 2.8 MM[1] Net Present Value (NPV) to 4.6 MM NPV. This clearly demonstrates the need for an iterative approach to decision making, where evaluations and underlying assumptions are revisited as new information becomes available.

6.4 Current Practice: BPEO Assessment

The case-study company approached the environmental design decision by conducting a BPEO Assessment. This is based on a normative/prescriptive decision model where the decision objective sets out to minimise environmental impacts relating to air, water and land using a structured decision framework. BPEO assessment is a requirement under Integrated Pollution Control (Environment Agency, 1997b) and the Radioactive Substances Act 1993 (Smith, 2002; Egan et al., 2003). Although this regulatory requirement does not apply to offshore facilities it is a well-recognised decision framework and the Client took the decision to apply the method proactively.

Design alternatives were generated and screened, resulting in five alternatives which proceeded to a full evaluation in the context of a number of decision factors. The BPEO document presents a number of explicit and implicit decision factors. Implicit factors include those which influence the decision which are not clearly defined as

1.MM is 'one thousand thousand' expressed in Roman Numerals. That is to say, £1000, 000.

attributes and are not universally applied to the set of alternatives. Explicit factors were clearly identified in the BPEO document.

Explicit decision factors

- Cost evaluation (CAPEX and OPEX)
- tonnes oil equivalent/year oil abatement
- fuel gas consumption
- heavy metal removal capability
- legislative requirements (current and future)
- installed weight
- produced water profile
- spatial requirement

Implicit decision factors

- experience / novelty of process
- potential for add-on technology / retrofit
- hook-up complications and installation requirements
- added complication to platform processes
- maintenance requirements and availability

The BPEO assessment tended towards a selective discussion of some of the costs and benefits relating to each alternative design. Weighting of decision attributes and the evaluation of options in relation to the attributes was not conducted entirely systematically or consistently. The contents of this Chapter investigates how a more structured MADM approach could have been employed, which is in line with guidance from the Environment Agency (Environment Agency 1997b, Egan et al., 2003).

6.4.1 Hierarchical Decomposition of Design Requirements to Obtain Environmental Decision Attributes

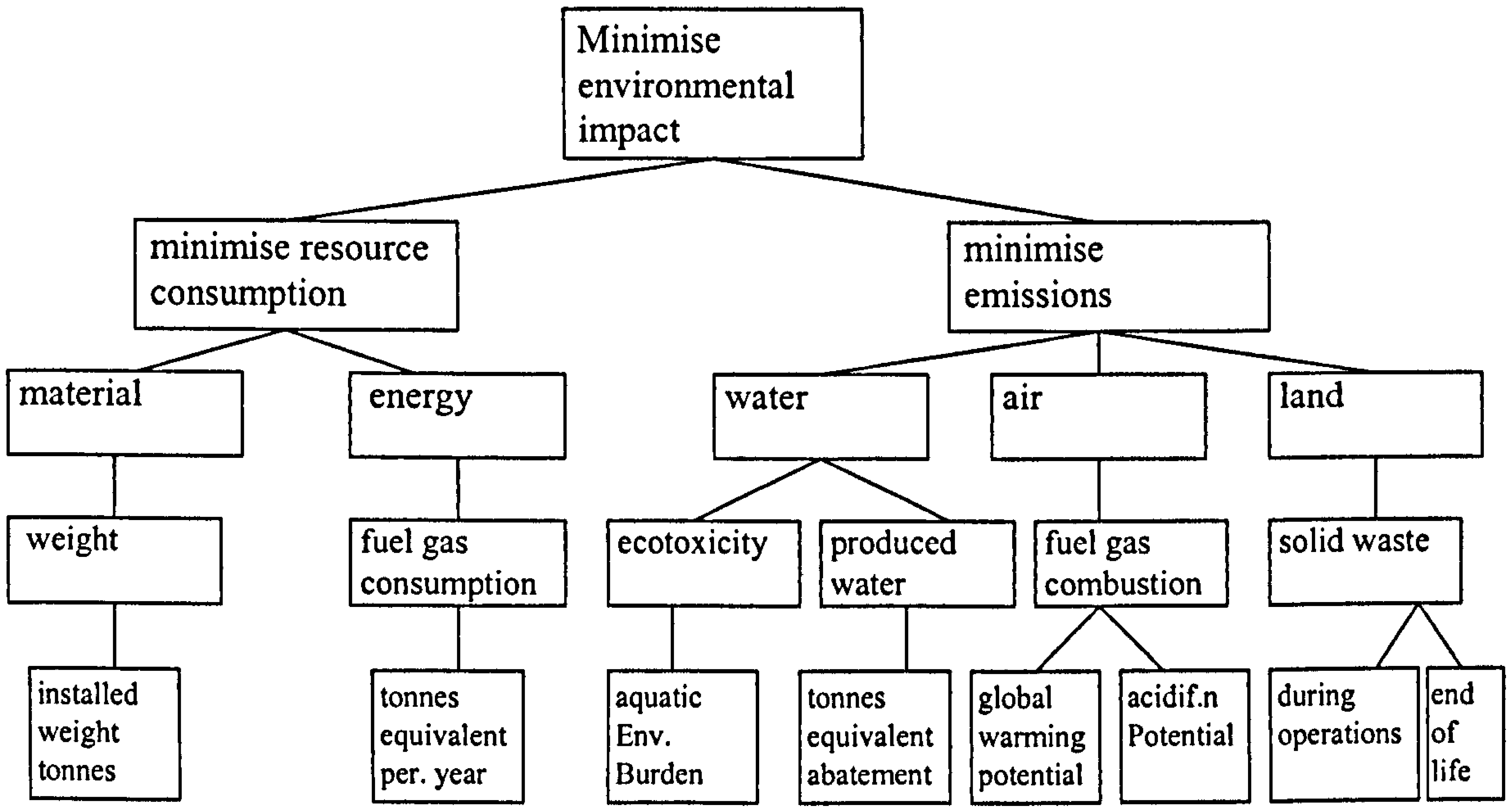
The quality of the evaluation depends upon applying a set of relevant attributes consistently to all design options. The attribute set should fulfil the following basic requirements (Keeney and Raiffa, 1976; DLTR, 2001):

- The attribute set should be complete.
- The attributes should be operational / simple to use.
- There should be no redundant attributes.
- They should be minimal and realistic in terms of time and manpower resource availability.
- They should be internally consistent and logically sound.
- Data requirements should be consistent with the importance of the issue under consideration.

Hierarchical decomposition is a useful method for determining the relationships between decision attributes and avoiding dependency and redundancy. These attributes may be constraints or functional requirements (Suh, 1990). However, no distinction is made here for simplicity. The difference is that constraints are precise values, dependent and maximised to define the design space. Whereas functional requirements are independent, minimal and usually operate within a value threshold.

In the context of eco-design, if the overall objective is to 'minimise environmental impact' this objective may be broken down into lower order attributes and expressed as measures of performance. Figure 6-2 shows the decomposition of an environmental objective into constituent attributes, to ensure independence and prevent double-counting.

Figure 6-2 : Hierarchical Decomposition of the Environmental Objective



6.5 The Application of Multiple Attribute Decision Making to the Produced Water Case-study

Based on Company A's requirement to select a suitable design option for minimising produced water discharges, a decision matrix was generated to summarise the performance of each option against each attribute. This matrix in Table 6-1 provides the underpinning data for the two MADM methods examined in this Chapter.

Table 6-1: Decision Matrix for Produced Water Treatment Options

	Option 1	Option 2	Option 3	Option 4	Option 5	Option 6	Option 7	Option 8
CAPEX	1.27 MM	1.67 MM	1.91 MM	2.17 MM	2.81 MM	3.97 MM	4.55 MM	9.4 MM
Installed wt. (tonnes)	101.1	101.1	139.5	139.5	124.4	205.0	92.3	92.3
Fuel consumptn.	200	200	200	200	200	700	350	350
Max te/yr abatement	5.52	5.52	16.56	16.56	11.04	16.56	19.90	19.90
Solid waste (operations)	0	0	0	0	0	1	0	0
Solid waste (end of life)	101.1	101.1	139.5	139.5	124.4	205.0	92.3	92.3
GWP	220.7	220.7	220.7	220.7	220.7	772.32	386.2	386.2
Acidification potential	35.0	35.0	35.0	35.0	35.0	122.5	61.25	61.25
EB aquatic ecotoxicity	0.03	0.03	0.03	0.03	0.03	0.00	0.03	0.03

6.5.1 Selection of Attributes

The nine selection attributes presented in Table 6-1 are used to evaluate eight design options. The attributes have been selected to satisfy key design objectives as discussed in Section 6.5.1. Essential feasibility aspects of the design space, such as weight and cost have been added. Ideally, the decision model would include whole life costs instead of capital cost. This would encompass availability and maintenance requirements. However, only figures were available for CAPEX so the model does not include operational expenditure incurred by shut-down and repairs.

Capital expenditure and installed weight are essential attributes that determine design feasibility on the alliance's behalf. These attributes are dependent; if equipment weight is increased, CAPEX will increase due to the extra pipework and supporting structural steel required. They are treated separately in the decision model as weight introduces additional complexity (for example, additional paint and protection system, piping, electrical and control systems, insulation and telecommunications).

The maximum capacity for the abatement of oily water measured in tonnes equivalent per year is a direct measure of the design options' efficiency. It also shows explicitly whether the client EDO to achieve an oil in water discharge concentration of 12 ppm is met by the design. Fuel consumption is another efficiency criterion which has a direct relationship with the global environmental effects of fuel gas combustion emissions, such as global warming potential and acidification potential, as well as operational expenditure.

Although the attribute 'fuel gas consumption' is directly linked with environmental effects and represents a measure of resource efficiency, global warming potential and acidification potential are included in the decision model as separate, additional attributes. This approach allows the separate environmental impacts to be assessed transparently, whilst avoiding redundancy.

An engineer may look at the criterion 'fuel consumption' and consider effects on operational expenditure, but may not account for global warming effects as this is a complex, uncertain environmental effect which someone without environmental training may overlook. The qualitative research described in Chapter 4 (see Section 4.3.25) demonstrates that design engineers may not have a comprehensive understanding of the relationships between engineering decisions and their environmental consequences.

Solid waste produced during operations will affect operational expenditure, waste transportation requirements, waste management, disposal requirements and the need for storage space on board the platform. Waste-type is considered on a qualitative basis. For example, where it is known that heavy metal contaminated waste will be produced. As such, an evaluation of 1 or 0 is ascribed to indicate the presence or absence of an operational waste problem. Solid waste at end of life is simplified in this model and is equated to the installed weight of process equipment. Therefore, the waste-type is not taken into consideration as exact data were not available. The main waste material will be structural support and pipework containing a large proportion of steel. Finally, ecotoxicity is included as a criterion. This relates to the environmental hazard associated with the heavy metals and production chemicals within the produced water.

6.5.2 Design Options for the Produced Water System

The alliance partnership generated the following options that were considered feasible and therefore warranted more detailed evaluation.

- Option 1: The base case option will include pretreatment followed by removal of dispersed oil via a hydrocyclone to below 12ppm. A hot water stripping process is used to remove dissolved oil to below 12 ppm.The design capacity of Option 1 is for 2000 bpd oil from day 1 of operations.

- Option 2: Dispersed and dissolved oil is removed as for Option 1. Oil removal capacity is 2000 bpd from year 3.

- Option 3: Dispersed and dissolved oil is removed as for Option 1. Oil removal capacity is 6000 bpd from day 1.

- Option 4: Dispersed and dissolved oil is removed as for Option 1. Oil removal capacity is 6000 bpd from year 3.

- Option 5: Dispersed and dissolved oil is removed as for Option 1. Oil removal capacity is 2000 bpd from day 1, increasing to 4000 bpd for year 3.

- Option 6: Represents the base case option plus the removal of heavy metals using a precipitation process.

- Option 7: Resurrect well for reinjection using existing tubing.

- Option 8: Drill new platform well using a spare drilling slot. This option will require drilling and completion with plastic coated tubing, including a standard tree and wellhead.

These options will be assessed against the nine selection attributes presented in Table 6-1. Note that options that involved the deferred installation of abatement equipment will cost more due to the lifting and hook-up complications offshore.

6.5.3 Generic Aspects of Eco-Design Selection

There are many MADM methods and it is a multiple attribute decision in itself to select the most appropriate, robust method for eco-design decision making. Al-Shemmeri, et al., (1997) discussed model choice for multi attribute decision aids for the ranking of water development projects and identified five characteristics that should guide the choice of MADM model:

Discrete or continuous alternatives: The case-study presents a decision that is taken at late conceptual / detailed design. At this point, design selection involves a restricted number of alternatives, determined by what the suppliers make available to the designer. For example, there are a variety of produced water treatment systems. Some parameters may be adjusted to fit the design specification but generally the system is selected from a range of pre-defined alternatives. Therefore, the MADM method must usually find the design optimum from a discrete set.

Ordinal or cardinal decision output: Essentially the design engineer wishes to find the optimal design. Uncertainty within the data and subjectivity of preference precludes exact cardinal evaluation.

Single step or iterative decision making process: The decision is likely to undergo several iterations as new information becomes available during the design process. For example, as a more exact estimate for produced water volume becomes known.

Sensitivity of results: Changes in the input parameters, for example an alteration of preference structure, should affect the final optimal solution in a logical manner.

Ease of use: Computationally simple MADM methods will increase the transparency of decision making, which is a requirement of the EIA process and makes the design process more easily auditable. In addition design engineers may have more confidence in methods that are rational and easily understood.

Two MADM methods are applied to the case-study in order to identify the preferred option:

- Technique for Order Preference by Similarity to Ideal Solution (TOPSIS)
- CODASID

6.5.4 Why TOPSIS / CODASID?

Four groups of MADM method exist; Utility-based; Direction-based; Distance-based and Outranking. TOPSIS and CODASID are both examples of outranking methods. These methods manipulate given preference information, allowing the designers to assign weights in a similar fashion to a Value Engineering study. However, it was considered potentially beneficial that both methods make fuller use of the information within the decision matrix compared with the Simple Additive Weighting method which is commonly used in BPEO assessments (DLTR, 2001).

6.5.5 TOPSIS

TOPSIS is a decision method which evaluates alternatives in relation to their *closeness to ideal* performance with respect to decision attributes (Hwang and Yoon, 1981). The method assumes that the increase or decrease in attribute utility is monotonic (consistent increase or decrease in value). The normalised matrix $\bar{D}$ is constructed by applying Equation 6.1 to the values in Table 6-1:

$$zij = y_{ij} / \sqrt{\sum_{i=1}^{n} y_{ij}^2} \qquad [6.1]$$

,where z_{ij} is an element of the normalised, weighted Z matrix, y_{ij} is an element of normalised matrix, i is the number of alternatives and j is the number of attributes.

Weights are then applied to the normalised decision matrix D (Appendix VI; Table 1) to create the matrix W$\bar{D}$ (Appendix VI; Table 2). Members of the design team weighted the attributes on a scale 0-10. Normalisation is then applied so these weights fall within the interval [0, 1] by dividing each weight value by the total sum of the weight vector.

Weights 0-10:[2, 4, 4, 6, 4, 3, 5, 4, 6]

W= [0.0526, 0.1053, 0.1053, 0.1579, 0.1053, 0.0789, 0.1316, 0.1053, 0.1579]

A direct weighting approach is used in this case and the vector reflects the purpose of the BPEO assessment and the environmental objectives of the client. The most importance is attached to environmental parameters 'oil discharge abatement' and 'ecotoxicity'. 'Global warming potential' is given the second highest weighting as this is a major operational environmental impact of an oil and gas production facility. However, the minimisation of fuel gas combustion is in conflict with the reduction of ecotoxicity as the plant which reduces ecotoxicity is powered by fuel gas combustion.

TOPSIS works with minimisation problems. Attributes which involve maximisation must be turned into minimisation by converting them to a negative number i.e. acid gas emissions must be minimised whereas tonnes equivalent of oil abated must be maximised.

In order to determine the score for each option, the distance between each option and the theoretical ideal option is calculated. The *ideal* alternative is determined as one which offers optimal performance for every attribute (see Table 6-2). The *available* alternatives are then evaluated in relation to the ideal value for each attribute using Equations [6.2] and [6.3].

$$S_i^{ideal} = \sqrt{\sum_{j=1}^{k} (x_{ij} - x_j^{ideal})^2} \quad [6.2]$$

$$S_i^{-ideal} = \sqrt{\sum_{j=1}^{k} (x_{ij} - x_j^{-ideal})^2} \quad [6.3]$$

, where Si is the distance of the alternative from an ideal or negative ideal point, j represents the attributes 1, ..., k, x_{ij} represents the performance of alternative i for attribute j, xj^{ideal} represents the best performance score for attribute j from the set of alternatives, and xj^{-ideal} represents the worst performance score for attribute j.

Table 6-2: Distance from Negative and Positive Ideal

	j1	j2	j3	j4	j5	j6	j7	j8	j9
+ Ideal	-0.0055	-0.0266	-0.0218	0.0741	0.0000	-0.0199	-0.0272	-0.0218	0.0000
- Ideal	-0.0410	-0.0590	-0.0762	0.0206	-0.0153	-0.0442	-0.0952	-0.0762	-0.0597

The closeness of each alternative (C*i*) to the ideal is then calculated and the alternatives are ranked based on this closeness index, the highest value denoting the preferred alternative.

$$C_i = \frac{S_i^{-ideal}}{(S_i^{-ideal} + S_i^{ideal})} \qquad [6.4]$$

, where C_i represents the closeness to the hypothetical ideal solution.

The decision outcome of the produced water case-study is shown in Table 6-3. It can be seen that Option 3 has the highest Ci value, which means that it is closest to the hypothetical ideal solution. However, Option 4 follows very closely and may be considered as a joint preferred option. The results give a clear indication that Option 6 should not be taken forward.

Table 6-3: Ranking of Design Alternatives for Produced Water System

Alternative: description	*Ci* Value	Rank
1 : Base case	0.6601	5
2 : 2000 bpd oil removal capacity from year 3	0.6595	6
3 : 6000 bpd oil removal capacity	0.7138	1
4 : 6000 bpd oil removal capacity from year 3	0.7133	2
5 : 2000 bpd day 1; 4000 bpd from year 3.	0.6891	3
6 : Base case plus heavy metal precipitation	0.3318	8
7 : Resurrected well injection	0.6796	4
8 : New well injection	0.6548	7

6.5.6 Sensitivity Analysis of TOPSIS

Sensitivity analysis is used to assess how a decision method responds to alterations of the preference structure. This helps to determine how robust the MADM output is and how much confidence should be placed in this part of the decision process. Some MADM methods may be sensitive to strong weighting of one attribute, whereas in other methods, the preferred choice may be derived by moderate performance with respect to several less important attributes. Different MADM methods will arrive at different answers, as indeed will different individuals. Therefore, it is important to perform a 'sanity check' of the outcome to ensure the method is providing logical results, as noted by Al Shemmeri et al., (1997) and discussed in Section 6.5.3.

The sensitivity of TOPSIS is investigated using different weight vectors (see Appendix VI) in order to establish whether the varying importance of attributes influences the decision outcome.

Table 6-4: Sensitivity of TOPSIS Outcome to Variations in Weight Vector

Weight Vector	Ci Value	Rank
Original	0.6601, 0.6595, 0.7137, 0.7133, 0.6891, 0.3318, 0.6795, 0.6548	3>4>5>7>1>2>8>6
E++	0.6189, 0.6183, 0.6573. 0.6568. 0.6386. 0.3764, 0.6273, 0.6092	3>4>5>7>1>2>8>6
E+	0.6394, 0.6388, 0.6845, 0.6840, 0.6632, 0.3544, 0.6527. 0.6317	3>4>5>7>1>2>8>6
C+F+	0.6740, 0.6728, 0.7250, 0.7240, 0.6993, 0.3362, 0.6774, 0.6292	3>4>5>7>1>2.>8>6
C- W- Ab+ G+ A+ E+	0.6356, 0.6355, 0.6986, 0.6985, 0.6708, 0.3429, 0.6598, 0.6546	3>4>5>7>8>1>2>6
C+	0.6671, 0.6658, 0.7188, 0.7177, 0.6924, 0.3438, 0.6766, 0.6270	3>4>5>7>1>2>8>6

Table 6-4 shows the relative difference of the Ci values in response to changing the importance of various attributes. Although the Ci value did increase for Option 6 as expected, increasing the ecotoxicity attribute's weight to 20% made no difference to the overall rank position.

In the case of weight vector variant (C-W-Ab+ G+ A+ E+), only the rank of alternative 8 changed from 7th to 5th rank position as the cost attribute became less influential during the optimisation.

Finally, the increased weighting of cost by 2.4% made no changes to the final rank order. Therefore, it appears that the initial TOPSIS result is relatively robust in the context of a range of weighting scenarios presented here.

As noted before, the changes in weights were relatively small. However, Option 3 remains first choice even when the original score for CAPEX is increased from 2 to 10 (22% of the weight). Extreme weighting of capital cost would eventually favour

Option 1 but such gross bias towards an economic argument would not be in line with balanced decision making. If the decision makers must impose a strict cost limit, it should be justified as a constraint and used to screen out infeasible options during option development. However, the use of cost thresholds as a constraint may preclude the consideration of some otherwise competitive design options.

In terms of making a decision, the MADM results would support the continuation of design work on Options 3 and 4. In addition, further design information should be gathered before Options 5 and 7 can be deselected conclusively. However, the deselection of Option 6 can be fully justified. The remaining options may be parked and revisited if new favourable information is generated during the design process, or if new developments result in the deselection of the preferred options.

6.5.7 Alternative Approaches to Direct Weighting

Direct weighting by a group of engineers has several disadvantages. Firstly, they may not be knowledgeable about environmental impacts and therefore offer little in addition to a layman's opinion. Secondly, they may have specific agendas which may reduce the importance that they allocate to attributes in order to support their personal objectives. Thirdly, the engineers or environmental experts may prefer a weighting system that is less dependent on their own personal judgements so that the decision outcome may be more acceptable to external stakeholders.

6.5.8 Combined Weighting System

Entropy is a measure of disorder associated with a system. The concept of entropy was originally applied to the field of thermodynamics by Boltzman in 1872. In 1948, the concept was generalised by Claude Shannon and applied to the field of information theory. In this context, entropy is used to determine the degree of uncertainty about a proposition or as a measure of information acquisition. Entropy is described by the function (Levine and Tribus, 1979):

$$S = -\sum_{i} p_i \ln p_i \qquad [6.5]$$

,where *S* represents the entropy of information and p_i represents the performance of Option i.

In terms of decision making, entropy can measure the agreement between sets of data. That is to say, the majority of weight is assigned to those attributes which are key differentiators between options. This approach works on the same principles as 'swing weighting' (DLTR, 2001), albeit in a slightly more structured way.

Sen and Yang (1998) demonstrates how the entropy of decision information may be calculated. From the normalised decision matrix, the performance of alternative i with respect to attribute j can be defined as p_{ij}. The entropy E_j measures the variation in performance of alternatives 1, ..., n for attribute j by the function:

$$E_j = -\alpha \sum_{i=1}^{n} p_{ij} \ln p_{ij} \text{ for all j} \qquad [6.6]$$

Therefore, if all p_{ij} values for attribute j are equal, E_j must equal 1.0.

$$\alpha = \frac{1}{\ln(n)} \qquad [6.7]$$

, where alpha is a constant which ensures that the entropy value is within the interval [0, 1].

Weights may either be based on the diversity of information or they may be allocated subjectively by the decision maker:

i. Weights are ascribed to attributes based on the degree of diversity, d_j, about the data set of each attribute (e.g. a high entropy value will give rise to a low diversity value and therefore a low weight, as the attribute in question is limited in terms of its ability to discriminate between options and is consequently not so important to the decision process).

$$d_j = 1 - E_j \qquad [6.8]$$

, where d_j represents the degree of diversity.

$$w_j = \frac{d_j}{\sum_{j=1}^{n} d_j}, \forall j \qquad [6.9]$$

Thus, when all alternatives have the same value for attribute j, dj = 0 because Ej = 1 as argued in Equation 6.6.

Application of this function to the produced water case study yields a weight vector of:

W= [0.0732, 0.0129, 0.0424, 0.0305, 0.6996, 0.0129, 0.0424, 0.0424, 0.0436]

The resulting weight vector places over two thirds of the weight on operational solid waste due to the data set's diversity. If the group of decision makers are not satisfied with such a dominated weighting scheme, the entropy approach can be modified to combine entropy with subjective value weights.

ii. Subjective weights $\hat{w}_j$ can be introduced in combination with w_j to obtain an aggregated weight:

$$\tilde{w}_j = \frac{\hat{w}_j w_j}{\sum_{j=1}^{n} \hat{w}_j w_j} \qquad [6.10]$$

, where $\hat{w}_j$ represents the subjective weight of attribute j contributed by experts, w_j represents the calculated entropy weight and j represents each attribute 1, ...,n.

External expert weighting can also be introduced to the decision problem in this way. For example, Eco-indicator 95 (Goedkoop 1995) developed weighting factors based on European environmental concerns (See Table 6-6), enabling a business to include knowledgeable views of the 'outside world'. However, it is unlikely that an external expert source will be available for all the decision attributes. In this case, those attributes not covered by Eco-indicator, such as cost, are given a weight factor of 1 so that their relative importance remains unchanged.

It should be noted that although globally accepted factors may add an expert dimension to the decision process, they cannot capture the influence of local geography with respect to environmental damage.

Table 6-5: Eco-indicator's Environmental Weights Relevant to the Produced Water Case Study

Environmental Effect	Eco-indicator Weighting Factors [Goedkoop, 1995]	Normalised Weights
Greenhouse Effect	2.5	0.1064
Acidification	10	0.4255
Waterborne heavy metals	5	0.2128
All other attributes	1	0.0426

Eco-indicator's weighting factors are introduced as subjective weight values $\hat{w}_j$. Normalisation of the subjective weight vector yields the weight vector $\hat{W}$:

$$W = [0.0732, 0.0129, 0.0424, 0.0305, 0.6995, 0.0129, 0.0424, 0.0424, 0.0436]$$

$$\hat{W} = [0.0426, 0.0426, 0.0426, 0.0426, 0.0426, 0.0426, 0.1064, 0.4255, 0.2128]$$

$$\tilde{W} = [0.0452, 0.0080, 0.0262, 0.0188, 0.4319, 0.0080, 0.0654, 0.2619, 0.1346]$$

The *combined* entropy-based weight has increased the original entropy weight of ecotoxicity from 0.0436 to 0.1346, and acidification receives a weighting increase of 54.2%. However, the attribute *tonnes equivalent of abatement* is reduced by 38.4%. Client targets show this attribute to be important, therefore the *combined entropy-based* weighting should include three elements:

- Variation within the data set.

- Environmental expert knowledge.
- Client targets.

A specific client target exists within Company A to reduce oil in water discharges to 12 ppm by 2005. Consequently, extra importance may be attached to the maximum tonnes equivalent of oil abatement in order to accommodate this target as it is fundamental that Company A meets their Client's target. The subjective weighting step is therefore altered to increase the importance of this attribute by a factor of 2. In addition, the client has an Environmental Discharge Objective for fuel usage as described in Appendix VI, so the weight of fuel consumption is similarly increased by a factor of 2. It should be noted that the factor 2 increase is subjective and would ideally be decided by a group of decision makers with Client representation. This results in a combined weighting system shown in Table 6-7.

It should be understood that the subjectivity associated with value weighting will always remain, even if world-leading experts were on hand to give their input to every business decision, and this fact should not be overlooked when using a data-driven process such as MADM.

Table 6-6: Combined Weighting System Inclusive of Client Targets

Environmental Effect	Weighting Factor	Normalised Weights
Greenhouse Effect	2.5	0.0980
Acidification	10	0.3922
Waterborne heavy metals	5	0.1961
Max te/yr abatement	2	0.0784
Fuel consumption	2	0.0784
All other attributes	1	0.0392

The final weight vector, derived using the combined entropy-based weighting system, is as follows:

Wj* = [0.0432, 0.0076, 0.0501, 0.0360, 0.4133, 0.0076, 0.0626, 0.2506, 0.1288].

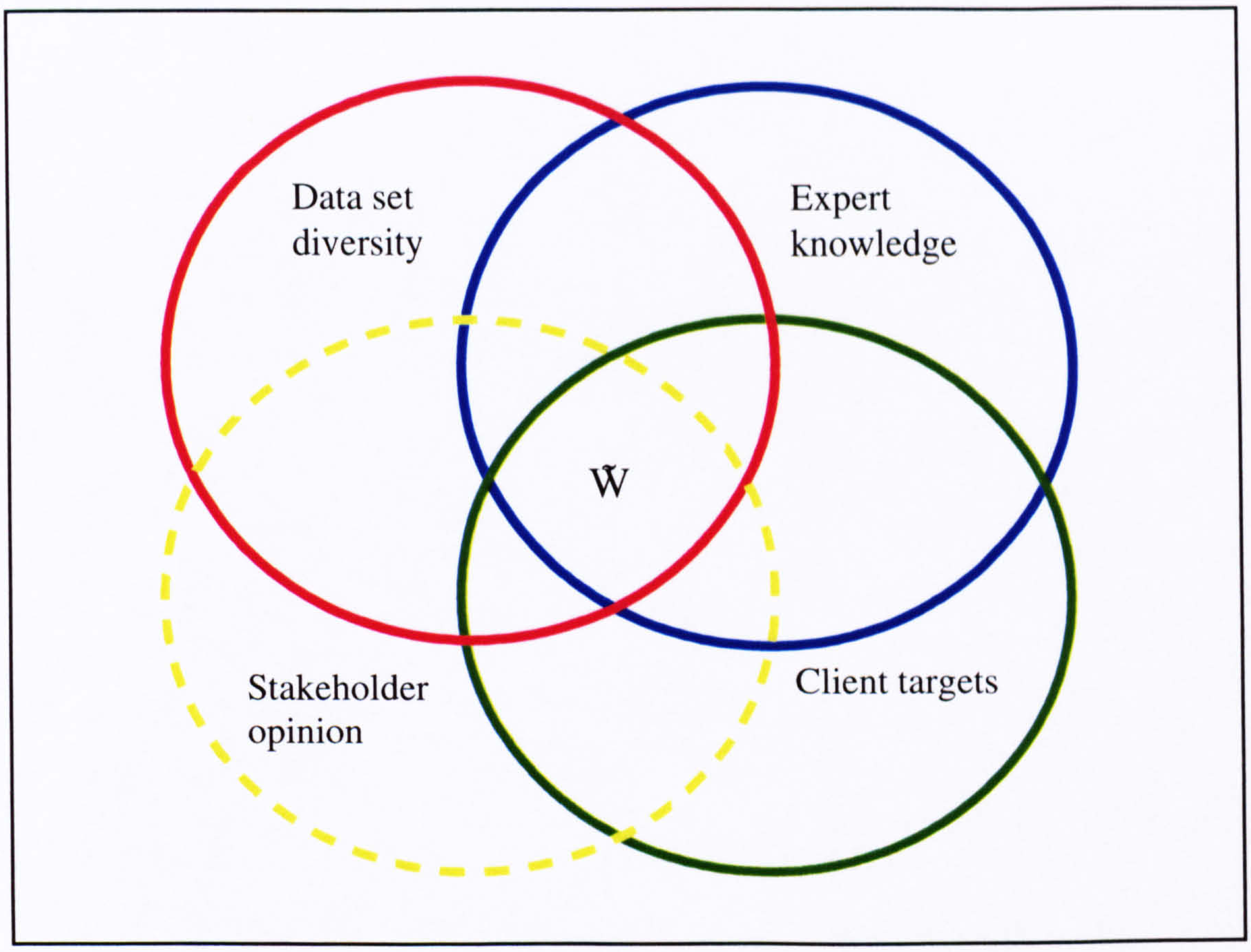
Table 6-7 shows the rank orders of design options for all three weighting systems.

Table 6-7: TOPSIS Ranking with Entropy Weight System

Weight System	Weight vector	TOPSIS Rank
Entropy weighting (Wj)	[0.0732, 0.0129, 0.0424, 0.0305, 0.6997, 0.0129, 0.0424, 0.0424, 0.0435]	3>4>1>2>5>7>8>6
Entropy plus Eco-Indicator weights (W_j)	[0.0452, 0.0080, 0.0262, 0.0188, 0.4319, 0.0080, 0.0654, 0.2619, 0.1346]	3>4>1>2>5>7>8>6
Entropy including Eco-Indicator and client target weights (Wj*)	[0.0432, 0.0076, 0.0501, 0.0360, 0.4133, 0.0076, 0.0626, 0.2506, 0.1288]	3>4>5>1>2>7>8>6

Finally, a fourth weighting dimension may be included to represent the views of external stakeholders, such as local residents or the general public. Stakeholder meetings may present a forum for obtaining weights from a sample of the public, which will include environmental risk perception. If a public consultation is not practicable, relevant value-set scenarios can be developed by the internal decision makers. The influence of external stakeholders is dealt with in Chapter 9. Figure 6-3 shows a possible combined weighting system that integrates the diversity of the attributes' data-sets, expert weighting, client targets and stakeholder values.

Figure 6-3: Combined Entropy Weighting System



6.5.9 MADM Based on Pairwise Comparisons

Concordance and Discordance Analyses by Similarity to Ideal Design (CODASID) uses pairwise comparisons between options to generate three pairwise comparison matrices (Sen and Yang, 1998). This makes full use of all the information in the decision matrix and is based on the ELECTRE methods developed in France (Roy, 1990).

Firstly, the decision matrix is normalised in order to achieve commensurate units, using a linear transformation.

$$r_{ij} = \frac{y_{ij} - y_{ij}^{min}}{y_j^{max} - y_j^{min}} \qquad [6.11]$$

, where r_{ij} is the normalised element obtained from the y values of the decision matrix (Table 6-1), and y_j^{max} and y_j^{min} are the best and worst y_{ij} values for each attribute.

All normalised attributes are transformed within the interval [0, 1], where 1 represents the best values and 0 represents the worst values:

$$R = \begin{bmatrix} r_{11} & r_{12} & \cdots & r_{1n} \\ r_{21} & r_{22} & \cdots & r_{2n} \\ \cdots & \cdots & \cdots & \cdots \\ r_{m1} & r_{m1} & \cdots & r_{mn} \end{bmatrix} \qquad [6.12]$$

The decision matrix and the relative weights are aggregated to form the Z matrix:

$$Z = \begin{bmatrix} z_{11} & z_{12} & \cdots & z_{1n} \\ z_{21} & z_{22} & \cdots & z_{2n} \\ \cdots & \cdots & \cdots & \cdots \\ z_{m1} & z_{m2} & \cdots & z_{mn} \end{bmatrix} \qquad [6.13]$$

,where $i = 1, ..., m; j = 1, ..., n$

Three indices are used to evaluate the alternatives' performance; the *preference concordance* index, the *evaluation concordance* index and the *discordance* index The preference concordance index is derived using evidence provided by the weight vector W. p_{kl} measures the gross importance of the assumption that alternative k is better than alternative l from the weight values wj. If a_k is the ideal alternative, then p_{kl} will be equal to 1 as this alternative will take the best value of all attributes and will thus be awarded every wj value, otherwise, $0>p_{kl}<1$.

$$p_{kl} = \sum_{j \in C_{kl}} w_j/S_p \qquad [6.14]$$

,where pairwise comparisons of alternative k with alternative l for each attribute j show k > l (based on the values of the Z matrix; Appendix IV, Table 4), p_{kl} represents the preference weight W that supports this dominance for attribute j. j is the index of all attributes concordant with the assumption that a_k P a_l

$$S_p = \sum_{j=1}^{n} w_j \qquad [6.15]$$

, where S_p is equal to 1 if the sum of the normalised weights is equal to 1.

The final preference concordance index is calculated as shown in Equation 6.16. This represents the net support for the assumption a_kPa_l based on preference information from W.

$$p_k = p(a_k) = \sum_{\substack{l=1 \\ l \neq k}}^{m} p_{kl} - p_{lk} \qquad k = 1, \ldots, m \qquad [6.16]$$

, where p_k is the net preference concordance that alternative k is superior to alternative l as derived from the pairwise comparisons obtained from Equation 6.14.

The evaluation concordance index measures the gross support of the assumption a_kPa_l using the normalised, unweighted evaluations. If a_k is the ideal alternative, e_{kl} will equal 1, otherwise $0>e_{kl}<1$.

$$e_{kl} = \sum_{j \in C_{kl}} |r_{kj} - r_{lj}| / S_e \qquad [6.17]$$

,where e_{kl} is the net measure of evaluation concordance that supports the inequality k > l, based on the values in matrix R (see Appendix VI; Table 3). r_{kj} is the normalised value of alternative k for attribute j, for those attributes where alternative k > j. For example, where ${}_kP_l$ for attributes 2 and 5, the evaluation concordance index is:

$$e_{kl} = |r_{k2} - r_{l2}| + |r_{k5} - r_{l5}| / S_e$$

S_e is the common scaling factor which is equal to the number of attributes associated witht he decision, if the decision matrix is normalised as directed:

$$S_e = \sum_{j=1}^{n} \max_{k,l \in M} \{|r_{kj} - r_{lj}|\} \qquad [6.18]$$

,where $k \neq l$ and M is the set of design options $\{1, 2, ..., m\}$

Similarly, the evaluation concordance index is derived as shown in Equation 6.19, representing the net support that a_k dominates all other alternatives based on the evaluation information given by matrix R given in Equation 6.12.

$$e_k = e(a_k) = \sum_{\substack{l=1 \\ l \neq k}}^{m} (e_{kl} - e_{lk}) \qquad k=1,\ldots,m \qquad [6.19]$$

, where e_k is the total support for alternative k, as derived from the pairwise comparisons expressed in Equation 6.18.

Finally the discordance index measures the evidence <u>against</u> the inequality $k > l$, based on evaluation and preference information obtained from the weighted, normalised Z matrix (Appendix VI; Table 4).

$$d_{kl} = \sum_{j \in D_{kl}} |z_{kj} - z_{lj}| / S_d \qquad [6.20]$$

,where d_{kl} represents the net discordance with respect to the inequality k>l.

$$S_d = \sum_{j=1}^{n} \max_{k,l \in M} \{|z_{kj} - z_{lk}|\} k=1,\ldots,m$$

, so that $0 \leq d_{kl} \leq 1$ for any (a_k, a_l).

$$d_k = d(a_k) = \sum_{\substack{l=1 \\ l \neq k}}^{m} d_{kl} - d_{lk} \qquad k = 1, \ldots, m \qquad [6.21]$$

The expression (d_{kl} - d_{lk}) quantifies the net disagreement with the assumption that alternative k is superior to alternative l, with respect to k's performance against *n* attributes.

Once the three net indices have been constructed, a preference matrix can be assembled from these indices, where alternatives are selected according to their performance within the preference space p(a), e(a) and d(a). The preference matrix thus represents an aggregated form of the original decision matrix. Elements of the preference matrix may be weighted to reflect the decision maker's confidence in the preference information and the evaluation information, and should conform to the following relationship:

$\lambda_1 + \lambda_2 + \lambda_3 = 1$, and $\lambda_1 + \lambda_2 = \lambda_3$

If both sources of information are regarded as equally reliable then the values will be assigned as follows:

i.e. $\lambda_1 = 0.25$, $\lambda_2 = 0.25$, $\lambda_3 = 0.50$

6.5.10 Application of CODASID to the Case Study

CODASID was applied to the produced water treatment system using the same decision matrix (Table 6-1). Similarly, weights derived from the combined entropy method were used to obtain a preference structure as described in Section 6.5.8. The normalised decision matrix and weighted normalised decision matrix are derived using Equations 6.11, 6.12 and 6.13, and the resulting data is presented in Appendix VI, Tables 3 and 4.

The preference concordance index, the evaluation concordance index and the discordance index are constructed using Equations 6.16, 6.19 and 6.21 respectively and the resulting data is presented in Appendix VI; Tables 5, 6 and 7.

The three indices are aggregated in the preference evaluation matrix (Appendix VI, Table 8), where p(a), e(a) and d(a) effectively become the decision attributes of the preference evaluation matrix. The closeness to ideal is evaluated using TOPSIS Equations 6.2, 6.3 and 6.4.

Table 6-8: Ranking of Design Alternatives Using CODASID

Description of alternative	Ci Value	Rank
1 : Base case	0.8937	5
2 : 2000 bpd oil removal capacity from year 3	0.8875	7
3 : 6000 bpd oil removal capacity	0.9790	1
4 : 6000 bpd oil removal capacity from year 3	0.9682	2
5 : 2000 bpd day 1; 4000 bpd from year 3.	0.9005	4
6 : Base case plus heavy metal precipitation	0.0000	8
7 : Resurrected well injection	0.9566	3
8 : New well injection	0.8878	6

The CODASID method was then reapplied, using the Entropy-based weight systems that were applied to the TOPSIS method in Section 6.5.8 (Table 6-7).

Table 6-9: CODASID Ranking with Weight Vector Variations

Weight System	Weight Vector	CODASID Rank
Direct weights	[0.0526, 0.1053, 0.1053, 0.1579, 0.1053, 0.0789, 0.1316, 0.1053, 0.1579]	3>4>7>5>1>8>2>6
Entropy (Wj)	[0.0732, 0.0129, 0.0424, 0.0305, 0.6997, 0.0129, 0.0424, 0.0424, 0.0435]	1>3>2>4>5>7>8>6
Entropy + Eco95 (W_j)	[0.0452, 0.0080, 0.0262, 0.0188, 0.4319, 0.0080, 0.0654, 0.2619, 0.1346]	1>3>2>4>5>7>8>6
Entropy + Eco95 + Client Targets (Wj*)	[0.0432, 0.0076, 0.0501, 0.0360, 0.4133, 0.0076, 0.0626, 0.2506, 0.1288]	3>4>1>2>5>7>8>6

The heavy weight placed on attribute 5 was due to the 'all or nothing' nature of this attribute, e.g. only one option produced significant solid waste due to the precipitation process for heavy metal removal. Such extreme weighting does not capture the driver to minimise discharges to sea and is therefore not in line with the Client's targets. Wj* represents the combination of Entropy, Eco-indicator weights and the Client Targets, which produces a more balanced weight system that agrees more closely with the direct weights.

6.5.11 Application of Sensitivity Analysis to CODASID

The sensitivity of the CODASID method to variations in the weight vector was investigated as for TOPSIS, using the same weight variations shown in Appendix VI.

Table 6-10: Sensitivity of CODASID Method to Variations in the Weight Vector

Weight Vector	Ci Value	Rank
Original	0.8937, 0.8875, 0.9790, 0.9682, 0.9005, 0.0000, 0.9566, 0.8878	3>4>7>5>1>8>2>6
E++	0.8784, 0.8713, 0.9765, 0.9646, 0.8873, 0.0000, 0.9520, 0.8776	3>4>7>5>1>8>2>6
E+	0.8867, 0.8800, 0.9778, 0.9665, 0.8944, 0.0000, 0.9543, 0.8830	3>4>7>5>1>8>2>6
C+F+	0.9052, 0.8965, 0.9718, 0.9576, 0.8938, 0.0000, 0.9097, 0.8270	3>4>7>1>2>5>8>6
C- W- Ab+ G+ A+ E+	0.8326, 0.8287, 1.0000, 0.9936, 0.8876, 0.0000, 0.9381, 0.8912	3~4>7>8>5>1>2>6
C+	0.8998, 0.8906, 0.9699, 0.9549, 0.8877, 0.0000, 0.9621, 0.8389	3>7>4>1>2>5>8>6

It is apparent that the results obtained from the CODASID method are reasonably robust, maintaining the same preference order when the weight allocated to ecotoxicity is increased to 20%. Although Option 6 performs well for ecotoxicity, its poor performance with respect to the other attributes counters any positive effect this may have.

When capital cost and fuel consumption are allocated more weight (C+F+) Options 1 and 2 dominate alternative 5 which costs more than £1 million more. It is clear from the decision matrix (see Table 7-1) that design Options 1 and 2 perform well in terms of cost, which becomes more significant as the weight of this attribute increases. The three alternatives perform equally in terms of fuel consumption, so fuel consumption has not influenced the relative rank order between these three options.

For the environmentally-biased weight vector variant (C- W- Ab+ G+ A+ E+), Option 8 moves from rank 7 to rank 4. This is explained by the reduced importance placed on cost and increased importance attached to abatement capacity, focusing the weight on attributes against which alternative 8 performs well. In addition, Options 3 and 4 tie in first place.

Finally, the increased weighting of cost by 2.4% has diminished the rank of Option 5 from 4th to 6th position as it performs comparatively badly with respect to cost. Therefore the key message to capture from this sensitivity analysis is that realistic changes in the weight vector do not change the rank positions of the most and least preferred options; 3, 4 and 6 respectively. This strongly supports the adoption of Options 3 or 4 which enable an increased capacity for oil removal during treatment, prior to discharge to surface waters within the Client's limit of 12 ppm.

6.5.12 A Comparison of TOPSIS and CODASID Results

Table 6-11 shows that there is close agreement between TOPSIS and CODASID results in the case of direct weighting. The weighting emphasis on abatement capacity and ecotoxicity is offset by the lower weighted attributes cost, fuel consumption, GWP and acidification potential.

It can be seen from the sensitivity analysis that CODASID responds slightly more to changes in the preference structure. In the case of the C+ weight variant, there was no change from the original weight vector with TOPSIS. Whereas the CODASID model showed that Options 1 and 2 gained in terms of their rank order. While this significantly changed the positions of the mid-options, the extreme best and worst options remained the same. However, the Ci values resulting from the application of

TOPSIS were more widely distributed. That is to say, the difference between the 1st and 3rd ranked options is 0.0246, compared with a difference of 0.0016 obtained using CODASID. Therefore, it can be said that the rank order achieved using TOPSIS is more decisive for 1st to 7th place.

Table 6-11: Comparison of TOPSIS and CODASID Results

Weighting system	TOPSIS	CODASID
Direct Weight	3>4>5>7>1>2>8>6	3>4>7>5>1>8>2>6
Entropy	3>4>1>2>5>7>8>6	1>3>2>4>5>7>8>6
Combined Entropy	3>4>5>1>2>7>8>6	3>4>1>2>5>7>8>6

A more radical disagreement over the rank order occurs when the entropy derived weight vector is applied. The preference structure is more extremely biased to operational solid waste and the CODASID method responds with a more significant change in the ranking compared with TOPSIS, where rank positions 1, 2, 7 and 8 remain unchanged. As design Option 1 outranks 3 with respect to three of the attributes, the CODASID method has ranked Option 1 as the preferred option. Option 3 only outranks Option 1 with respect to abatement capacity. However, this outranking is based on a significant difference in the context of abatement capacity so this corresponds with TOPSIS's underlying 'distance from ideal' optimisation process.

Overall, the TOPSIS results are determined by the magnitude of difference in terms of performance and has delivered a decisive rank order that is relatively insensitive to realistic changes in the weight vector. However, CODASID produces a less decisive rank order for the first seven options, although it clearly shows that Option 6 is the worst alternative. This method shows more sensitivity to changes in the weight vector and allows weighting of the preference and evaluation indices to account for the decision maker's degree of confidence in the two types of information, providing a more thorough model of the decision.

Neither method supports the Client's preference for re-injection due to the expense, the relative energy consumption and on the grounds of eco-toxicity. It should be noted that the scores allocated with respect to eco-toxicity were based on whether the process removed the heavy metals from the environment entirely. It should be noted that this last point is a precautionary stand-point as re-injection does reduce the number of exposure pathways by sequestering the contaminants within the sea bed. However, without further information to confirm how re-injected contaminants behave in the marine environment, it was considered that a pessimistic stand-point should be taken.

6.6 The Benefits of Applying MADM to Eco-Design Selection

MADM decision support could provide the mechanism which is currently missing from the design process of the two case study companies (see Chapter 4). MADM presents a systematic basis to trade-off environmental inputs and controls as identified through the qualitative research studies (client targets, current and future legislative limits, HAZOP and ENVID actions and Engineering Design Principles), with non-environmental attributes, such as cost, and weight. Where important choices need to be made, the decision making is often undertaken within groups, such as a Value Engineering study. However, those decisions that are not recognised as sufficiently important for a group decision process are frequently taken with no formal decision support and with no documented output. As such, the decision process is subject to implicit preferences, and the variable levels of knowledge and experience of individual engineers. In order to ensure eco-design is optimised, individuals need a methodology to support decision optimisation and to produce documented output as part of an audit trail.

A decision support tool must have flexibility so that it may be applied to a wide variety of decision situations. Decision support that concentrates on design for recycling or design for environment will have limited application within the design process. The questionnaires identified that the engineers within the case study companies wished to deal with environmental issues as a fully integrated aspect of design. As such, a tool must allow the trade-off of environmental attributes with non-environmental attributes to ensure a practicable solution is found. MADM decision support allows complete freedom with respect to choice of decision attributes and as such is not restricted to environmental problems. It is already used in various forms within the design process and its use is supported by specific environmental decision making guidance, such as BPEO (Environment Agency, 1997b; Smith, 2002; Egan et al., 2003), and BAT (Environment Agency, 2000).

6.6.1 Understanding the Limitations of MADM

It should be recognised that there are important stages of decision making which come before and after the mathematical optimisation and sensitivity analysis. Much work must be done to frame the decision before mathematical analysis can take place, such as defining the decision objective, selecting the decision attributes and identifying and screening options. The choice of decision attributes is critical to the decision outcome. Defining attributes through the process of hierarchical decomposition described in Section 6.4.1 is a key activity that will allow the decision maker to enhance their understanding of the problem. In addition, the identification and screening of options is a major activity that may have to be revisited as the decision process progresses.

Prescriptive decision analysis does not purport to produce a scientifically proven result. However, it provides a system that will allow the decision maker to define explicit preferences and develop solutions systematically and rationally, helping them to gain a deeper understanding of the problem.

MADM methods, such as TOPSIS and CODASID offer no provision to account for uncertainty associated with the decision beyond the application of sensitivity analysis. Chapter 9 will examine uncertainty more thoroughly as this is often a key factor in sustainable engineering design decision making, particularly during the early stages of design. In addition, the methods considered in this chapter are appropriate when quantitative estimates are available.

6.7 Concluding Remarks

Both methods support the decision process by providing a systematic approach to option evaluation, and the use of either method will ensure that all options are compared on equal terms. It is not possible to say that TOPSIS or CODASID is the best method on the strength of one case study. However, they both have strengths which are worth highlighting. TOPSIS is computationally simpler and therefore more transparent. Simplicity is a key advantage for decisions that will be submitted to Stakeholders for comment. However, CODASID does respond more sensitively to changes in the weight vector and enables weighting of the preference and evaluation information in accordance with confidence levels.

In the context of environmental issues MADM tools, such as CODASID and TOPSIS, offer many advantages:

- MADM offers a fully integrated approach to design decision making in situations where environmental impact must be traded off against non-environmental attributes.

- A MADM approach addresses the lack of eco-design decision making mechanism aimed at the individual design engineer, as identified for the case-study companies in Chapters 4 and 5. In addition, the methods presented here could support BPEO and EIA decisions with improved use of the information provided by the matrix compared with the Simple Additive Weighting model. However, the improved use of information comes at the expense of simplicity, and therefore transparency of the decision may be lost.

- Preferences and evaluations are made explicit and therefore assist the documentation and audit processes.

- CODASID offers a method that makes full use of the information, allowing the decision maker to adjust the weights in accordance with the decision makers confidence in the preference and evaluation information.

- TOPSIS is computationally simple and provides transparency in terms of the decision outcome.

- A MADM approach will require the decision maker to analyse the problem in a similar manner to Value Analysis. As such, the users will be familiar with the fundamental evaluation and weighting steps.

- The output data generated during MADM could provide an eco-design output through which progress towards eco-design can be monitored and reported as part of an Environmental Management System.

7 REVIEW OF FUZZY MULTIPLE ATTRIBUTE DECISION MAKING

7.1 Introduction

The previous Chapter described a case-study on produced water that contained a reasonable level of design detail. That is to say, quantified estimates of weight, cost and emissions were available. However, it is often necessary to begin the decision making process in advance of quantified estimates, where the decision makers only have a subjective appreciation of the comparative performance of options with respect to attributes. This subjectivity is further increased when we deal with complex or less tangible decision attributes, such as resource efficiency, potential for out of envelope events or prejudice to uses of the sea.

This type of problem has often been solved using pairwise comparisons to generate an ordinal ranking of options. However, fuzzy sets can offer a more advanced approach to evaluating subjective attributes and dealing with the associated imprecision without the incidental loss of information which often arises with ordinal ranking.

This Chapter summarises the principles behind fuzzy decision making and outlines why this approach has particular relevance to eco-design and sustainable design.

7.2 Fuzzy Sets and Decision Making

Fuzzy sets and their basic properties were introduced by Zadeh (1965). The application of fuzzy sets to decision making in an uncertain environment was initially explored by Bellman and Zadeh (1970), expressing decision criteria or attributes as fuzzy subsets.

Fuzzy Multiple Attribute Decision Making (MADM) enables the treatment of uncertainty relating to evaluations and weights. The classical MADM model has been modified for fuzzy applications using two approaches; the rating or combinative approach and the outranking approach. MADM is adapted for imprecise evaluations to be expressed as degrees of set membership rather than using crisp values as shown in Chapter 8.

7.3 Linguistic Variables in Decision Making

Interest in using fuzzy sets has provided the foundation for expressing decision variables linguistically as opposed to using crisp numerical values. Linguistic variables are expressed as words or sentences in a natural or artificial language (Zadeh, 1975[a]), and are represented as fuzzy sets. Membership to these sets are expressed within the interval [0, 1] which represents the degree of membership of an entity u to the linguistic variable X (for example; very good, good, medium). X is a sub-set of the base linguistic variable U (for example, option performance). X places a restriction on U, the universe of discourse, so that only a certain subset of U has membership of X. This provides the basis for fuzzy decision making and has proved to be useful in capturing the vagueness associated with humanistic systems (Cleeren et al., 1993; Novak and Perfilieva, 1998). In some cases, the underlying base variable is numerical, such as age. In this case, U may be a set of integers (1-100 years old). In other cases, the base variable itself is subjective, for example beauty.

In natural language expressions used during decision making, we frequently use the linguistic equivalent of operators. For example, a decision maker may judge an alternative to be satisfactory if *most* of the specified attributes are satisfied. *Most* behaves like a weak *and* operator, whereas the linguistic equivalent to a pure *and* operator is *all*. *All, most, many* and *at least* α are examples of Regular Increasing Monotone (RIM) quantifiers. That is to say, the degree to which x satisfies the linguistic quantifier Q increases as x increases. RIM quantifiers are the most appropriate group of quantifiers as they imply that the more attributes that are satisfied, the better the solution (Yager, 1996).

$Q(0) = 0;\ Q(1) = 1;\ Q(x) >= Q(y) \text{ if } x > y$

The interpretation of linguistic quantifiers is further refined by the addition of linguistic hedges. Examples of linguistic hedges include *very* and *more or less*. In these cases, *very* behaves as a concentrator where satisfaction increases more sharply as x satisfies the linguistic quantifier. Conversely, *more or less* acts as a dilator where satisfaction increases in a more gradual fashion (Zadeh, 1975[b]). Both linguistic quantifiers and hedges are used everyday in decision workshops during the dialogue that surrounds option evaluation and attribute weighting.

7.4 Fuzzy Set Operations

Several fuzzy set operations exist that can be used to combine the evidence of two fuzzy sets during decision making. This is important when aggregating the evaluations of an option for several attributes to give a total performance measure. In addition, evidence must be combined when there is more than one decision maker, in order to produce a group evaluation.

Firstly, the union operation (logical AND or MIN operator) comprises the most pessimistic evidence in the final aggregate. Secondly, the intersection operation (logical OR or MAX operator) will produce an aggregate containing the most optimistic evidence. Thirdly, a simple averaging operation will generate the final evaluation from the mean of the linguistic evidence (Delgado et al. 1993). Finally, there is a family of operators known as the ordered, weighted averaging (OWA) operators.

OWA operations produce aggregates that fall between the extremes yielded by the union and intersection operators. Therefore the final aggregate will be a compromise between the most optimistic and most pessimistic evidence. Of particular interest to this research is the sub-group, the Ordered Weighted Averaging (OWA) operators (Yager, 1988; Yager and Kacprzyk, 1997). Evaluations are ordered, from highest to lowest score and the degree of 'andness' and 'orness' of the aggregation is determined by the composition of the weight vector (see Section 8.2.1). For example, a weight vector that emphasises the importance of the initial, high-score, evaluations will result in an or-like aggregation operation.

In Chapter 8 the fuzzy decision problem is essentially decomposed into 'option performance' and 'attribute importance'. For example, the fuzzy evaluation of an option's performance is interpreted as the degree to which the ith alternative (A_i) satisfies the jth attribute, C_j, for all attributes j=1, ..., n. Thus, $C_j(A) \in [0,1]$.

Variables, such as option performance and attribute importance, are described by type 2 fuzzy sets (Zadeh, 1975; Klir and Folger, 1988) where the membership grades of the fuzzy set are themselves type 1 fuzzy sets[1]. For example, option A_i has a degree of membership to the fuzzy variable 'very bad' with respect to C_j which relates to 'cost'. 'Very bad' is itself a fuzzy set where the grade of membership has a vague relationship to precise numerical cost values captured by the linguistic term 'very bad'. Such vagueness is typical at early conceptual design where exact cost estimates are not available and the decision makers must work with a imprecise appreciation of good and bad cost performance.

7.5 Weighting Approaches in Fuzzy MADM

In MADM, weighting is usually included to express preference structure (the corresponding importance of attributes or group members). However, the weight vector of the OWA operator confers or diminishes orness by placing emphasis on higher or lower values within the evaluation set (Yager 1997). Therefore, further adaptation of the OWA operator is required to include preference structure. Torra

1. The membership grades of type 1 fuzzy sets are expressed using precise, real numbers. For instance, in the case of the variable 'age', the membership grade of u to the fuzzy value 'very old' is between 75 and 90 years old.

(1997) defines a new combination function called the weighted ordered weighted OWA (WOWA) and discusses how this may be applied as a linguistic-WOWA. Two methods may be used to capture preference weights during an OWA operation. The first method uses an importance transform function, *G*, which combines the degree of orness associated with *W* with the preference weights *u*. This combined weight function is used to recalculate evaluation scores. Thus for an or-like operator, a score with a high preference weighting will increase in relation to the scores of less preferred options. Finally, these recalculated scores are aggregated using the weight vector *W* (Yager, 1997). This method is suitable for numerical variables and was therefore not applied in the following research chapter as the focus is on linguistic evaluations.

The second method demonstrates how importance can be directly integrated with the weights of the OWA operation using linguistic quantifiers Q (Yager, 1996). This method complements Herrera's method (see Chapter 8) as it works directly on the weights and therefore does not pose added complexity when using linguistic variables. The quantifier selected to guide the aggregation in Chapter 8 is '*most*'. It is assumed that *most* of the attributes should be satisfied by the chosen alternative and *most* group members should agree upon the attribute weight allocation. Different quantifiers will be appropriate for different problems.

$Q_{most}(r) = r^2$,where r denotes the normalised preference weights (Yager, 1996).

Transformation of the OWA vector *W* using linguistic quantifiers is also addressed specifically for linguistic variables (Herrera and Herrera-Viedma, 1997).

7.6 Fuzzy Decision Making and Sustainable Development

Decision tools based on fuzzy sets were applied to water resource management over twenty years ago (Znotinas and Hipel, 1979). The uncertainty associated with aspects of sustainable development has meant that the use of fuzzy sets is particularly pertinent. In the context of environmental systems, there may be uncertainty relating to the likelihood of an event, the imprecision of information, the quantification of values, the complexity of the system, the practical limitations of measurement and inadequacy of knowledge and information (Borri et al., 1998).

Applications have broadened to other areas related to sustainable development, such as pollution control (Silvert, 1997). In this case, the acceptability of each environmental impact was expressed as a partial fuzzy membership function, and these were combined to give the aggregated membership function which represented the total acceptability of the option. This paper discusses some of the compensatory effects of various aggregation options and relates this to regulatory compliance, a non-compensatory process.

Ducey and Larson (1999) presented a simple methodology for evaluating forest management decisions which affect sustainability. Each alternative is evaluated by three individuals against five criteria; timber supply, site productivity, water quality, wildlife and social equity. The divergence between the optimistic and pessimistic aggregates was used to determine conflict amongst the decision makers.

Cross impact matrices have been adapted to use fuzzy linguistic variables, obviating the original requirement for crisp values during the process of Environmental Impact Assessment (Parashar et al., 1997). In this paper, the positive and negative impacts of the Indian textile production industry is evaluated under various policy scenarios.

Munda et al., (1995) suggest that quantitative and qualitative variables may need to be mixed during the evaluation of alternatives and they use a fuzzy outranking MADM method to evaluate 3 alternative transport schemes using pairwise fuzzy relations. The degree of membership for each fuzzy relation was determined for each pair of alternatives, for each decision attribute. This evidence was then combined to find the degree of truth for pairwise relations, for example *a1 is better than a2*. Finally, a rank order of alternatives was achieved by calculating the net positive and net negative flows (see explanation of the outranking methods in Section 5.3.3). Similarly, a fuzzy outranking approach for environmental assessment was applied to select the optimal choice from four sinter production alternatives (Geldermann et al, 2000). In this instance, preference relations are expressed as trapezoid fuzzy intervals. These, in conjuction with a weighting vector, were used to determine a fuzzy outranking relation for each paired comparison. As for Munda's method, the net flows of preference evidence are used to determine a rank order. As this is a direct aggregation method, the aggregated fuzzy judgements must be defuzzified using the Centre of Area method. The decision attributes in this paper were purely environmental and based on impact categories from Life-Cycle Analysis.

7.7 Fuzzy Group Decision Making

Decisions relating to sustainable design are frequently undertaken in a group setting, involving a number of decision makers from different disciplines. This ensures a broad knowledge base within the decision making team which is necessary due to the diversity of attributes and information that will be discussed.

Group decision making is a dynamic process, involving changing levels of information, participants' preferences, concealed motivations, tactics, aspirations and emotions. Classical, rational models of decision making are ill equipped to capture such humanistic complexities. However, if one accepts the limitations of any normative or prescriptive group decision making model, it is still possible to support this high level cognitive process with a systematic decision making methodology (Jelassi, 1990).

Some aspects of group dynamics are not conducive to obtaining the best solution in the search space. For example, choice shift or *risky shift*, group polarisation, groupthink and deleterious interpersonal processes may all reduce the quality of the final decision. Some of these problems can be reduced by strong facilitation of the group discussion or by the use of decision methodologies, such as the Delphi method. This method combines multiple evaluations, however, the decision makers remain isolated from one another during the decision process (Davis and Hinsz, 1982).

The area of group decision making has inspired much research activity which spans three centuries. In France, Borda (1781) and Condorcet (1785) examined the election of a candidate through the aggregation of votes. This area was further developed in the 1800s by Dodgson (1858), Nanson (1883) and Arrow (1950). Good accounts of the development of election methods are available (Hwang and Lin, 1987; Fishburn, 1990). These methods involve the aggregation of ordinal rank evidence from multiple decision makers. However, it is often important to include the magnitude of preference, subject to data quality. The group-MADM model can be extended to aggregate multiple preference structures, facilitating a more rigorous decision analysis compared with the ordinal approaches. The application of such a method is explored in Chapter 8.

7.8 Summary

MADM methods based on numerical evaluations can generate a false sense of confidence in the resulting rank order and the numbers do not convey imprecision, a result of uncertainty and incomplete data that is often associated with early deign decisions. However, fuzzy MADM enables the option evaluation process to account for imprecision. The use of linguistic terms better reflects the intent behind the option scores and weights, which are often 'best guesses' in the absence of high quality information.

Linguistic evaluations need to be aggregated in the same way a numerical scores, in order to determine the overall performance of each option. The linguistic equivalents of these aggregation operations can be subtly modified by linguistic hedges, offering control over the degree of compensation. One type of operator used to aggregate linguistic terms is the Ordered Weighted Averaging operator, which offers a compromise between the need to satisfy all attributes, and conversely, the need to satisfy just one attribute. OWA operators will allow different levels of compensation, depending on the distribution of the weight within the vector of linguistic evaluations. In addition, value weights can be combined with ordered weights to introduce preference structure to the decision.

The use of linguistic terms expressed as fuzzy sets during the evaluation of options can be useful in the context of sustainable engineering design as imprecision and subjectivity are frequently associated with decisions in this area. In particular, the linguistic approach is effective for group-based decisions.

8 FUZZY MULTIPLE ATTRIBUTE DECISION MAKING

8.1 Introduction

Fuzzy MADM offers an alternative approach to the methods introduced in Chapter 6. Here, the preference structure and evaluations can be expressed using fuzzy variables. Each variable belongs to the universe of discourse (a universal set) U, which contains all sets relevant to the investigation. Linguistic terms can be used to describe the following fuzzy relationships encountered during decision making:

- The membership of an alternative to a performance category for an attribute e.g. 'cost', as shown in Figures 8-1 and 8-2.

- The membership of an attribute to an importance category e.g. the attribute 'cost' is of high importance.

In both cases, fuzzy sets can be used to describe the degree of membership of the alternative or attribute to the variable in question. Often, an individual will map the object to an evaluation category without precisely determining the boundaries between them. That is to say, at what quantified price a purchase become 'very good', or 'VG,' as opposed to 'good', or 'G'. It is this imprecise behaviour in decision making which is better captured by a fuzzy model rather than one that uses variables described by crisp values. Figure 8-1 illustrates the fuzzy membership of a object to a range of evaluation categories.

Figure 8-1: The Fuzzy Relationship Between an Object and Associated Linguistic Evaluation Categories

The membership of an alternative costing £x to the evaluation category 'very good' can also be represented as shown in Figure 8-2.

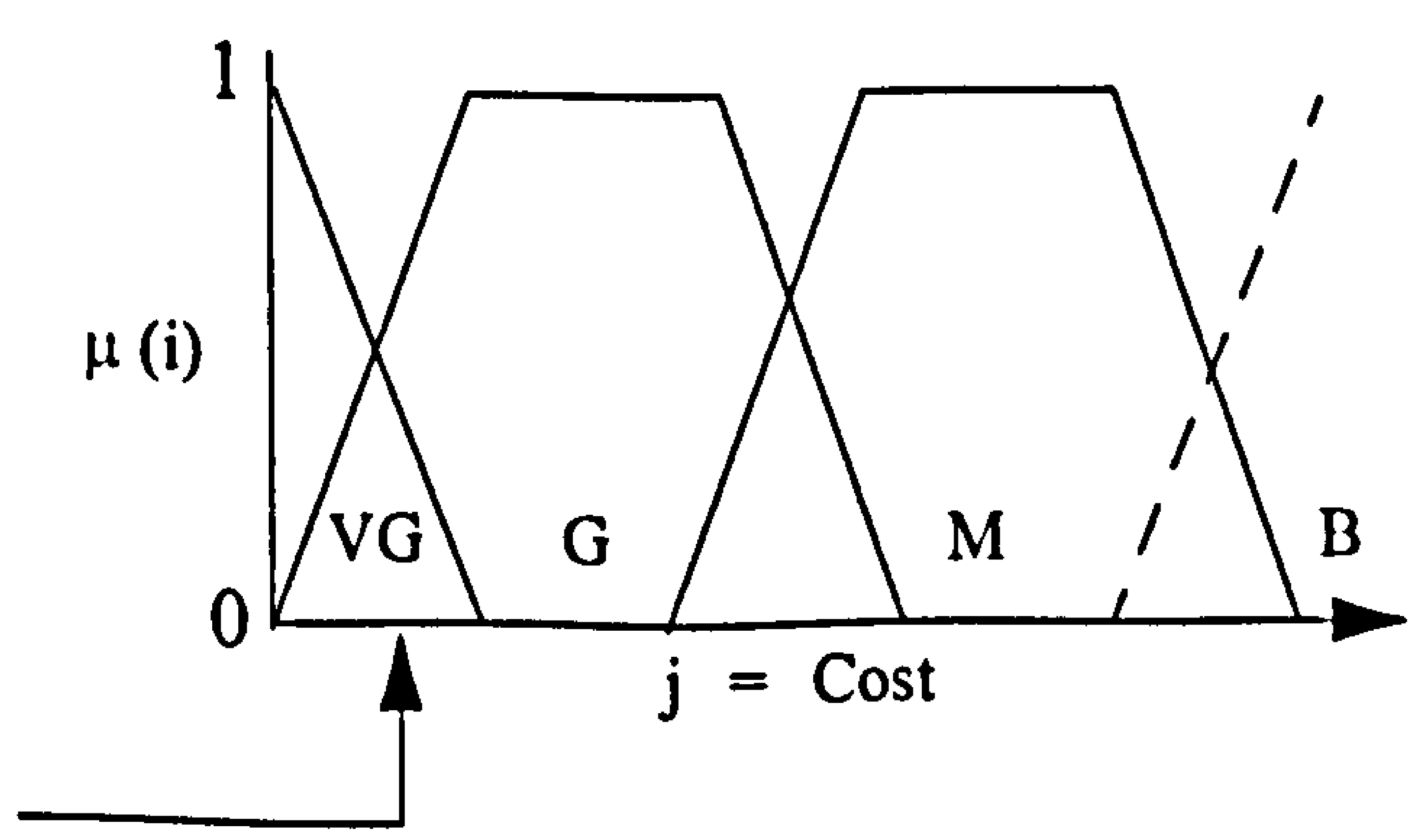
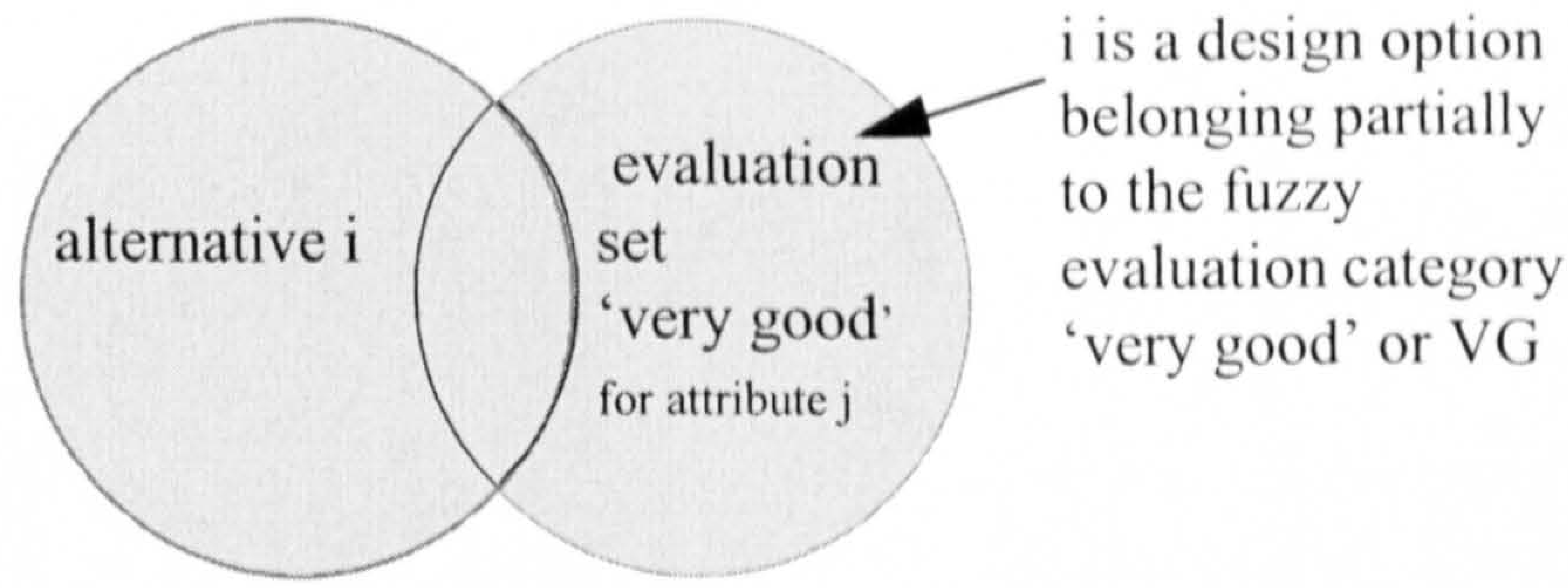


Figure 8-2: An Alternative's Fuzzy Membership to an Evaluation Category



The vagueness associated with a human judgement over whether an alternative belongs to one evaluation category or another may be described numerically (Zadeh, 1973), or as a linguistic fuzzy variable (Zadeh, 1975[a]; Zadeh, 1975[b]). The latter approach can be very useful during the early stages of design when detailed cost estimates are rarely available or when it is difficult to express an attribute quantitatively, as is the case for attributes such as visual nuisance, odour, or socio-political decision attributes.

Once the fuzzy set memberships have been determined, logical operations can be applied. For example, when evaluating a design option with respect to a specific decision attribute, the option will have membership to one or more of the linguistic variables on term set T. The term set contains all possible linguistic evaluations, for example T = [Very High, High, Medium, Low, Very Low]. Decision makers must agree what degree of resolution the term set should have and which linguistic values should be included.

As design decisions are often conducted in groups, these linguistic terms must somehow be combined to achieve a group consensus. This may be achieved using the 'and' operation (set intersection), the 'or' operation (union) or the 'andor' operation which falls between the two which are described as the Ordered Weighted Averaging (OWA) operators. The fuzzy 'and' operation is expressed by Zadeh's min operation and selects the most pessimistic judgement from the range of judgements presented. In contrast, the fuzzy 'or' operation is the equivalent to the max operation where the most optimistic judgement is selected as the combined group judgement (Yager, 1982):

$$x \text{ 'and' } y = \text{Min}\,[x, y]$$

$$x \text{ 'or' } y = \text{Max}\,[x, y]$$

The choice of operator determines the degree of compensation allowed. For example, the 'and' operation allows no compensation between attributes or group members' evaluations. If the membership functions of 'cost' and 'global warming potential' are aggregated utilising the intersection, the low values in one attribute cannot be compensated by high values in the other. If aggregation is performed using the union, total compensation is allowed, where the aggregated performance value is equal to the maximum performance obtained for either attribute.

Neither zero or full compensation is typical of a group decision making process. However, the OWA operators allow a more realistic degree of compensation where the final aggregate reflects a compromise between the most optimistic (union) and most pessimistic (intersection) evaluations.

8.1.1 The Introduction of Descriptive Decision Theory to Prescriptive Decision Models

Multiple attribute decision making using fuzzy linguistic variables allows us to introduce some elements of descriptive decision theory into prescriptive decision support. For example, descriptive decision theory addresses how people really think and talk about their perceptions and choices, (Bell et al, 1988), which rarely involves precise, quantified evaluation. People will use a range of vocabulary, syntax and semantics to convey their judgement under uncertainty. For example, when an engineer is asked to evaluate the global warming potential of a set of design options, uncertain estimates of fuel consumption, emissions and environmental consequences have to be considered. It is often more realistic to ask for an evaluation on a linguistic scale than to devise a quantitative evaluation.

8.1.2 Research Objectives

Engineering design decision making is often carried out in multi-disciplined groups, such as during Value Engineering studies. Decision making is often undertaken under time pressure and with a lack of complete information. The decision making method must therefore handle value judgements and qualitative data to truly reflect the human decision making environment. This is one of the possible applications of Zadeh's work on linguistic variables, which has been developed to allow varying degrees of importance to be attached to linguistic information (Herrera and Herrera-Viedma, 1997).

This chapter describes a decision case-study presented to an engineering team who were asked to evaluate a set of options against a series of attributes using a decision conference. However, their evaluations were given as linguistic assessments. Comparisons were made between the directly aggregated individual assessments and the group consensus achieved in a discussion led by a trained facilitator.

The objectives of this research were to:

- Investigate the application of Herrera's direct aggregation method (Herrera and Herrera-Viedma, 1997) to an industrial case-study comprising environmental considerations
- Evaluate how closely the direct aggregation method approximates the group consensus evaluations reached through discussion
- Compare the results from the direct aggregation method with two original, non-fuzzy ranking methods.

8.2 Herrera's Direct Aggregation Method

Firstly, the term set is constructed. For example, [VH, H, M, L, VL] where each term represents a fuzzy evaluation category, e.g. very high, high, medium, low, very low. The number of terms in the term set determines the resolution of the linguistic assessment. For example, a term set with eleven labels allows the decision maker to be fairly precise about his or her answer, as opposed to selecting from a set which only contains high, medium or low, which may not adequately convey the discriminatory power of the decision makers' natural language. An odd number of terms are usually presented to offer a mid-point evaluation.

Linguistic evaluations can be modelled as fuzzy sets and it is considered that linear trapezoidal membership functions offer a reasonable representation. Trapezoid membership functions (Figure 8-3) are described by the four-tuple (a_i, b_i, α_i, β_i); the coordinates of the membership function. Therefore, the linguistic terms in the term set each represent a trapezoid membership function:

VH = very high= (1, 1, 0.25, 0)

H = high= (0.7, 0.8, 0.15, 0.15)

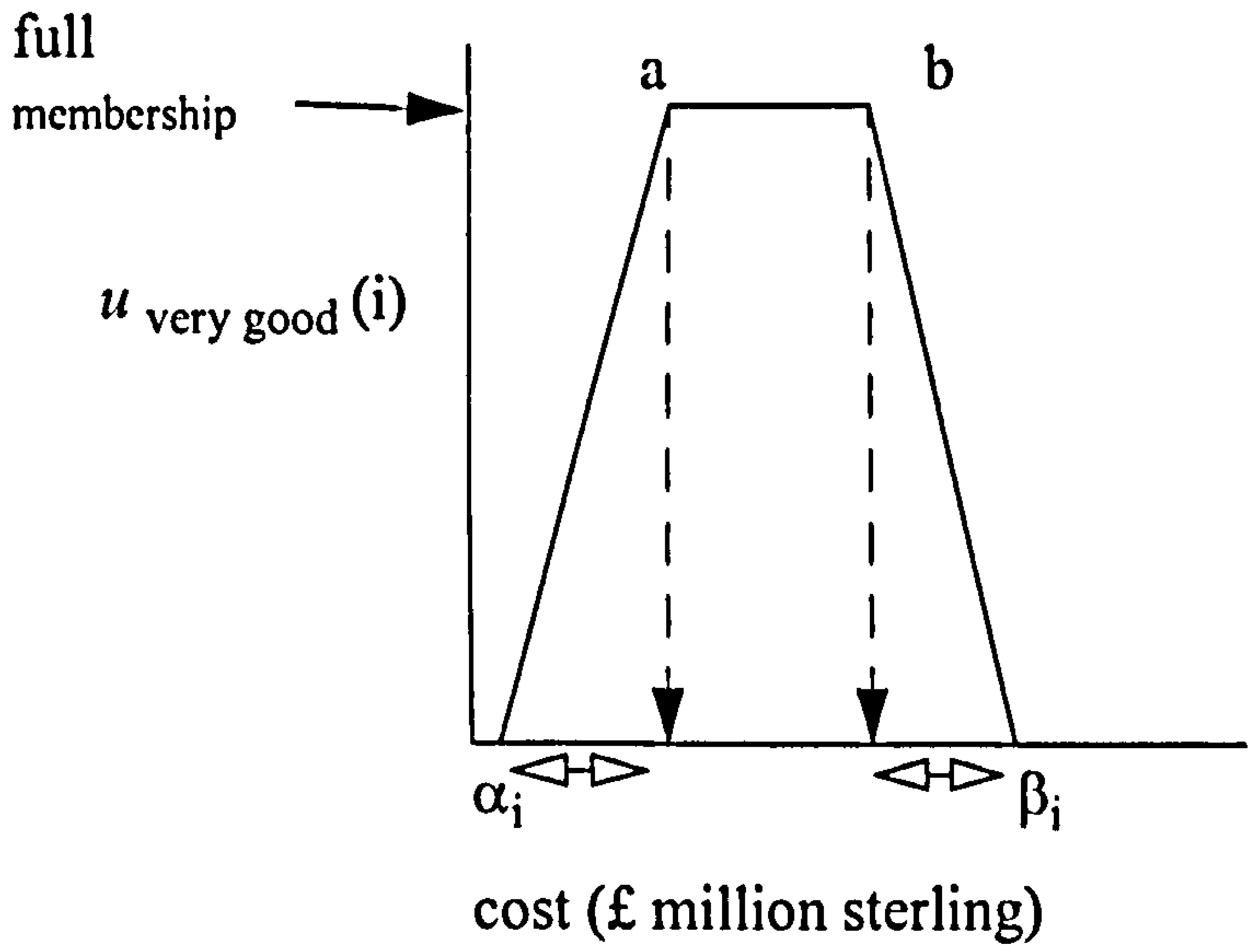
M = medium= (0.4, 0.6, 0.05, 0.05)

L = low= (0.2, 0.3, 0.15, 0.15)

VL = very low= (0, 0, 0, 0.25)

In the case of linguistic label 'H', a_i could equal 0.7 and b_i could equal 0.8 for example. Costs between these two points would have full membership to the set 'H'. The points α_i, β_i, which represent zero membership, and costs between α_i and a_i would have partial membership.

Figure 8-3: The Membership Function of Alternative *i* to the Label 'Very Good' With Respect to the Attribute *Cost*



In direct aggregation methods, the membership functions are not used for the aggregation operation. However, their role is retained in a symbolic sense. Aggregation is performed directly on the linguistic labels themselves to avoid linguistic approximation. Linguistic approximation arises where the final result does not equate to a predefined linguistic term in the term set so the nearest approximation is selected. This can potentially introduce error and incur a loss of information. Instead, the direct aggregation operation is performed using the Linguistic Ordered Weighted Averaging operator (LOWA) based on the Ordered Weighted Averaging operator (Yager, 1988).

Herrera's direct aggregation method, applied in this Chapter, comprises two main steps; normalised weight allocation and label aggregation.

Normalised weight allocation

$$W \bullet B^T = \{C^m w_k, b_k, k = 1, \ldots m\} \quad [8.1]$$

$$= w_1 \otimes b_1 \oplus (1 - w_1) \otimes C^{m-1}\{\beta_h, b_h, h = 2, \ldots, m\} \quad [8.2]$$

$$B = \sigma(A) = \{a_{\sigma(1)}, \ldots, a_{\sigma(n)}\} \quad [8.3]$$

where,

$a_{\sigma(j)} < a_{\sigma(i)} \quad \forall i < j$

and σ is a permutation over the label set A.

$\oplus$ and $\otimes$ represent addition and multiplication operations for sets.

• C^m refers to the combination operation of m labels. In this sense it describes the pairwise aggregation of linguistic labels that belong to a universal set, in order to achieve an aggregated label (see Figure 8-4). B^T denotes the reordered label vector A, in line with the order of term set T.

• Linguistic evaluations are obtained from a group of decision makers and presented as Vector A, {VL, L, VL, M} which represents a collection of linguistic judgements, e.g. Very Low, Low, Very Low and Medium.

• A is reordered to produce Vector B,{M, L, VL, VL}which corresponds with the order of descending values of term set T; Very High (VH) = 4, High (H) = 3, Medium (M) = 2, Low (L) = 1, Very Low (VL) = 0.

• Each evaluation is associated with a weight which travels with the linguistic label during the reordering step, shown later in Table 8-1.

• Aggregation commences with the combination of the two most pessimistic labels, denoted as b1 and b2. The label that arises from this aggregation operation is then combined with the next term, b3, and so on.

• W = the weight vector representing either the importance of attributes, or importance of group members. This weight may be modified by the application of a linguistic quantifier as described in Section 8.2.1 and Appendix VII.

• β_h represents the normalised weight of the b elements of vector B. This is calculated by dividing the original weights, w_h, of the elements in C^{m-1} by the sum of the remaining weights $(1 - b_1)$ so the total weight for m labels equals 1.0.

$$\beta_h = w_h / \sum_{k=2}^{m} w_k, h = 2, \ldots, m \qquad [8.4]$$

w_h = is the weight of the next element in vector W which must be re-normalised against the remaining weight (w_2, w_3, ..., w_m) once the first round of the aggregation operation has taken place. This process of weight renormalisation occurs after each combination operation, until the final aggregate is achieved.

$\sum_{k=2}^{m} w_k, h = 2, \ldots, m$ = the sum of the weight vector allocated to the remaining labels once the first weight element (w_1) has been used in the first combination.

Label aggregation

Once the weights have been renormalised, aggregation may proceed, starting with the two lowest term values first.

$$k = \min \{T_{max}, i + \text{round}(w1 * (j-i))\} \qquad [8.5]$$

where k is the new linguistic label after combination operation C^n

T_{max} is the largest term value on the term set T

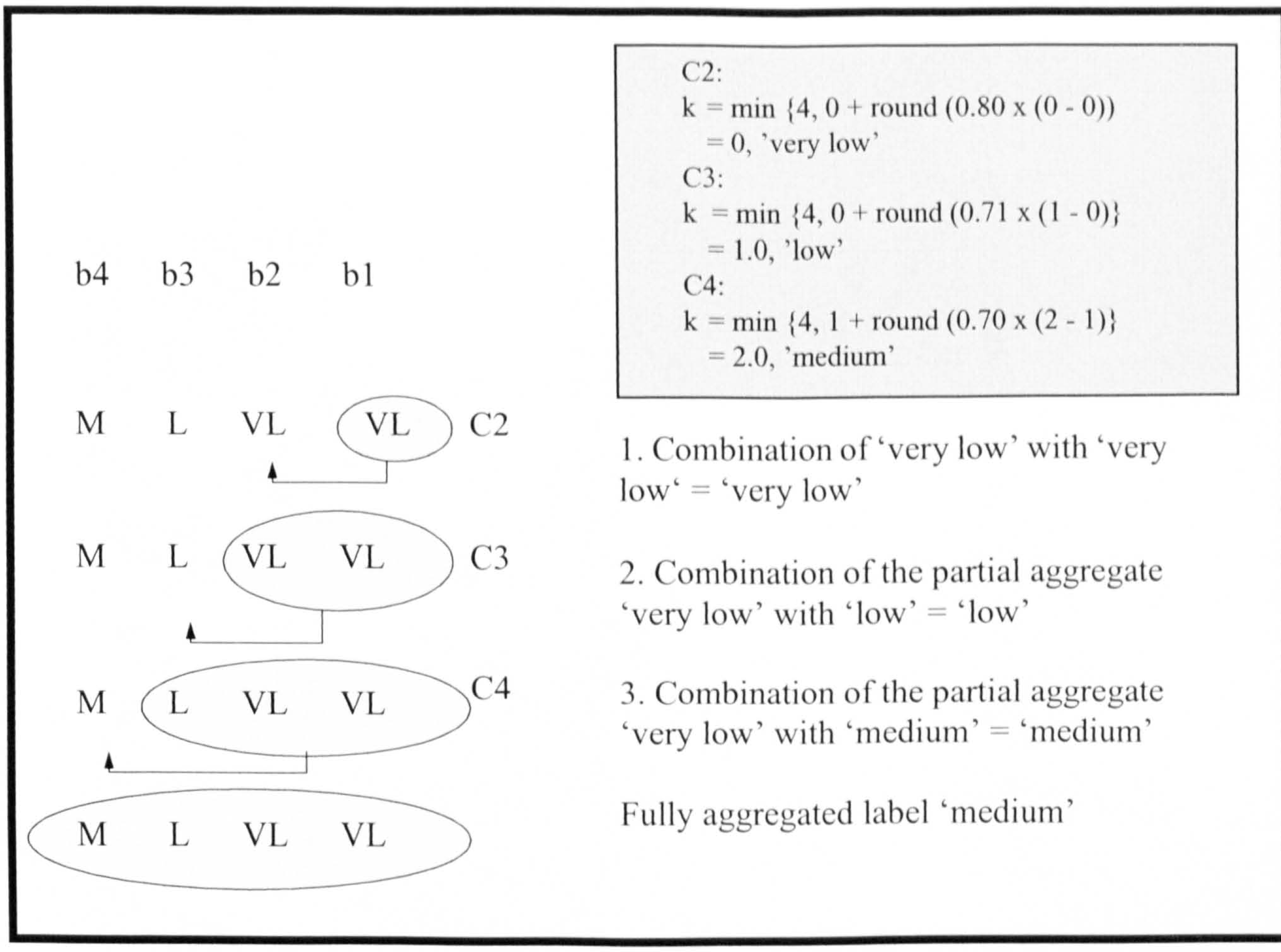
i is the term value that represents the label aggregate from the preceding combination operation.

j is the term value that represents the new linguistic term to be aggregated with i.

$j \geq i$ with respect to the order of the term values in T.

For example, in the case of the third combination, C3 in Figure 8-4, i = the aggregate of {L, VL, VL} and j = M. This results in the final label 'medium'.

Figure 8-4: Herrera's Combination Process



8.2.1 Computation of the Weight Vector During Quantifier-Guided OWA Aggregation

The role of the weight vector has an important role during fuzzy set decision making. If a high weight is allocated to the highest value label (note that the highest value label will be b1), this will ensure that an or-like aggregation operation will occur. That is to say, the most optimistic linguistic labels will have the most influence on the final decision outcome:

The weight vector for a pure 'or' operator is as follows: [1, 0, 0, 0]

Let us assume the B vector shown in Figure 8-4 is associated with the following weights: [0.6M, 0.1L, 0.1VL, 0.2VL]

It is clear that the weight factor is closer to the 'or' operator than the 'and' operator as 60% of the weight is assigned to the most optimistic label. Therefore, more compensation will be allowed during the aggregation operation. However, it may be desirable to control how much influence an important group member has on the decision if the objective is to obtain a decision that satisfies 'most' of the group. This type of situation requires a composite weight vector that takes account of the level of expertise attached to group members, in addition to accounting for the required degree of group majority.

As the degree of compensation is regulated by the weight vector *W*, it is essential to have a systematic method for weight generation. The fuzzy decision making model presented here implements the quantifier-guided approach as described by Yager (1997). Following Yager's premise that the class of regularly increasing monotone (RIM) quantifiers best represent satisfaction during the decision process, the quantifier 'most' is used in conjunction with subjective preference/importance weights to formulate *W*.

Yager (1996) represented the quantifier 'most' as $Q(r) = r^2$, as r^2 increases at an increasing rate with r. As r is the cumulative value of the weights as shown below, the $Q(r) = r^2$ quantifier encourages meeting more of the decision attributes or satisfying more of the decision makers. Yager subsequently expounded the following approach for the generation of OWA weights which enables the designation of preference weights in addition to quantifier-guided control of the degree of compensation allowed:

- Set A, composed of linguistic labels $a_1, \ldots, n$, is constructed with corresponding subjective preference weights $u_1, \ldots, n$ (relating to attribute or group member importance).

- Labels are reordered corresponding to the ordering of the term set to produce the ordered B vector, from high to low.

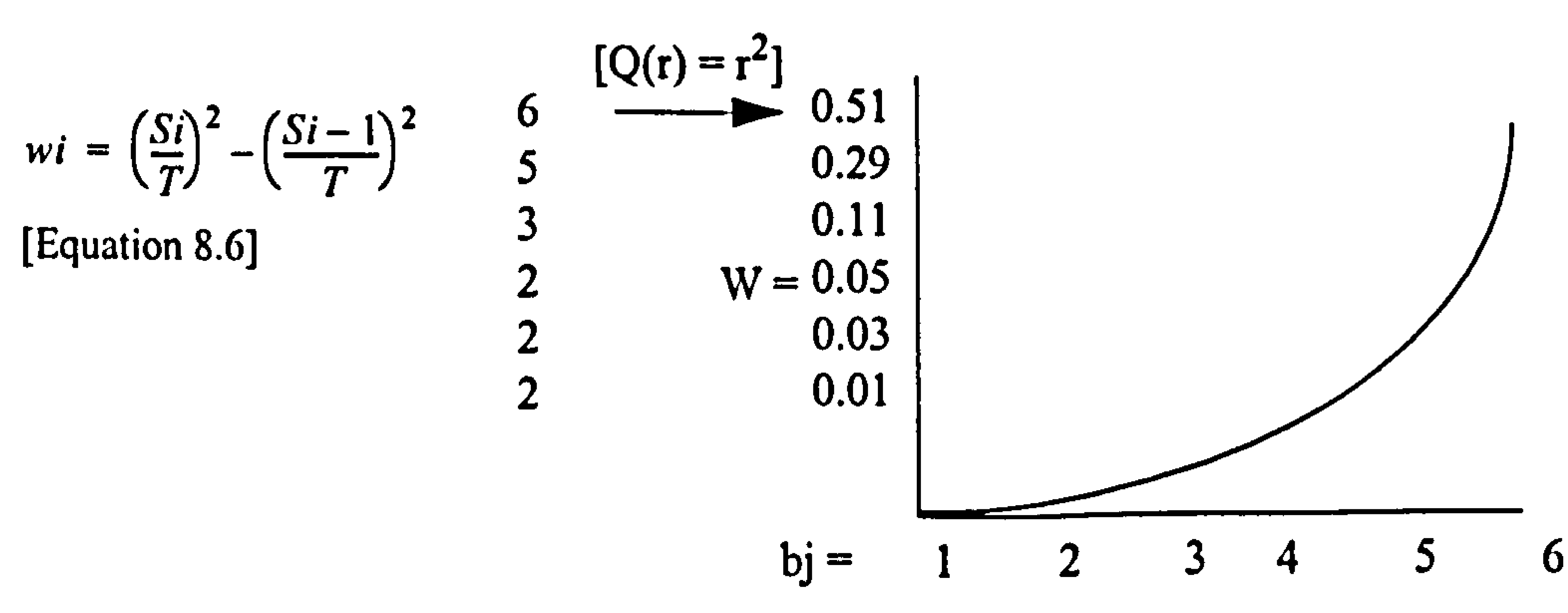
• Preference weights travel *with* the original linguistic label and are subsequently denoted by $v_1, \ldots, n$. This allows the incorporation of subjective importance weightings in addition to the 'andness - orness' concept introduced by the quantifier. A worked example is shown in Appendix VII.

$$w_i = Q\left(\frac{Si}{T}\right)^2 - Q\left(\frac{Si-1}{T}\right)^2, i = 1, \ldots n \qquad [8.6]$$

,where $Si = \sum_{k=1}^{i} v_k$ and $T = \sum_{k=1}^{n} v_k$, v_k represents the reordered preference weights and Q represents the Quantifier function.

Figure 8-5 illustrates the concept of quantifier-guided weight generation using the quantifier 'most, and demonstrates the 'and-like' nature of the operation. To facilitate this, it is helpful to normalise the weight values assigned by the decision makers, even though a separate normalisation step is not performed in the actual operation. The effect imposed by the quantifier Q(r) = r² on the weights can clearly be seen.

Figure 8-5: Quantifier-Guided Weight Generation: Q ='most'



In essence, an increasing proportion of quantifier-related weight is allocated as progressively more pessimistic judgements are satisfied and 'most' of the group members or attributes are fulfilled. By using a RIM quantifier to place weight on the most negative evaluations, this method provides a vehicle for a precautionary decision approach. However, the overall decision is governed by the most pessimistic judgements *as a function of* subjective importance weights or *v* values.

This method of weight generation was combined with Herrera's linguistic label aggregation method in the fuzzy MADM model presented in this chapter. In addition to using the mathematical representation $Q(r) = r^2$ this chapter introduces a weaker (less and-like) representation of 'most' $Q(r) = r^{1.5}$. This enabled a comparison regarding which type of quantifier-guided aggregation yielded results closest to the intuitive approach. This quantifier is referred to in this chapter as 'weak most'; the linguistic equivalent to *roughly most, practically most* or *virtually most,* where the linguistic hedge dilates the membership function of the quantifier (Schmucker, 1984). Further work would be required to determine which hedge is most closely modelled by the function $Q(r) = r^{1.5}$. It would be interesting to experiment with some of the recent modifier functions developed from empirical studies (Cleeren, et al. 1993; Novak and Perfilieva, 1998).

8.3 Method of Research

A case-study selection problem was assembled with the project collaborator, where six decision makers were asked to consider six options in terms of five attributes. The decision making workshop was organised as follows:

- Information packs were distributed three days in advance of the workshop. This introduced the problem, the definitions of the attributes and the case-study data.

- On the day of the workshop, the background to the problem was explained and evaluation scheme was introduced in a presentation.

- Individuals were asked to intuitively rank the options in order of preference, without any group discussion.

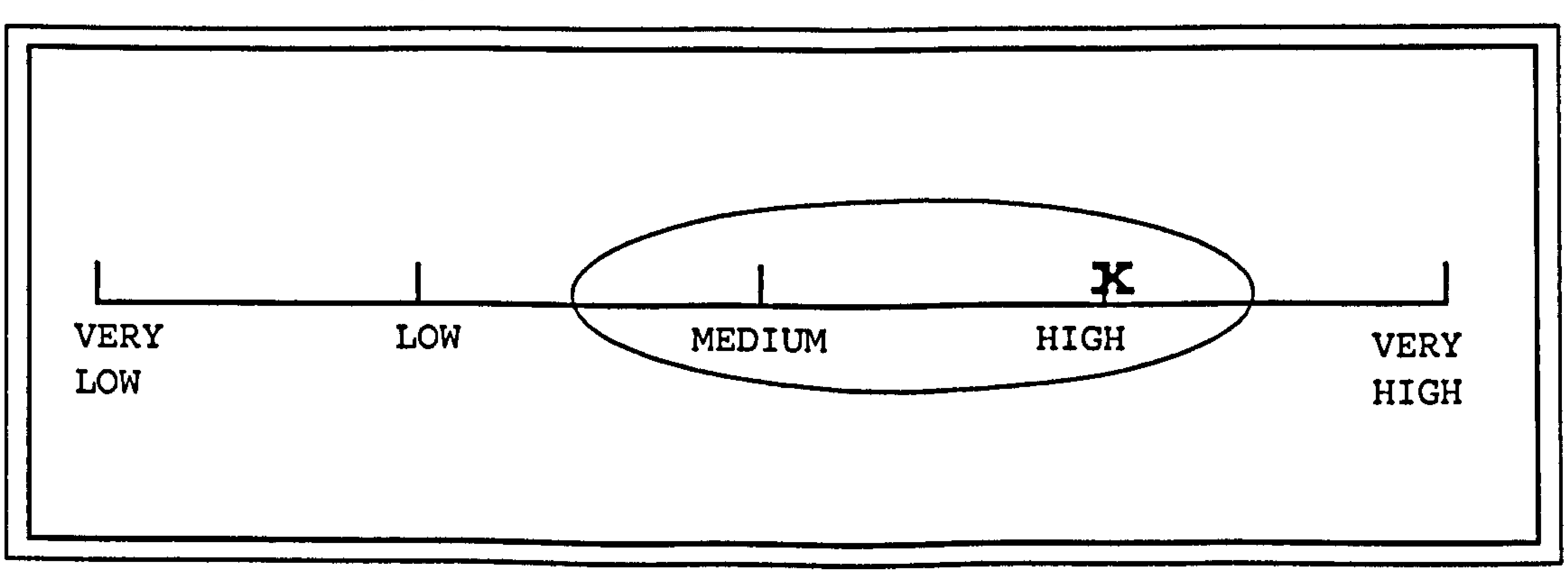
• Individuals then performed systematic assessments by evaluating each option against each individual decision attribute, as defined in the information packs and during the presentation.

• An open discussion was held, led by a trained facilitator. The group assessed the options and importance of attributes as a consensus.

• Individuals were asked to perform their final, intuitive option ranking.

Decision makers were asked to assess the importance of each attribute individually using a term set; $T_{attribute}$ = {very high, high, medium, low, very low}. They were later asked to reach a group consensus on attribute importance during the discussion phase of the programme. Group members then assessed the performance of each option in relation to each attribute using the term set; $T_{option\ perf}$ = {extremely good, very good, good, medium, low, very low, extremely low}. Decision sheets were provided based on Figure 8-6. They were also asked to include their halo of uncertainty, which indicates the decision maker's most optimistic and pessimistic judgement (extreme left and right boundary of halo) and their 'best guess' (as marked by the cross).

Figure 8-6: Example of Assessment Worksheet



8.3.1 Case-Study: Determining the Best Action in the Event of Heat Exchanger Failure

A build up of Cobalt-60 in a cooling pond was affecting the pond water return line and three heat exchangers. The condition of the heat exchange plates was unknown and the build up of activity made routine maintenance activities unsafe. Replacement of the heat exchangers was complicated as the original design was no longer available from the original suppliers. Six options were presented to the group of six decision makers, all of whom work in the civil nuclear industry as described in Appendix VII. All options were at the conceptual phase of design.

8.3.2 Selection of Decision Attributes to Meet the Decision Objective

Due to the complex nature of most sustainable decision making within LMTO industries, the choice of attributes must be made with care. A list of attributes which only captured the environmental aspects of the problem would often lead to unacceptable solutions as so many other aspects must be taken into account. For example, a solution must be acceptable in terms of the human safety risks (such as dose uptake), as well as accounting for technical factors, such as the level of pond cooling that can be achieved. In relation to this case-study, potential environmental impacts include the anticipated environmental effects and the accidental release of contaminated effluent.

8.4 Results of the Case Study Group Decision Analysis

The following fuzzy MADA approach is based around three key steps:

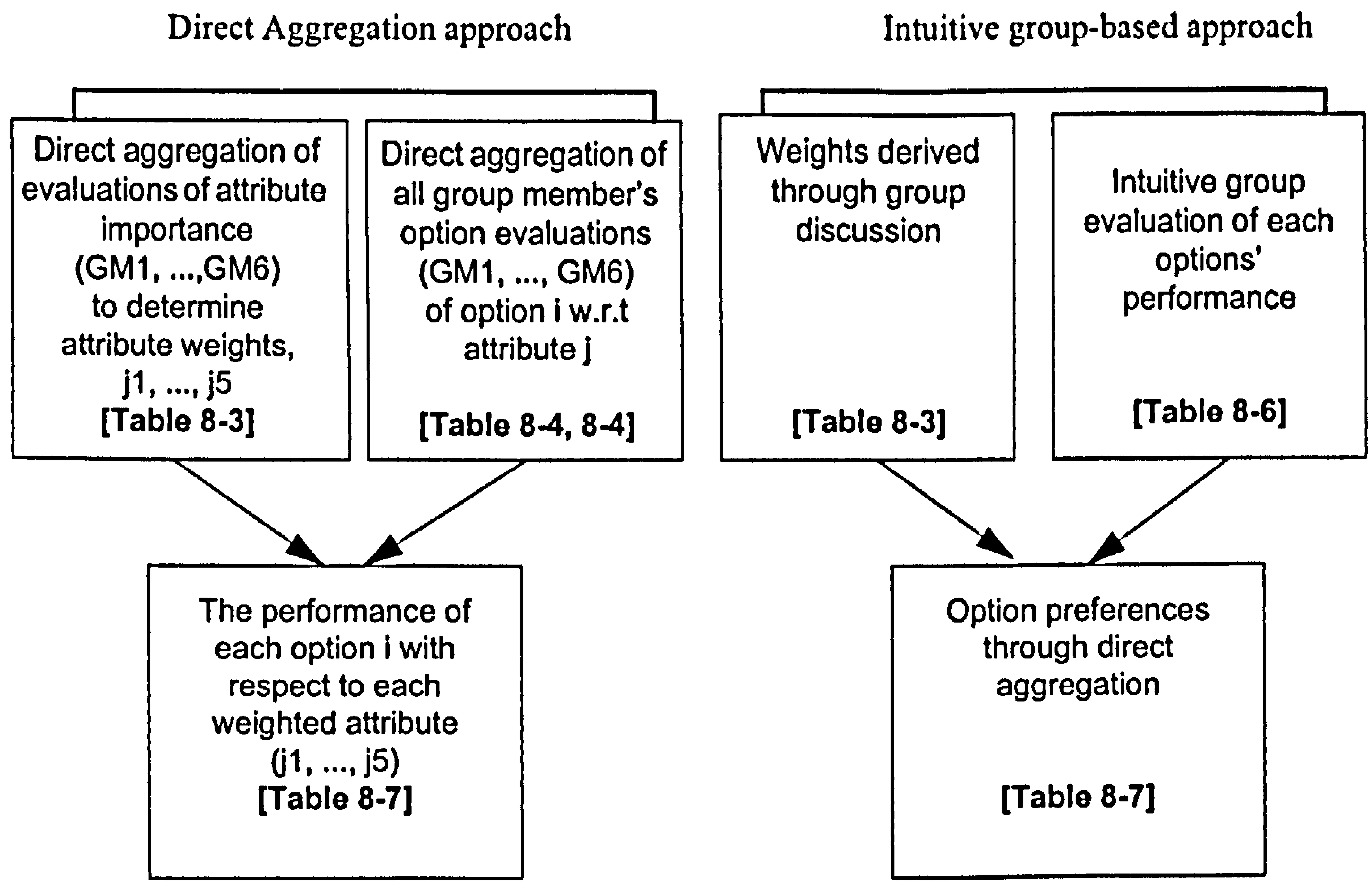
- Determining the importance of each attribute.
- Obtaining evaluations for each option in relation to each attribute.
- Combining the evaluations with the weights to determine the overall performance for each option, known as the decision function, *D(x)*.

Two decision making approaches were applied to the case study; direct aggregation[1] of group members' linguistic evaluations using Hererra's methodology and evaluations derived from facilitated group discussion. Figure 8-7 gives an

1. Note that the direct aggregation approach involves three rounds of direct aggregation. The first round determines how each single option performs with respect to each (unweighted) attribute.The second round forms a consensus linguistic weight from the six group members linguistic evaluations for attribute importance. The third combines this evidence to obtain a performance measure for each option with respect to all, weighted attributes.

overview of the decision making approach taken and indicates the relevant results tables.

Figure 8-7: A Guide to Results



8.4.1 Direct Aggregation

Results were processed on an Excel spreadsheet. Firstly, the weights are normalised for each partial vector as described in the worked example (see Section Appendix VII).

$$C^5 \{(0.010\ H), (0.030\ H), (0.050\ M), (0.113\ M), (0.288\ M), (0.510\ L)\}$$

$$= 0.010 \otimes H \oplus C^4\{(0.030H)(0.051M)(0.114M)(0.291M)(0.515L)\}$$

Renormalisation is undertaken for C5 through to C2. Then the labels are aggregated, starting with the lowest first.

The linguistic labels given for the importance of cost were obtained from the six group members. The weights are based on the relative importance of each group member (*U* = *u1, ..., u6*), modified by the quantifiers 'most' and 'weak most'.

Relative importance was defined on a scale of 1-10. GM 3 was considered the most knowledgeable as this individual was most familiar with the cooling pond design (u_3=6). GM 6 had much experience (u_6=5) and GM 1 had environmental knowledge which conferred extra weight as the minimisation of environmental impact was the primary goal of this decision making case-study (u_1=3). The remaining group members were all given an importance rating of 2, resulting in the following weight vector; U= [3, 2, 6, 2, 2, 5]. This was clearly subjective and served to illustrate how importance weights might be applied. If differential weighting is not considered necessary, all group members could be weighted equally. This weight vector was applied to both option performance evaluation and attribute importance evaluation.

8.4.2 Determining the Importance of Attributes

Table 8-1 shows an example of the quantifier-guided weighting for the importance of the attribute *cost*. The resulting weights, w_j, are fed into Herreras' aggregation method to combine weighted evaluations. The same computation was done for *radiological dose uptake, confidence in technology, resource efficiency* and *out of envelope potential.*

Where the same labels are given but the *U* weight values are different, the least important group member's evaluation is ordered first, maximising the final % of W given to the duplicated linguistic evaluation. This is illustrated by Table 8-1 by the three medium (M) evaluations. The pessimistic final evaluation 'low' (L) was due to the 'anding' nature of the quantifier and the high importance of the group member who assigned the label (6L).

Table 8-1: Quantifier Guided Weights for the Importance of Cost, Q = 'Most'

	GM1	GM2	GM3	GM4	GM5	GM6
aj	M	H	L	H	M	M
uj	3	2	6	2	2	5
Re-order from high to low:	1st	2nd	3rd	4th	5th	6th
vjbj	2H	2H	2M	3M	5M	6L
wj	0.010	0.030	0.050	0.113	0.288	0.510
Aggregated Label	L					

The computational steps for obtaining attribute weights using direct aggregation are as follows:

- Without discussion, each group member assigned their linguistic evaluation relating to the importance of each attribute *j1, ..., j5.*
- These evaluations were collated for the 6 group members.
- Group member importances (*u1, ..., u6*) were allocated as for the evaluation of option performance.
- Importance weights were modified by the quantifiers W_{MOST} and $W_{WEAK\ MOST}$ to enhance conservatism within the aggregation operation.
- The importance evaluations from GMs 1 to 6 were aggregated using Herrera's method separately for each attribute. This step was repeated twice, for Q = 'most' and Q = 'weak most'.
- The resulting directly aggregated labels for attribute importance were converted

to their numerical equivalent on the term set (*u1, ..., u5*). These weights must be expressed numerically for final option performance evaluation (Table 8-7).

Table 8-2: Uj Values

Label	Tj	Uj
VH	4	5
H	3	4
M	2	3
L	1	2
VL	0	1

The results achieved through direct aggregation were compared with the intuitive discussion results which were obtained as follows:

- A group consensus was acquired through facilitated discussion, one label for each attribute.
- Each label representing intuitive attribute importance was converted to its numerical equivalent (see Table 8-2) and utilized as the attribute importance weights (*u1, ..., u5*) for the final option performance evaluation. Final decision outcomes D(x) for each option were amassed by quantifier-guided direct aggregation.

There was exact agreement between the Q 'most' and Q 'weak most' guided aggregates. Furthermore, there was close agreement between the direct aggregates and the intuitive discussion results. *Cost* and *dose* were given a more pessimistic evaluation using the quantifier-guided technique. However, there was only a difference of one place on the term set T.

Table 8-3: Attributes Weights Achieved Through Direct Aggregation and by Intuitive Group-Based Discussion

GROUP MEMBER	COST	DOSE	TECH	RSCE	OOE
GM1 (uj[a]=3)	M	M	H	H	M
GM2 (uj=2)	H	H	M	L	M
GM3 (uj=6)	L	H	H	M	H
GM4 (uj=2)	H	VH	M	L	VH
GM5 (uj=2)	M	H	H	L	H
GM6 (uj=5)	M	H	H	L	H
Direct Aggregate (Q=most)	L	H	H	L	M
$uj_{attribute}$	2	4	4	2	3
Direct Aggregate (Q=weak most)	L	H	H	L	M
$uj_{attribute}$	2	4	4	2	3
Evaluation from group discussion	M	VH	H	L	M
$uj_{attribute}$	3	5	4	2	3

a. uj = subjective importance weights

Table 8-3 shows how three methods of achieving linguistic evaluations for attribute importance using direct aggregation of individuals' values and values derived through group discussion.

8.4.3 Obtaining Evaluations for Each Option in Relation to Each Attribute.

Tables 8-4 and 8-5 show the results for the directly aggregated evaluations for option performance using the quantifier 'most' and 'weak most' respectively. Each label is an aggregate produced from the six GM judgements using Hererra's method and the same GM importance weights presented in Table 8-1, denoted as uj. Those evaluations which have changed as a result of using the weaker quantifier are underlined in Table 8-5.

Table 8-4: Directly Aggregated Linguistic Evaluations for Option Performance: Quantifier = 'Most'

OPTION	COST	DOSE	TECH	RSCE	OOE
1	B	B	B	M	VB
2	M	M	G	M	B
3	B	B	B	B	B
4a	B	VB	B	M	B
4b	B	B	M	B	M
5	VB	B	VB	VB	VB

Table 8-5: Directly Aggregated Linguistic Evaluations for Option Performance: Quantifier = 'Weak Most'

OPTION	COST	DOSE	TECH	RSCE	OOE
1	B	B	B	M	VB
2	M	M	G	<u>G</u>	B
3	B	B	B	B	B
4a	B	<u>B</u>	B	M	B
4b	B	B	M	B	M
5	VB	B	VB	VB	VB

Table 8-6 shows the evaluations of each option with respect to each (non-weighted) attribute where group members provided a consensus evaluation determined as a group, rather than individual evaluations combined ex-situ using Hererra's method.

Table 8-6: Consensus Evaluations Reached Through Group Discussion

OPTION	COST	DOSE	TECH	RSCE	OOE
1	B	B	B	VG	B
2	M	M	VG	G	M
3	M	M	M	M	M
4a	B	B	B	M	B
4b	M	M	G	B	M
5	VB	B	VB	B	VB

Direct aggregation (Table 8-4 and 8-5) produced a more pessimistic result compared with the consensus achieved by the facilitated discussion between the six GMs (Table 8-6). The 'weak most' quantifier more closely matched the intuitive discussion outcomes. In particular, Option 3 was judged to give medium performance for all attributes during discussion. However, when group members gave their individual evaluations prior to group discussion, Option 3 was considered to give bad performance for all attributes. Agreement was reached with respect to Option 4a between the intuitive discussion results and the 'weak most' guided direct aggregation.

8.4.4 Combining Evaluations with the Weights to Determine *D(x)*

In order to determine the overall preferred option, the option evaluations must be combined with attribute importance weights. In order to do this, it is necessary to convert the linguistic weights assigned to attribute importance to their numerical equivalents, as described in the last computational step of Section 8.4.2. These numerical weights are applied to Tables 8-4, 8-5 and 8-6 in order to achieve D(x) under four scenarios, as shown in Table 8-7.

Quantifier functions 'most' and 'weak most' were applied to the reordered U values (Vj) to obtain W_{MOST} and $W_{WEAK\ MOST}$ for final option evaluation, as described in Equation 8.6. For direct aggregation, the final weight values were applied to the directly aggregated option performance values in Table 8-4 and 8-5 to obtain the overall performance of each option as denoted by $D(x)$. The discussion-based attribute importance values were applied to the discussion-based option performance values (Table 8-6).

Table 8-7: Weighted Evaluations $D(x)$

Option	1	2	3	4a	4b	5
Direct aggregated, weighted evaluation Q = most	VB	B	B	VB	B	VB
Direct aggregated, weighted evaluation Q = weak most	B	M	B	B	B	VB
Group discussion evaluation Q = most	B	M	M	B	M	VB
Group discussion evaluation Q = weak most	B	M	M	B	M	VB

Table 8-7 demonstrates that the 'weak most' quantifier best matches the intuitive values reached through group discussion. Q=most guides the aggregation toward the most pessimistic evaluation set and also leads to a less decisive preference structure in this case.

Table 8-8 shows the results of the group member's ordinal ranking obtained before and after group discussion. Group members ranked the options entirely intuitively, without systematic evaluation or weighting. The group member's rank orders were combined using the Borda and Condorcet approach (Hwang and Lin, 1987) to obtain a collective rank order. This was done to provide an indicator of how discussion may have changed the original evaluation of individuals.

Table 8-8: The Comparison of Individual Rank Orders Before and After Discussion

Group member	1st Individual rank	2nd Individual Rank
GM1	-	2 > 3 > 4b > 4a > 1 > 5[a]
GM2	2 > 3 > 4b > 4a > 5 > 1	2 > 3 > 4b > 4a > 1 > 5
GM3	2 > 3 > 4a > 4b > 1 > 5	2 > 3 > 4a > 4b > 1 > 5
GM4	-	2 > 4b > 4a > 3 > 5 > 1
GM5	4a > 4b > 5 > 2 > 3 > 1	2 > 3 > 4a > 4b > 5 > 1
GM6	3 > 2 > 1 > 4b > 4a > 5	2 > 3 > 1 > 4b > 4a > 5

a. Unfortunately, only post-discussion rank orders were obtained from group members 1 and 4

8.4.5 Changes in Ordinal Preference Structure Due to Discussion

Table 8-8 shows that GM2 swapped the original rank order of Option 5 and Option 1. The discussion process led this decision maker to rank Option 5 as the worst option which conforms to the post-discussion group majority. GM5 also revised his/her decision with respect to Option 5 after discussion, indicating that new information, pressure to conform or a changed understanding of this option occurred during the discussion process. This decision maker completely revised his/her preference structure except with respect to Option 1.

8.4.6 Demonstration of Consistent Ordinal Ranking Proceeding Group Discussion

After discussion, the ordinal rank orders between the group members was highly consistent, with clear agreement on first place (Option 2), contrary to the initial rank orders. There was also strong agreement regarding second place where only GM 4 did not select Option 3. However, 3rd, 4th and 5th places diverged more, indicating a less consistent preference structure amongst the group. There were 4 votes for Option 5 and two votes for Option 1 as worst option, which was considerably more consistent than the rank orders given before discussion. Clearly, the discussion process led the group to a more consistent preference structure.

8.4.7 Comparison of Directly Aggregated Evaluations, Group-derived Evaluations and Combined Ordinal Ranking

Table 8-9 shows agreement between first and last place for all methods. One of the key differences is the strength of preference structure. The 'most' guided direct aggregation exhibited a very weak preference structure whilst consistent with the stronger preference profiles elicited through the other methods. Similarly, the group-derived consensus failed to distinguish a clear best option, which was shared between option 2, 3 and 4b. Direct aggregation guided by the 'weak most' quantifier produced a distinct first and last place. Uncertainty surrounded the preference order of the Mid-options 1, 3, 4a and 4b, in agreement with the pre-discussion ordinal ranking that revealed indifference between Option 4a and 4b. This is to be expected as 4a and 4b are very similar options so one would expect this (recollect that 4a will replace gaskets, whereas 4b will replace the entire exchanger). There was also indifference apparent between Option 1 and 5 in agreement with the 'most' guided direct aggregation.

Table 8-9: Comparison of Option Rank Orders for Each Method

Method	Rank Order
Hererra's direct aggregation (Q = most)	2 ~ 3 ~ 4b >1 ~ 4a ~ 5
Hererra's direct aggregation (Q = weak most)	2 > 1 ~ 3 ~ 4a ~ 4b > 5
Group discussion (Q = most)	2 ~ 3 ~ 4b > 1 ~ 4a > 5
Group discussion (Q = weak most)	2 ~ 3 ~ 4b > 1 ~ 4a > 5
1st individual ranking (Borda method)	2 > 3 > 4a ~ 4b > 1 ~ 5
2nd individual ranking (Borda method)	2 > 3 > 4a > 4b > 1 > 5
1st individual ranking (Condorcet method)	2 > 3 > 4a ~ 4b > 1 ~ 5
2nd individual ranking (Condorcet method)	2 > 3 > 4b > 4a > 1 > 5

Post-discussion ordinal ranking produced a complete set of outranking relationships with no indifference relations (~). This results from the close agreement between post-discussion rank orders which minimises the possibility of tied scores during the Borda and Condorcet aggregation methods.

8.4.8 Measure of 'orness'

Relative optimism or pessimism may be analysed by applying Yager's measure of 'orness'. (Yager, 1988). The measure of 'orness' or tendency towards optimistic values conferred by the aggregation quantifier-guided OWA operator can be calculated as follows:

$$orness(W) = \left(\frac{1}{n-1}\right) \sum_{i=1}^{n} ((n-i) \bullet W_i) \quad [8.7]$$

where, n is the number of elements, i is the ith term in the evaluation set and wi is the ith weight value.

- $Q_{MOST} = 0.31$
- $Q_{WEAK\ MOST} = 0.38$
- $Q(r)^{1.25} = 0.435$ (numerically less precise than weak most, simulating the difference between linguistic hedges; *most, nearly most* and *more or less most*).
- the group's intuitive weighting of subjective attribute importance = 0.544

The orness of the 'most' quantifier demonstrates that it is a strong 'and' operation. The operations guided by 'weak most' and $Q(r)^{1.25}$become progressively less 'and-like' resulting in less emphasis on the pessimistic label weights. It is interesting to note that the 'orness' of the group's intuitively-derived importance weights for each attribute essentially gives rise to an averaging operation.

Q becomes increasingly satisfied as x increases, where x represents the proportion of the decision making group. Satisfaction of 100% is equivalent to the agreement of all six GMs. The dilatory behaviour of the linguistic hedges is shown, where the satisfaction of the hedged quantifiers is greater at values of $x < 1$ compared with the un-hedged quantifier 'most'.

8.4.9 Influence of Preference Weights on the Aggregation Operation

The influence of ordered preference weights V on the weight vector W is demonstrated by Table 2 in Appendix VII. Q 'most' and Q 'weak most' were each applied to a set of six V variants to see how the order of preference weights can affect the results of quantifier-guided aggregation operations. In addition, the normalised V values were illustrated to represent weights derived without quantifier guidance. It can be seen that as the maximum V value moves from pessimistic to optimistic judgements, W_{MAX} corresponds with V_{MAX} but with a progressively decreasing magnitude. When 'weak most' was applied to [2,2,2,2,2,6], W_{MAX} reached a peak of 0.5. The reverse preference structure [6,2,2,2,2,2] produced a W_{MAX} value of 0.23. For comparison, the W_{MAX} achieved during the 'most'-guided operation for the V vector [2,2,2,2,2,6] was 0.6. Whereas, W_{MAX} for the reverse preference vector [6,2,2,2,2,2] fell to 0.14.

In terms of practical decision making, where subjective preference weight is placed predominantly on pessimistic evaluations in combination with an 'and-like' quantifier, W is maximised. Conversely, where subjective preference weight is placed on optimistic values it acts to reduce the influence of the 'and-like' quantifier and W is reduced in magnitude (Appendix VII, Table 2).

8.5 Discussion

8.5.1 Group Decision Making through Structured Discussion

It was not the aim of this research to investigate how decision outcomes are produced in a group as extensive work has been done previously (Janis, 1982, Belbin, 1981). Much of the work is now presented in text books (Jennings and Wattam, 1998, Brandstatter et al. 1982). However, the results show that group discussion has influenced the ranking which shows a more defined preference structure after group discussion. One cannot evaluate the use of prescriptive group decision support tools without taking into account some important benefits of group decision making. Some important influences of group-based discussion are illustrated in Appendix VII:

- Excerpt 1: Group discussion helps gain a deeper understanding in general.
- Excerpt 2: Contributions of expert knowledge helps improve information quality.
- Excerpt 3: A consensus may be formed contrary to unvoiced or overwhelmed individual opinion.
- Excerpt 4: Discussion can help dispel misunderstanding.
- Excerpt 5: Discussion helps to define attributes more precisely, ensuring that all group members make their evaluations from the same perspective.

8.5.2 Agreement and Disagreement Between Approaches

- Option performance

Quantifier-guided evaluation disagreed with the evaluations generated through group discussion due to their focus on pessimistic judgements. There was closer agreement between the operation guided by 'weak most' and the intuitive evaluations reached by the group. This observation was supported by the higher 'orness' value of this quantifier. The optimism displayed by the group's evaluations may be governed by the facilitator. He or she mentally processes the verbal dialogue and proposes a consensus evaluation label. A good facilitator will attempt to remove bias from this process. Further tests on the transcripts could examine the degree of correlation between the verbal dialogue and the final label selected by the facilitator. This kind of test could be useful during the training of a facilitator.

- Attribute importance

Agreement between 'most' and 'weak most' quantifiers shows that the difference in 'orness' has not affected the final aggregate in this case. Once again, the intuitive evaluations diverged from the direct aggregates, placing more importance upon *cost* and *dose uptake*. This provides another example of the group's tendency towards 'or-like' behaviour during evaluation. Strongly dilating linguistic hedges, such as 'more or less' may simulate the group's decision process more closely than the quantifiers applied in this case-study. Such work is worthy of further investigation but is beyond the time-frame of this thesis.

- Weighted evaluations

Increased disagreement was evident once option performance and attribute weights were combined. Although no longer a purely intuitive approach (group evaluations were subject to one round of direct aggregation), group discussion diverged from the 'most' guided evaluation with respect to Options 1, 2, 3, 4a and 4b (Table 8-7). However, 50% correlation existed between group discussion results and 'weak most' guided evaluations, further supporting the dilation of the original 'most' membership function. However, in relation to the rank orders achieved by these methods, much agreement is evident between 'most' guided aggregation and group discussion. Therefore, although the evaluations disagreed, the disagreement was consistent so that the rank order of both approaches corresponded very closely. Conversely, the rank order obtained using $Q_{WEAK\ MOST}$ disagreed with the group's discussion-based judgements over first, third, fourth and fifth place. Discordance was also evident regarding indifference relations between options which is discussed in the next section.

There was close agreement between the Borda and Condorcet methods (Hwang and Lin, 1987). In addition, there was general agreement between these ordinal methods and the other approaches in relation to 1st and 6th place. The marked difference lies with the preference profile of the mid-values.

8.5.3 Decisive Preference Profiles Mask Uncertainty

Historically, there has been criticism of the Borda and Condorcet methods where the absence of strict majorities could not be addressed in the final preference order (Hwang and Lin, 1987). However, both methods yielded strong preference profiles in this case-study, particularly after discussion. One must question whether strict majorities are essential to decision making or whether they may lead to false certainty. Table 8-9 shows that the group-derived and directly aggregated results disclosed far more indifference relations between options.

8.5.4 Ordinal Ranking Before and After Group Discussion

Borda's ranking method allocates a score to each rank and the sum of these scores represent the group preference profile. However, the method has been criticised for the equal spacing between scores. Therefore, it can be the case that an option that scores consistently for second place may out-rank an option which scores for first place several times but scores once for last place, lowering the final score of that option. In addition, the method sometimes fails to select a majority candidate (for example, 2 ~ 3). Condorcet's function places weight on options that confer majority. Pairwise majority comparisons form the basis of this method and the number of times an option 'wins' determines the final preference profile. This method may give rise to cyclical majorities (for example, 1>2, 3>1, 2>3). In this case, Condorcet offers no method for determining the best option. Both methods have the advantage of simplicity with respect to concept and computation.

Prior to group discussion, both ordinal ranking methods yielded the same result. Both methods displayed an equal preference for 4a and 4b and Option 1 and 5 share last place. After the group discussion the preference profile was better defined, although the Borda and Condorcet methods disagreed with respect to third and forth place. This demonstrated the increased influence of majority with the Condorcet method. Otherwise, there was close agreement. The results indicated that group discussion had clarified the group member's preference profiles (see Table 8-8). Consistency amongst group members increased for third and last place, demonstrating that group discussion assisted the convergence of individual opinion. This may indicate that a learning process had occurred, illustrated by the excerpts in Section 8.5.1 and Appendix VII. The phenomenon of 'choice shift' is well documented in group decision theory texts, and is explained by; information integration and social comparison (Brandstatter, 1982).

8.5.5 Comparing Non Fuzzy and Fuzzy Methods

Most non-fuzzy set based multiple attribute decision making methods do not capture vagueness and uncertainty associated with the decision. An exception to this generalisation are the outranking MADM approaches which recognise that indifference and weak majorities can be included as useful information, thus addressing uncertainty associated with the outranking relations between pairs of options.

Direct aggregation extends this view by treating decision variables as fuzzy sets, capturing uncertainty at the most fundamental level. An important feature of this method is the ability to simulate descriptive elements of decision making, that is to say, the reality of human decision making process. Vagueness and uncertainty pertaining to decision process are communicated as subtle linguistic expressions, which can be modelled by the use of linguistic quantifiers and linguistic hedges as demonstrated in this Chapter. This choice of the RIM quantifier was based on an assumed underlying logic that, in reality, the more agreement achieved between group members, the more acceptable the solution will be. Comparisons of the quantifiers 'most' and 'weak most' demonstrate how the selection of the quantifier and hedge can be manipulated to simulate the intuitive group-based evaluations. Of the 'orness' values calculated in Section 8.4.8, $Q(r)^{1.25}$ provided the closest simulation of the intuitive result.

The direct aggregation method symbolically manipulates membership functions without the loss of information and need for linguistic approximation incurred by indirect aggregation. By using linguistic approximation, one is introducing new terms to the term set which raises questions regarding inconsistency of linguistic interpretation.

The fuzzy set-based method introduced in this chapter facilitated a comprehensive model of descriptive group decision making. However, the results shown in Table 8-8 show that the results achieved through ordinal ranking provided a reasonable indicator of best and worst decision option with the advantage of computational simplicity.

The closest simulation to the intuitive group result achieved through ordinal ranking was obtained using 'most' guided direct aggregation. Yet, in terms of correlation of the unaggregated intuitive evaluations, 'weak most' guided direct aggregation offered the closest approximation.

Although these linguistic direct aggregation models provide a more comprehensive and subtle model of human decision making processes, they add more complexity. This has negative implications on the transparency of decision making and auditability which has become a prerequisite of business decision making, particularly with respect to Environmental Impact Assessment and other forms of product environmental risk assessment. However, there is scope for further simplification and method standardisation which will improve these deficiencies.

8.5.6 Simulation of Intuitive Decision Making Processes

It is reasonable to question the arguments for and against the simulation of intuitive group-based evaluations. Approximation of the group discussion-based result was used in this research as a benchmark of the various model's performance as set out in the initial objectives. However, group decision making processes are subject to pressures to conform (Stewart, 1998; Brandstatter et al. 1982) and unwarranted optimism due to shared responsibility of the outcome, a phenomenon identified by Janis as *groupthink* (Beach, 1997).

Groups have been found to produce more extreme decisions than would have been predicted from the mean of individual evaluations before the discussion was conducted (Steiner, 1982). This is known as *risky shift* and can result in extreme optimism or extreme pessimism within a group. Anomalies of group behaviour have been linked to specific cases of human error (Reason, 1990). Therefore, if individual evaluations are obtained privately after discussion, direct aggregation may combine the benefits of information integration without some of the disadvantages of reaching a group consensus.

8.6 Conclusion

Different group decision making methods have been evaluated with respect to simplicity, transparency, ability to capture human decision making processes and decisiveness of result. Classical normative decision theory does not reflect the 'fuzzy' nature of human decision making, which is frequently not made up of systematic, clearly defined steps and crisp values. Preferences are often imprecise and inconsistent. Performance evaluation is often associated with a high degree of uncertainty which is not accurately modelled by ordinal ranking or numerical probability (Kacprzyk and Fedrizzi, 1990).

The use of a fuzzy linguistic scale offers advantages compared with an ordinal and cardinal scale. In the case-study, although evaluations could not be expressed by precise numbers, the decision makers felt that they could go further than determine whether one option was better than another. Individuals intuitively knew to an uncertain degree by *how much* an option was better or worse. The stronger the measurement scale, the more operations are made possible (Yager, 1982). In addition, by retaining natural language expressions, decision makers are constantly mindful that decision analysis is not an exact science.

Referring back to the objectives in Section 8.1.2, this Chapter has investigated the application of Herrera's methodology to a case-study which has potential to cause environmental impact through resource consumption and potential for an accidental environmental release due to an out-of-envelope event. One cannot conclude from a single case-study whether Herrera's methodology offers superior results. However, it is possible to confirm that, in this case-study, Herrera's methodology reflects the group discussion-based outcome more closely than the ordinal ranking methods. In addition, uncertainty between options is evident in the final result as it is presented as a fuzzy linguistic variable. This supports the premise that the use of fuzzy linguistic variables captures some of the descriptive traits of group-based decision making. It is possible that the divergence from the discussion-based results may confer advantages by eliminating unjustified conformity and optimism. It is therefore suggested that a group discussion is used to clarify aspects of the decision problem and to provide a platform for the introduction of expert knowledge. This can then be followed by private individual assessment, capitalising on the strengths of both methods.

The utilisation of linguistic variables makes it more difficult for the decision makers to anticipate the outcome of operations upon the linguistic terms. This has advantages as it is more difficult to manipulate the decision outcome and introduce hidden agendas.

In comparison with the non-fuzzy ordinal ranking methods, the aggregation of fuzzy linguistic evaluations using the LOWA operator enables fuller use of the evidence during the decision. Once again, there is reasonable agreement between the outcomes of these two approaches, with the exception of Option 1. As stated before, the Borda and Condorcet ordinal ranking methods only enable the decision maker to express outranking relationships. No scale of intensity is introduced, therefore Option 1 may have consistently outranked other options by a very small magnitude. Conversely, the fuzzy linguistic variable method integrates group member importance, subjective attribute importance; the decision maker's evaluations (on a scale of relative intensity), uncertainty encompassed within the fuzzy sets and the 'orness' of the quantifier-guided operator.

Potential exists for further work to extend this study beyond a case-study approach and to gain a general sense of how decisions reached through quantifier-guided aggregation of linguistic variables compares with intuitive, discussion-based decisions.

9 INTEGRATING SOCIETAL RISK PERCEPTION INTO SUSTAINABLE DESIGN DECISION MAKING

9.1 Introduction

Research into current practice indicated that societal risk perception is sometimes taken into account during design decisions but in an *ad hoc* manner. For example, some respondents from the semi-structured interviews (see Chapter 4) made the following comments:

Quote 1: Cable Selection

(researcher) Do you account for public risk perception when you are putting your strategies together?

(interviewee) Yes we would. I think at a higher level. Even at a simple level. If we use PVC cables and there is a fire then the public will see a pool of smoke over [the plant] which is not good. Whereas with low smoke and fume cables they don't see it.

Quote 2: Insulation Selection

(researcher) Has that (HAZOP study participation) had any influence from an environmental point of view?

(interviewee) [Interviewee discussed the selection of cladding materials]

- it is particularly an issue that if there were a fire near some cladding material you would get a ball of black smoke which looks bad so we have looked at the argument for using rock wool insulation material. In terms of product performance it makes the material heavier and a lot more expensive. Because a lot of our building envelope designs have to withstand extreme wind conditions and weather conditions it does not perform as well and we have to spend a lot of money making it work[1].

This interview data indicated that a more systematic method of integrating

1. Note that minimal punctuation is used because the passage is a transcription and it is best practice to minimise the amount of interpretation on the transcriber's behalf.

societal risk perception into design decisions would be an improvement on current practice.

9.2 Aims and Objectives

Risks associated with environmental and societal elements of sustainable development are often complex, subjective and uncertain, leading to some difficult trade-offs between risks and benefits (Pidgeon and Beattie, 1998). Furthermore, some of the attributes may not be easily expressed in numeric terms. For example, design decision makers may wish to consider the risk of a project, as perceived by the local population. The question of how to integrate subjective, uncertain and qualitative decision attributes with objective criteria, such as cost and reliability, must be addressed in order to resolve conflicts effectively and transparently during the design process.

This Chapter presents a methodology that will provide an indication of the level of perceived risk that may be associated with a project at an early stage of the design process. This will enable project managers to formulate an appropriate Stakeholder management plan and communications strategy, and to improve the design in terms of its perceived risk. The two aims of this Chapter are:

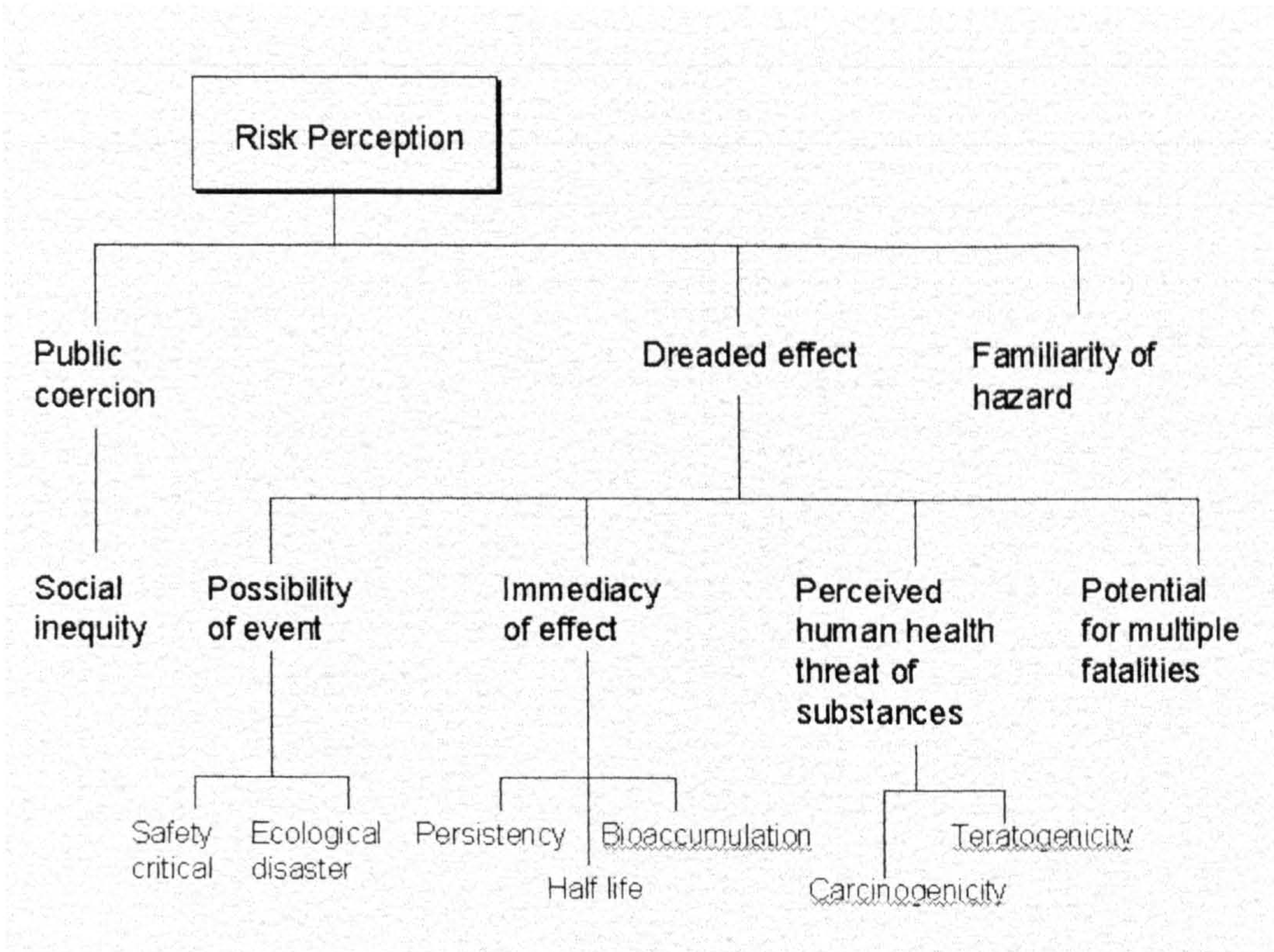
- To capture some of these factors as a set of risk perception indicators
- To apply these societal risk perception indicators to the fuzzy MADM methodology presented in the previous chapter, thus providing an holistic decision support framework for sustainable design.

9.3 The Attribution of Perceived Risk

Research in the field of cognitive psychology has provided much of our understanding of public risk perception, mainly through the use of the psychometric model. This approach was initiated by Starr (1969) who reported that the voluntariness of hazard exposure was the primary factor behind risk acceptability. Further psychometric research and behavioural decision studies have revealed that other factors are considered to augment the degree of risk attributed to an event by society (Slovic, 1980; Barr, 1996; Pidgeon, 1998, McDaniel et al, 2000; Sohn et al. 2001). Examples are, controllability, social equity, irreversibility, observability, immediacy of effect, necessity, familiarity and issue salience. This list is not exhaustive. Many different factors are hypothesised to increase risk perception.

What factors cause the public to attribute risk to an event? People are less concerned with risk probability and more concerned with risk possibility (Jackson and Carter, 1992, Walker, *et al.*, 1998). Probability deals with the occurrence of an event within a population, for example an oil tanker may have a 99.5% chance of completing its route with no major release of oil to the environment. Possibility addresses the specific question of whether this particular tanker will arrive without the occurrence of such an event on the occasion in question. During product design, risk assessment will be conducted to substantiate preventative safety measures. Resources are allocated based on the estimated frequency and magnitude of potential out of envelope events. These events are often identified using HAZOP-style workshops through a series of 'what if?' analyses. However, when our premeditated knowledge of a process or event is incomplete, the decision will be based on incomplete information. Latent omissions may then lead to a catastrophic system failure, the causal events of which could potentially have been identified but had not been recognised by the decision makers (Reason, 1990). Figure 9-1 illustrates the key factors that can contribute to the perception of risk.

Figure 9-1: Risk Perception Indicators of the Decision Framework



These contributors to perceived risk have been well-researched in psychological disciplines. The next Section shows how these factors can be evaluated and combined to determine suitable measures to eliminate or manage these risks during sustainable engineering design.

9.3.1 Public Coercion

The sense of public coercion surrounding a proposed LMTO product can contribute to the perceived risk associated with a project and can be assessed by qualifying the opportunities that the public have had in contributing to the decision making process. Onshore projects, such as incineration plants, nuclear fuel reprocessing facilities and coastal wind farms will all generate local and national public opinion.

Forecasting how many publicly available documents will be released, the level of public readership and how many focus group meetings are planned to be held will indicate the level of public involvement. These factors were used in order to establish a linguistic assessment for the degree of societal coercion associated with the project at the design and planning stage. This is based on the assumption that the greater the degree of stakeholder consultation, the smaller the sense of coercion will be. These indicators were evaluated using linguistic labels, {VH(very high), H(high), MH(moderately high), M(medium), ML(moderately low), L(low), VL(very low)}each representing a trapezoidal fuzzy set membership function as discussed in Section 8.2 of Chapter 8.

Social inequity may also contribute to the public's sense of coercion. Risk perception may be elevated if industrial developers target locations inhabited by vulnerable populations, such as groups of low socio-economic status (Barr, 1996). The social equity of the proposed development was assessed on the same linguistic scale. For example, if a section of society has already been subjected to a number of other contentious projects compared with neighbouring communities, the social inequity of the development would be evaluated as 'high' or 'very high', depending upon the nature of the current and previous developments.

Finally, the evaluations regarding the number of publicly available documents, estimated readership, organisation of focus group meetings and social inequity were combined to achieve an overall linguistic assessment for 'Degree of Public Coercion'.

9.3.2 Potential for a 'Dreaded' Effect

This indicator concerns the perceived potential severity of effects (operational release of substances or out of design envelope event) without taking into account their estimated frequency. This indicator was divided between human safety and environmental effects and was treated as a combination of four factors:

- Event possibility
- Immediacy of effects
- Perceived potential for widespread human health effects
- Potential for multiple human fatalities.

Event possibility: Members of the design team can evaluate the perceived possibility of a catastrophic human safety event on the fuzzy scale {VH, H, MH, M, ML, L, VL}. For example, will the inventory of the product contain substances that can react and cause an explosion under any circumstances? Disregarding technical risk assessment that would indicate that the probability of this event is acceptably low, the decision maker must ask himself 'is this event possible?'. The decision maker's personal construct of events may lead to a high or low risk perception depending on his or her risk taking profile; hierarchist, egalitarian, fatalist, individualist or hermit (Adams, 1995; and Thompson, 1990). Thus, it is proposed that these value judgements should be made in a group context where possible.

Immediacy of ecological effect: Research has shown that a delayed effect of an event may contribute to a higher societal risk perception and is included in Vlek's *Basic Dimensions Underlying Perceived Riskiness* (Vlek, 1996). For example, long term, global level environmental risks, such as climate change. Potential ecological effect evaluation is complex and the cause-effect relationship between human activities and ecological consequences are poorly understood, relative to human health risks (McDaniels et al., 1996). It has also been found that uncertainty relating to the probabilities and consequences of risk exposure will often reduce the public's acceptance of a risk (Pidgeon and Beattie, 1998), and such uncertainty is common in relation to delayed effects.

The exposure concentration of a pollutant is determined by the chemical and physical characteristics of a compound as well as its pathway through the ecosystem to the final receptor. A determinant of perceived ecological risk is the immediacy of a pollutant's effect. For simplicity, the methodology presented in the Chapter treats immediacy as a combination of persistency and bioaccumulation potential. Both were evaluated using the UK Environment Agency's hazard assessment as a guide (Environment Agency, 1997b).

The persistence of a substance is evaluated by determining the percentage of substance degradation in air, water or land over a specified time period. However, as the conditions of the receiving environment may be uncertain (when the release of the substance is a hypothetical out of envelope event), the persistency was assessed linguistically, again using the UK Environment Agency's method as the basis for the linguistic scale.

If relevant to the project concerned, radioactive half life may also be assessed using a linguistic scale. Traditional risk assessment would express this numerically. However, this indicator relates to the public's *perception* of persistency, measured in vague terms. It is assumed that a substance with a half life of approximately a human lifetime would be perceived by society as very highly persistent as such a substance will affect the environment of future generations. A more rigorous approach would be to empirically research the relationship between half life and the public's conjecture of persistency. However, this is beyond the scope of this research.

The variables above can be expressed using a linguistic scale, which is constructed according to expert judgements or stakeholder dialogue (Table 9-1). It is important to remember that the scale represents risk perception. For example, if a significant quantity of a pollutant remains perceptible to the public after a month, significant public concern is likely to be generated, regardless of the scientific threat posed by the substance. Even relatively inert substances can cause apprehension upon accidental release to the environment.

Table 9-1: Linguistic Scale for Substance Persistency

Risk perception	VH	H	MH	M	ML	L	VL
Radioactive half life	>80 (years)	10-80 (years)	1-10 (years)	30-365 (days)	10-30 (days)	1-10 (days)	<24 (hours)
Persistency (% remaining after 28 days)	60 - 100	40 - 60	30 - 40	20 - 30	10 - 20	5 - 10	0 - 5

The bioaccumulation potential (Table 9-2) of a substance will also partly determine the immediacy of the ecological effect if a substance is released into an aquatic environment (Environment Agency, 1997). The octanol-water partition coefficient K_{OW} represents the tendency of a substance to distribute in different phases. Hydrophilic substances are characterised by low K_{OW} values and will not accumulate significantly in living organisms. Substances with high K_{OW} values will traverse an organism's lipid membranes and bioaccumulate in fatty tissues (Baird, 1995).

Table 9-2: Bioaccumulation Potential Based on the Octanol-Water Partition Coefficient

Risk perception	VH	H	MH	M	ML	L	VL
$\log_{10} K_{OW}$	>6	5-6	4-5	3-4	2-3	1-2	<1

(Figures based on Environment Agency, 1997b)

Perceived human health threat of substances: Human safety issues related to environmental discharges can be evaluated according to well-known dreaded effects, such as cancer-causation and birth defect propensity. The 'dread' associated with these substances is increased by several factors. Their effects are perceived as indiscriminate and unfair, often affecting those who gain no benefit from the industrial activity (Barr, 1996). There is also a temporal delay between the release of a substance and the carcinogenic or teratogenic effects upon the local population. In addition, the link between the substance and its effect is usually complex and uncertain. Therefore, substances of this nature will be connected with a high degree of public intolerance and fear.

Assessment of teratogenicity, carcinogenicity and potential for widespread toxicological effect was used to provide an indication of perceived dread. For example, the teratogenic and carcinogenic properties of dioxins have been investigated using animal models and are widely perceived to present a health risk to humans. The perceived risk of a product that releases dioxins, such as an incinerator, is likely to be evaluated as VH using the linguistic scale {VH, H, MH, M, ML, L, VL}. It is important to remember that this evaluation covers *perception*. Therefore, it is not directly related to factors used in aleatory risk assessment. If a local newspaper reports that a chemical plant is producing polychlorinated biphenyls (PCBs) the public are more concerned with the perceived consequences of the discharge, rather than the quantity of substance or the estimated probability and consequences of its release (Walker et al, 1998).

Scientific guidelines for substance prioritisation exist with respect to human health effects. Specific guidelines exist for industrial sectors, such as the guidelines for *Priority-Setting Regarding Offshore Substances and Preparations* (Danish EPA, 1999). Generic guidance maybe obtained from the European Directive on the classification, packaging and labelling of dangerous substances (67/548/EEC). Risk phrases from this legislation have been used as the basis for the linguistic scale in Table 9-3. Examples of a risk phrases are:

- R46 May cause heritable damage
- R21 Harmful if in contact with skin

Table 9-3: Linguistic Expressions of Toxicological Risk

Linguistic term	Risk Phrase	Human Toxicological Characteristics
VH	R46, R47, R49, R60-64	Teratogenic, causative agents of heritable damage
H	R33, R39, R45, R48	Carcinogenic, cumulative effects and irreversible effects
MH	R26-28, R35, R40, R42	Very toxic
M	R20, R21, R23, R24, R41, R43	Toxic / Harmful by inhalation or skin contact
ML	R22, R25, R34	Toxic or harmful if swallowed or causes burns
L	R36-R38	Irritant
VL	No risk phrase	No perceptible human health effects

Potential for multiple fatalities: Human safety related to possible critical physical events can be evaluated according to the possibility of failures, such as collision, explosion and fire. It is well-documented that one-off accidents that involve multiple fatalities or injuries are considered as less tolerable by the public than high frequency individual fatalities, possibly because of the different levels of perceived control (Slovic et al, 1984). This is supported by a research project prepared for the UK's Health and Safety Executive which found that the focus group subjects primarily evaluate risks in terms of consequences rather than probability (Walker et al. 1998). Therefore, design team members are able to identify multiple fatality scenarios associated with the product life-cycle and forecast the resulting dread factor as perceived in linguistic terms.

9.3.3 Familiarity of Hazard

Another psychological dimension of risk is hazard novelty. Unknown hazards, such as the potential threat of Genetically Modified Organisms (GMOs) or Bovine Spongiform Encephalopathy (BSE) are likely to generate a higher perceived risk than familiar hazards, such as smoking, automobile transport and alcohol consumption (Slovic, 1987). Table 9-4 provides a linguistic scale to help evaluate the risk contribution from this factor.

Table 9-4: Novelty of Hazard

Linguistic assessment	Hazard novelty
VH	Totally new hazard
H	Hazard previously unknown to country
MH	Hazard previously unknown to region
M	Hazard previously known of but not personally experienced
ML	Hazard rarely experienced by individuals
L	Hazard experienced by individuals annually
VL	Hazard experienced personally, daily or weekly

The combined assessments relating to the societal risk perception indices illustrated in Table 9-5 can help predict the product's total perceived risk at conceptual design. The case-study which follows demonstrates how linguistic evaluations were aggregated to form a combined risk perception evaluation which may then be traded off against other design criteria during design decision making and used for the comparative assessment of alternatives.

9.4 Linguistic Aggregation

Zadeh, (1975a) introduced the concept of a linguistic variable, where H denotes the linguistic variable, for example 'teratogenicity' and T(H) is the term set of H on which H is evaluated, for example, very high, high, medium. The term set is a scale of natural language expressions which the decision maker uses to capture his evaluation under uncertainty (refer to Chapter 8). However, as risk perception represents a negative or undesirable performance index, two modifications were made to the methodology presented Chapter 8:

- The term set T was reordered as follows: VH = 0, H = 1, MH = 2, ..., L = 5, VL = 6
- When ordering the B vector (see Chapter 8, Section 8.2), pessimistic values must be placed on the left. In this instance, high measures of risk perception must be placed on the left as it is a negative indicator. This ensures that $j > 1$, as stipulated in Chapter 8, Equation 8.5.

This demonstrates how the methodology can be used for both positive and negative performance indicators. Alternatively, one could convert the risk perception indices to a positive index, for example public risk acceptability.

Firstly, the term set T was constructed; $\{VL, L, ML, M, MH, H, VH\}$. The number of terms in the term set determine the resolution of the linguistic assessment. The semantic of the terms is given by a fuzzy value in the interval [0, 1]. It is important to remember that the linguistic terms represent a fuzzy variable that could be described graphically as a membership function. As linguistic evaluations are only approximations it is considered that linear trapezoidal membership functions offer a reasonable representation.

The aggregation operation is performed using the quantifier-guided LOWA operation as described in previously in Chapter 8. As long as the evaluation labels are ordered in Vector B from optimistic on the left to pessimistic values on the right, $Q(r)^2$ will place more weight on the pessimistic values, encouraging an 'and-like' aggregation operation.

The linguistic assessments may be derived as a group consensus or by an individual, such as a reputation manager or senior project engineer. Similarly, the importance weights (u_i) of risk perception indices must be agreed upon in a reasoned and transparent process. Weights and evaluations could also be obtained directly from stakeholders during a stakeholder dialogue meeting.

Once the aggregated risk perception index has been achieved this may be considered an end-point in itself, enabling the direction of resources toward public consultation processes or design alterations. Alternatively, this may be then applied to a multiple attribute decision making process as described in Chapter 8. In this instance, the linguistically expressed qualitative measure of public risk perception is traded-off against other decision attributes in order to identify the satisficing solution. Vlek and Keren (1992) describe this strategy and the potential for benefit-risk traps, where benefits or risks are given excessive weighting due to variable clarity relating to presentation, perceptual-cognitive limitations, marketing pressures or disproportionate salience.

9.5 Hypothetical Example (based on Environment Agency Report, 1997)

A proposal was under review to design and build a new incineration plant for the disposal of BSE (Bovine Spongiform Encephalopathy) infected cattle carcasses and OTMS (Over Thirty Months Scheme) cattle carcasses. The facility would be fueled by gas oil and would burn an estimated 1.1 tonnes of animal waste per. hour. The plant would produce solid, aqueous and air borne emissions containing a low concentration of prion protein, dioxins, organic matter, NO_x, SO_x, carbon monoxide and carbon dioxide. An independent risk assessment considered that the infectivity in waste streams would be negligible as the prion protein should be destroyed in the combustion chambers, designed with a minimum residence time of two seconds at 850°C.

The company placing the bid must conduct an Environmental Impact Assessment in accordance with the Town and Country Planning (England and Wales) (Environmental Impact Assessment) 1999 Regulations in order to obtain local planning permission. This places a requirement on the developer to publish notices in the local press indicating where the public may obtain a copy of the project's Environmental Statement. The public may then make objections to the planning authority. In addition, a public inquiry may be held by an independent appointed by the Secretary of State. The developer does not propose to hold stakeholder meetings with local residents unless specifically requested to do so by members of the community. The facility would provide a small number of jobs and produce electricity. National media coverage related to the BSE crisis was moderate following a recent high level campaign. Furthermore, increasing beef sales indicated that issue salience was falling. Social inequity would feature strongly in relation to this project as the proposed location was in a heavily industrialised area of low socio-economic status.

Using the social risk perception indicators, a social risk perception profile was constructed using linguistic evaluations from term set T (Table 9-5). In a real application, this process could be conducted by the project Board including representatives from the engineering design team.

T = [VL, L, ML, M, MH, H, VH]

Table 9-5: Linguistic Evaluations of Each Risk Perception Indicator

Code	Societal Risk Perception Indicator	Evaluation	Weight
Pc	Lack of public consultation	M	5
Si	Social inequity	H	5
Sc	Perceived possibility of safety critical event	MH	3
Ei	Perceived possibility of major ecological impact	M	2
Pr	Persistency	ML	2
Hl	Length of half life	-	
Bp	Bioaccumulation potential (K_{OW})	VL	2
Ht	Perceived human toxicity	VH	5
Hn	Hazard novelty	VH	3

A = [M, H, MH, M, ML, VL, VH, VH]

U = [5, 5, 3, 2, 2, 2, 5, 3]

B = [VL, ML, M, M, MH, H, VH, VH]

V = [2, 2, 2, 5, 3, 5, 3, 5]

The final ordered, weighted opinions (*vi, bi*) are assembled as described in Table1 of Appendix VII:

[2VL, 2ML, 2M, 5M, 3MH, 5H, 3VH, 5VH]

$Q(r)^2$ = [0.012, 0.075, 0.078, 0.185, 0.093, 0.281, 0.132, 0.143]

$Q(r)^{1.5}$ = [0.037, 0.124, 0.099, 0.196, 0.088, 0.242, 0.105, 0.109]

$Q(r)^{1.25}$ = [0.064, 0.154, 0.107, 0.194, 0.082, 0.216, 0.090, 0.092]

Aggregation was conducted using the two quantifiers analysed in the previous chapter; Q = 'most' and Q = 'weak most'. In addition, $Q = (r)^{1.25}$ was also applied as this corresponded most closely with the intuitive aggregation operation of the previous case-study group (see Section 8.5.5 of Chapter 8). It would be unfounded to hypothesise that this quantifier is representative of all group consensus building. However, it offers a useful comparison against the more pessimistic quantifier guided functions.

9.6 Results of Incinerator Case-Study

The societal risk perception indices of the incinerator project from Table 9-5 are aggregated as follows:

Pc ⊕ Si ⊕ Sc ⊕ Ei ⊕ Pr ⊕ Bp ⊕ Ht ⊕ Hn

⊕ represents the operator for addition during the aggregation of sets.

Table 9-6 demonstrates the sensitivity of the final aggregated label to the different quantifier functions. The subsequent discussion of results is based on the label ‘medium high’ as the less extreme quantifiers were found to represent the intuitive group decision making processes most closely.

Table 9-6: Aggregated Risk Perception Indicators

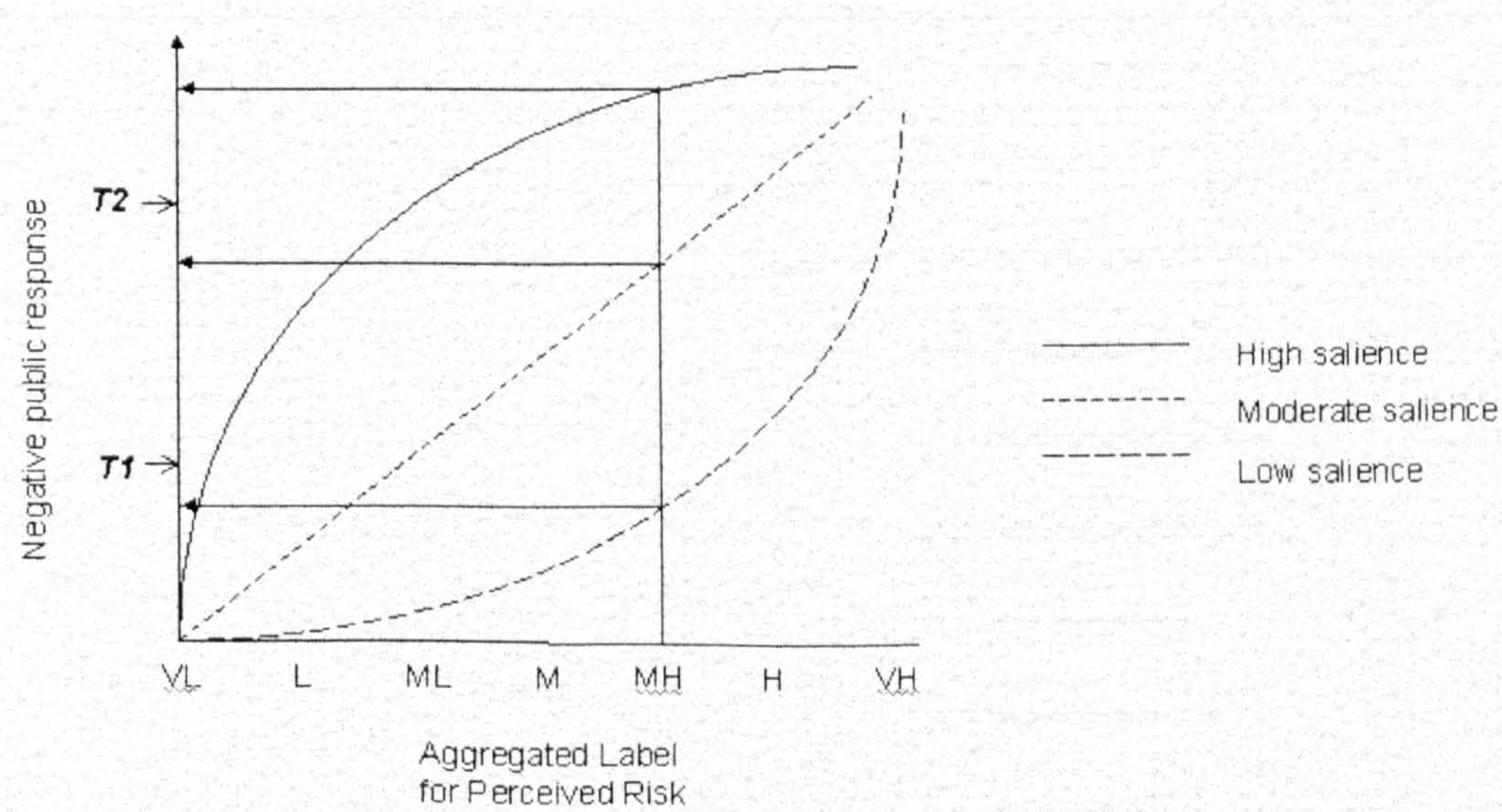
Quantifier	Aggregated Linguistic Label
$Q(r)^2$	H
$Q(r)^{1.5}$	MH
$Q(r)^{1.25}$	MH

Once the combined linguistic evaluation for perceived risk was determined, the negative public response was estimated based on three scenarios of issue salience. An issue’s salience describes how prominent an issue is with respect to a single individual or the collective mindset of a human population. Research has shown that the salience of an issue can be influenced by the amount, type and tone of media coverage that a particular event receives (Downs, 1972):

> “[an issue] leaps into prominence, remains there for a short time, and then, though still largely unresolved, gradually fades from the center of public attention”
>
> (Downs, 1972)

The threshold of concern (*T*) is the point at which the perceived risk exceeds acceptability and the perceiver (local residents or specific critical groups) determine to act. The perceiver may be an individual or a collective from a section of society. The exceedance of *T* is described as an all or nothing response (Kirkwood, 1993) and is a variable subjective measure, unrelated to quantitative risk assessment. It is a personal construct of the perceiver and is not directly related to the reality of the project impacts.

Figure 9-2: The Relationship Between Perceived Risk and the State of Issue Salience



9.6.1 How is T Determined?

Whereas quantitative risk is a static figure, perceived risk oscillates in accordance with the issue-attention cycle. It is unlikely that a project manager or communications specialist will feel confident enough to set a single threshold to represent the views of a local community or the wider public. As different subgroups within the community will have different personal constructs relating to the project, it is expected that several thresholds will be examined during a sensitivity analysis step. The following factors should be taken into account when constructing the salience scenarios:

- The potential benefit of the project to the perceiver; *if the individual will gain advantages due to the project, for example employment prospects or increased house prices, the threshold level would be set higher.*

- An individual's assessment of whether they will personally be exposed to the risk; *an individual whose family never use rail transport is not likely to take action in the case of passenger safety issues of a rail development.*

To illustrate the influence of issue salience on perceived risk tolerance, the conceptual design stage of the BSE carcass incineration plant was considered. The proposed site would be located no closer than 3 miles from the nearest residential area and the application for planning consent was ready for submission.

Firstly, the decision maker must establish the vulnerable societal groups. This is based on the critical group approach used in the safety risk assessment of radionuclide discharges, where sections of the public are considered to be particularly exposed due to their lifestyle or proximity (DETR, 2000). Stakeholder Group 1 is hypothetically composed of residents on a local housing estate who would notice minor deposits of particulates from the flue gas under certain conditions. The stacks would be clearly visible and the drinking water supplies would be taken from groundwater, a possible pathway if leakage from the plant sewer contained wash water used to clean spills of infected animal parts. This group would be unfamiliar with risks related to the incineration of infected bovine carcasses and only a small number of people would benefit from employment opportunities related to the plant.

Stakeholder Group 2 are hypothetically located 3-6 miles away and are employed mainly by the agricultural and cattle farming sectors. As such, they would have minor concerns in relation to ash particle attachment to crops and soil contamination. They are not expected to notice visible deposits of particulate matter and the plant would not visible from most of this catchment area. However, this group may suffer economically if perceived health risks attached to local produce led to reduced sales. Clearly, each Stakeholder Group will have different threshold levels of concern, shown as *T1* and *T2* (Figure 9-2).

9.6.2 Utilisation of Perceived Risk Scenarios During Product Design

The aggregated risk perception value examined under the varying salience scenarios was used to indicate whether the conceptual product could meet with public opposition. If it appears that aspects of the product may lead to exceedance of the threshold value, the decision maker must take action if he or she intends to include society as a stakeholder. The decision maker must establish the level of perceived risk which would be tolerated under various states of salience. Figure 9-2 shows that, in this example, only a perceived risk evaluation of VL will not go beyond *T1* if the issue is highly prominent.

The overall risk perception evaluation of 'medium high' signifies that this project will not initiate public action under low salience conditions. However, as the BSE issue was hypothetically considered to be moderately salient with respect to the general public, this project would be expected to generate some public action amongst the local community. Therefore, the project team or the Client may reconsider their initial standpoint with regard to public consultation.

As an issue escalates in terms of public interest, less affected Stakeholder Groups will perceive that the risk of a project breaks the threshold of risk acceptability. Therefore, the decision maker must determine who the key Stakeholder Groups are. Once the groups have been identified, along with their likely concerns, risk managers must carefully assess the salience scenarios. Once the most likely salience scenarios have been established, project management can develop risk perception management strategies for a range of conceivable situations. The scenario approach is used as the level of risk perception attached to an issue has a dynamic nature and assessment is clearly subjective. However, the framework proposed in this chapter attempts to introduce a systematic approach to this type of decision factor, whilst retaining the vague nature of the underlying variables and the intuitive disposition of the risk perception process.

9.6.3 Framework for the Assessment of Risk Perception

The LOWA aggregation process is used here to form a combined risk perception evaluation. This, in conjunction with estimated threshold levels for Stakeholder Groups and scenario prediction, form the basis of a systematic framework for the consideration of societal risk perception. The key steps are:

- Identify product aspects which may lead to unacceptably high perceived risk during the product life-cycle.
- Determine the risk perception indices relevant to the product life-cycle.
- Evaluate the product design in terms of perceived risk using linguistic expressions.
- Establish preference weights as an internal project exercise or in conjunction with stakeholders. Use preference weights to assemble the weight vector W, guided by an appropriate quantifier.
- Identify scenarios which may raise the state of salience of aspects relating to the

project life-cycle.

- Identify critical groups amongst society and estimate their threshold levels.

- Identify situations where threshold levels would be exceeded and address these sensitive aspects of product design where feasible. Where aspects of the design remain that have the potential to create significant perceived risk, focus groups should be identified and assembled as part of stakeholder consultation plan. Independent parties may be used to facilitate the discussion to avoid polarisation and the creation of a negative issue salience.

While it must be noted that the benefits of using this framework has yet to be tested empirically, the use of a systematic process offers an improvement to the current ill-defined implicit processes as identified during the semi-structured interviews in Chapter 5. There is much scope for empirical research to establish the benefits of decision making frameworks which include society as a stakeholder (Bier, 2001). Whereas much research has been done regarding stakeholder communication processes and the crafting of public messages, little has been done on developing indices for decision making approaches that include public risk perception from the outset. The framework presented in this chapter allows the evaluation of public risk perception with or without public consultation. While public polling may be suitable for large scale projects it may not be practicable for smaller scale projects. In addition, the framework may enable the project team to estimate the level of Stakeholder involvement required and to ensure that sufficient resources are allocated in terms of time, capital and expertise.

These considerations will determine the *type* and *scope* of consultation process that will be implemented, such as surveys and focus groups. The practice of public surveys is complex in terms of engaging a representative and sufficiently large sample and the opinions which are gathered are devoid of the dyamic dialogical processes which the public use to formulate viewpoints in reality (Walker et al., 1998). In addition, previous psychometric studies have been criticised for imparting too little information prior to asking subjects to make their judgements, making these studies unrealistic (Okrent, 1998). A framework presented by Sohn et al. (2001) evaluated the perceived risk associated with six options for spent nuclear fuel management based on key risk perception factors. However, this framework assumes that public polling is feasible. Furthermore, no account is taken of the oscillating levels of issue salience which can be affected by the process of public consultation itself.

Decision support frameworks formulated in order to estimate public risk perception will not account for the social dialogue which contributes to a person's assessment of risk. This is based on the argumentational model where personal views arise as constructs of interactive dialogue and argument (Walker et al., 1998). This reinforces the importance of group discussion which was examined in Chapter 8 and Appendix VII. However, the framework may provide an indication of extent of the projects societal impact and may be used to justify holding an interactive discussion.

9.7 Concluding Remarks

This Chapter has presented a framework for the consideration of societal risk perception. Risk perception is a complex psychological process and cannot be approached in a prescriptive manner. However, our knowledge of contributing factors towards the perception of risk can be broken down into qualitative indices which may be used to assess the level of societal impact associated with large made-to-order products and processes at conceptual design. A few examples of risk perception indicators have been discussed which provide the basic metrics for a proposed framework for the evaluation of public risk perception. The uncertainty inherent within these risk perception indicators have been accounted for by using fuzzy linguistic variables. Clearly, the decision outcome will not provide an exact measure of risk perception associated with a project. It is impossible to precisely predict the thoughts and fears of a local community or national population. However, a framework that encourages systematic evaluation will help a project team consider societal impacts more thoroughly. This is essential if a project team is to develop a suitable communication and consultation strategy without incurring excessive costs or project delays. It is important that such a strategy is implemented early in the design phase so that Stakeholder views may be taken into account, moving away from the Decide Announce Defend approach. As a result, the public are likely to be more supportive of industrial developments once involved as consultees in early design.

10 DISCUSSION

10.1 Introduction

Each Chapter has presented individual discussions and conclusions throughout the thesis. This Chapter aims to provide an integrated discussion that answers the high-level research aims presented in Section 1.5.

In order to do this, an over-arching sustainable engineering design framework is presented that helps to place the MADM-based approach into an organisational context.

10.2 The Consideration of Environmental and Societal Impact during Sustainable Engineering Design

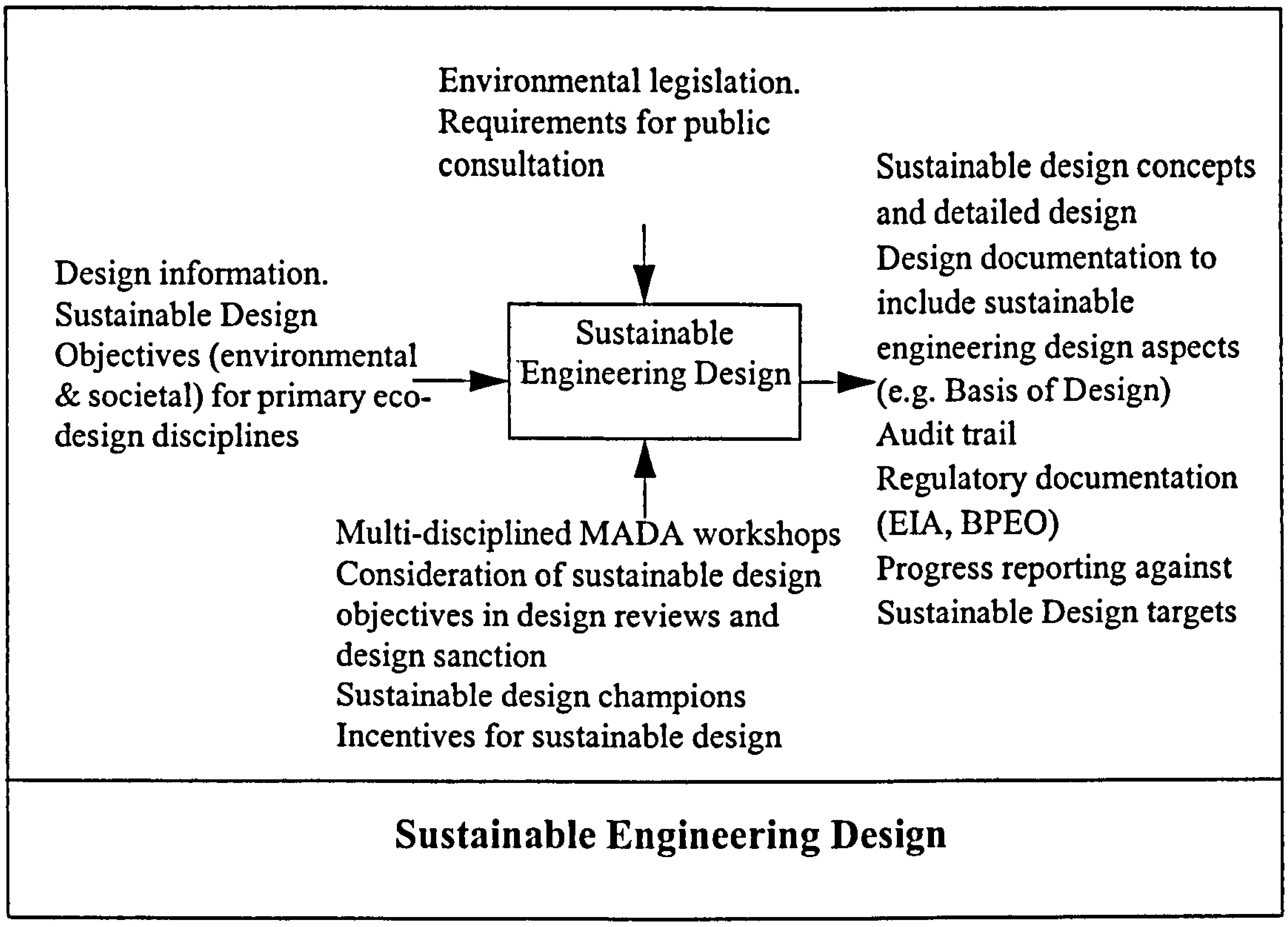
It was hypothesised that the environment is inadequately integrated during the early stages of the LMTO design process. This is supported by recent surveys that show that eco-design strategies and objectives are often vague and unclear, even in some of the world's largest companies (Charter, 2001). Qualitative research investigations were designed to test this hypothesis within two case-study organisations and several opportunities for improvement were identified. In particular, a key requirement for a mechanism to enable transparent decision making at early conceptual design was identified. Such a mechanism would need to be suitable for the low quality and availability of information that is inherent at early design, when there is insufficient data for a HAZOP (Swann and Preston, 1997) or Life Cycle Analysis (Boustead, 2000). The increased importance of environmental issues means that it is no longer sufficient to add the keyword 'environment' to a Value Engineering study (Kelly and Male, 1993), as this keyword represents an aggregation of distinct factors. The qualitative research also suggested that this mechanism would need to be supported by the provision of relevant information and environmental targets in order to deliver improved design concepts, and to provide a recorded decision trail to demonstrate how design decisions have taken environmental impacts into account.

Sustainable Development is achieved by balancing economic, environmental *and* societal factors. This balancing act is complicated by the difficulty in expressing environmental and societal factors in precise, quantifiable terms as is possible for economic factors. This could explain why these factors are inadequately captured during LMTO design. In terms of achieving Sustainable Engineering Design, the need to consider the environment during design is a relatively mature concept compared with the consideration of impacts on society. Therefore, the potential to improve the integration of societal factors into design is assumed to be even greater than the need for environmental support identified by the qualitative research. In order to address both issues, Chapters 6 and 8 demonstrate how environmental and societal attributes of perceived risk can be balanced using MADM methods. However, it was considered that attributes of perceived risk must be considered in a separate decision model as they are directly related to environmental, safety, technical and economic attributes and would lead to double-counting and inter-dependence. However, the overarching framework presented in this Chapter brings the outputs of both models together to provide an integrated framework for sustainable engineering design.

10.3 Sustainable Engineering Design Framework

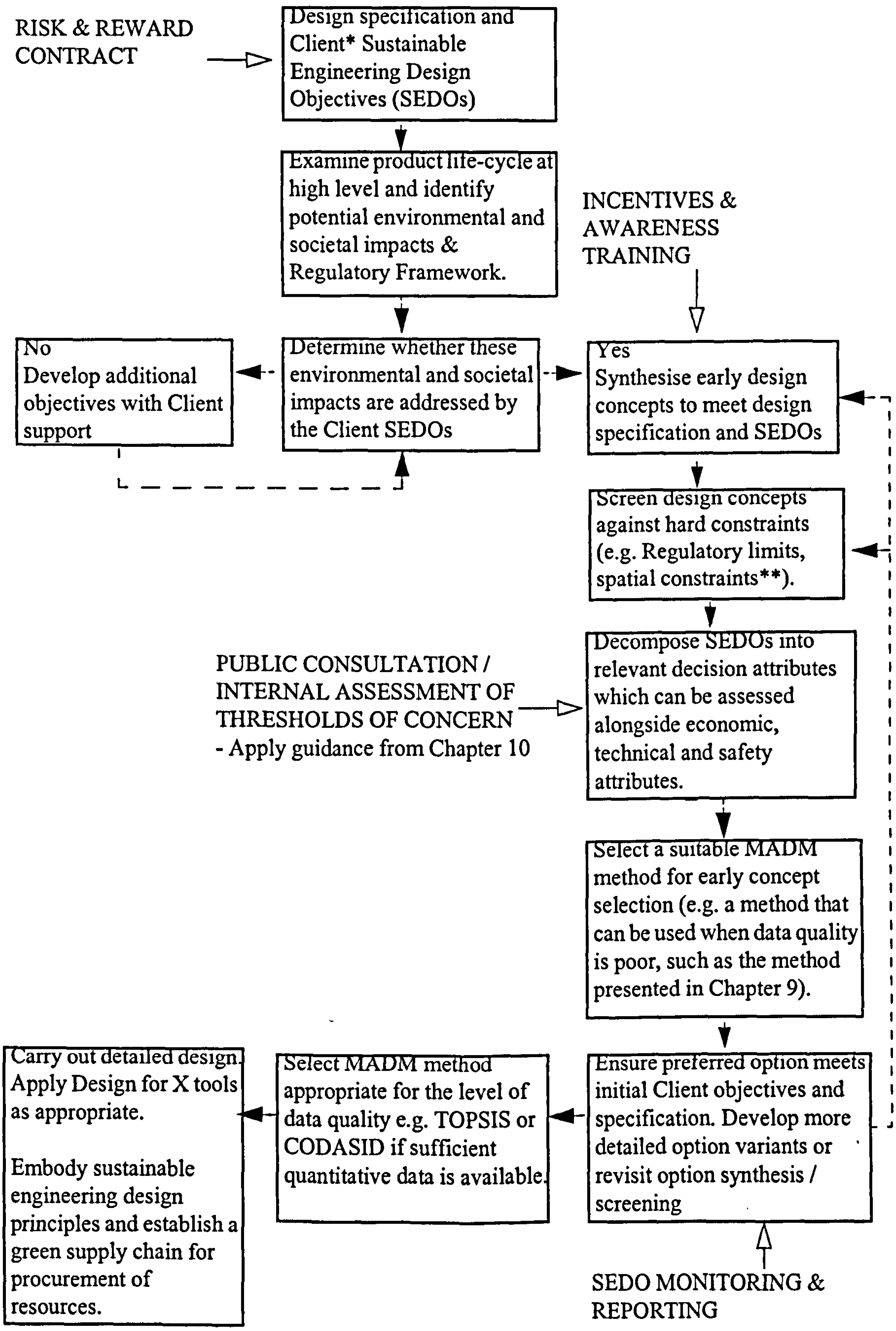
It is necessary to consider the reality of the design process during the development of a framework. At a simple level, businesses can examine how sustainable their design process is by reviewing their design activities and identifying relevant inputs, controls, mechanisms and outputs. Figure 10-1 shows the main elements that are necessary to ensure sustainable design, as identified in the qualitative research presented in Chapter 4.

Figure 10-1: High Level Inputs, Controls, Mechanisms and Outputs for Sustainable Engineering Design



However, Figure 10-1 does not capture the evolutionary nature of the design process (Pahl and Beitz, 1996). It is important to undertake sustainable design activities at the correct point in time and to recognise the iterative nature of design (French, 1985). The overarching framework for Sustainable Engineering Design is shown in Figure 10-2 and gives an indication of the sequence of sustainable engineering design activities. It is important to note that environmental and societal considerations are introduced at the initial stages of design when Sustainable Design Objectives are used to create strong drivers up-front (Fiksel, 1996). The presence of environmental and societal considerations is then maintained as the design moves from an initial concept to a detailed solution. The framework is generic so that it can be adapted to align with the design processes of individual organisations or projects.

Figure 10-2: Sustainable Engineering Design Framework



* A Client could be internal (e.g. a project sponsor) or external.
** A constraint is a design requirement that cannot be compromised and is not fulfilled by the design concept in question.

It is essential to understand that MADM sits within a wider business decision making framework and that it cannot achieve sustainable engineering design in isolation. The Client, along with the Regulators, must provide the initial sustainable design drivers (Fiksel, 1996) which are handed down to the contractor using tangible mechanisms, for example by setting out a risk and reward contract which converts any successes or failures into monetary terms. This will help foster an environmentally and ethically aware workforce.

A life-cycle approach should then be adopted when identifying potential environmental, ethical or societal impacts (Keoleian and Menerey, 1994; Fiksel, 2001). Decision makers should examine each phase of the project, from the extraction of resources to decommissioning, abandonment and site restoration. This should help to target effort and resources at the most significant impacts in order to generate a manageable number of Sustainable Engineering Design Objectives (SEDOs). The agreed list of SEDOs should be well-defined and issued to the Sustainability Champions who would be responsible for establishing clear targets and requirements, and communicating them to the design teams. For instance:

- An assessment of risk perception based on scenario prediction and MADM will be conducted once the initial design concepts have been formulated and screened (see Figure 10-2). The assessment will involve the Engineering Manager, a Stakeholder liaison expert, a senior representative from the Safety and Environmental department, a representative from Process and Mechanical engineering and a relevant external expert, such as a Regulator or representative from the Local Council.

- The siting of the proposed project will be undertaken equitably and will aim to minimise impacts to local communities. If the potential for impact is considered to be significant, a Stakeholder Engagement programme will be developed and implemented *prior to* detailed design. Progression to detailed design will be dependent on the satisfaction of this requirement.

• The hierarchy of waste management principles will be accounted for during all design decisions that could lead to discharges to air, water and land. Any misalignment with these principles will be recorded and discussed with the Regulators before the design concept can be progressed further.

• The discharge of substance *x* will be 15% lower than the expected regulatory limit at the anticipated time of commissioning.

Incentives and awareness training should be established locally within the design team environments, ensuring that the initial drivers permeate through the organisation. These should be targeted at relevant teams and individuals to maximise the motivational benefits, supported by designated Sustainablity Champions as suggested in Chapter 4.

Design synthesis is the process during which initial, high-level solutions are derived. These are usually concerned with achieving the key functional requirements of the specification and solution variants are found by searching in the feasible region of the design space (Pahl and Beitz, 1996). This search is directed by the key functional parameters which may include environmental parameters if the product has a primary environmental function. However, it is often the case that the aim of the product or process is not specifically environmental but needs to ensure that only environmentally acceptable solution variants are taken forward for further development. This is an important step and is known as option screening (DLTR, 2001; Environment Agency, 1997b; Goodwin and Wright, 1998). The solution variants are screened against hard constraints, which represent design requirements that must be met by the design concepts. In addition to project-specific constraints, generic constraints are likely to be cost boundaries, design standards and regulatory requirements from environmental, health and safety. It is suggested here that any solution variants that would fail the specified SEDOs are also screened out if there is sufficient confidence that a particular variant would fail. However, as the level of information quality would be low at this early stage, the scope for deselecting design variants will be limited.

Once the design concepts have been synthesised and screened, the concepts are examined for any potential factors that could generate perceived risk with respect to local, national and international communities. These factors provide the basis for determining whether any of these short-listed design concepts could exceed the threshold of concern under foreseeable scenarios, as described in Chapter 8. The identification of foreseeable scenarios is a significant task and it is envisaged that they would be generated using an unstructured 'what if' approach. If it is found that any of these options could breach the threshold of acceptance, it may be necessary to consider external consultation. Alternatively, these options could be carried forward until it is established whether they represent the preferred option prior to seeking Stakeholder opinion. This will save effort and will reduce the demands on the time of external Stakeholders, which is often given on a voluntary basis. This will help to prevent a Company wasting its resources on a design that would never have been tolerated.

It may not be necessary to screen out those options that fail the threshold of concern if the designers are able to improve the design concepts from an environmental and ethical viewpoint. For example, if a particular option must be sited close to a Site boundary the development of this design could place more emphasis on mitigation measures. For instance, by minimising any visual impact using natural land contours or by examining the possibilities of creating artificial screening. Once the design team has developed outlines of how stakeholder concerns may be addressed through improved design and mitigating measures, it may be considered necessary to undertake external consultation to determine if this option should be developed further.

The screened design concepts may then be assessed using a MADM approach which is suitable for the low level of data quality one would expect at early concept design. The SEDOs should be broken down into clearly defined decision attributes as shown in Figure 6-3 of Chapter 6. This will enable the evaluation of the design variants against a range of environmental factors along with safety, technical and economic aspects. The choice of attributes should focus on what truly discriminates between options to avoid redundant assessment.

During this level of MADM it is likely that uncertainties and information gaps will be identified. These may be recorded during the MADM workshops and used to generate a list of actions to be closed out before the next level of assessment or an reiteration of the initial assessment. Once the first level of MADM is complete the options should be reviewed against the SEDOs with the Client and options may be deselected if these objectives are failed. If most of the options fail the SEDOs it may be agreed with the Client that further option synthesis is necessary. If sufficient options pass the SEDOs and other key objectives, these options should continue to be developed.

Successful concept variants will be progressed in terms of design detail which will be increasingly quantitative and detailed. For example, siting locations may be known more exactly and links to infrastructure may be considered. If the level of information quality is sufficient, it may be appropriate to apply a method such as TOPSIS or CODASID to support the selection of the preferred concept design. Once the preferred option is selected, detailed design can take place. This process should adopt the same basic sustainable design objectives and Sustainablity Champions can help identify more detailed environmental and societal challenges for key product sub-systems. For example, the selection of insulation materials or fire-fighting foams may account for the minimisation of environmental and societal impacts. In addition, it is at this stage that suppliers should be assessed in terms of social and environmental impacts. For instance, the sustainability of their source materials, their processes and waste management, their history of legal compliance and consideration for their local community.

There is a growing business case for adopting such a framework in order to manage the social, ethical and environmental impacts of LMTO projects (Carne, 2001; Charter and Tischner, 2001; The Antidote, 1996). These considerations represent project risks that, if left unaddressed, could lead to the late discovery that a design is not practicable, leading to significant losses. Alternatively, if an unsustainable design is built and commissioned, Regulators may not grant consent for operations until expensive abatement equipment is added to the process. In the worst case scenario, the design may reach the operational or decommissioning phase of the life-cycle and receive national or international criticism as a result of unacceptable risk it presents to society and the environment.

Many regulatory processes involve considerable time and resources on the part of the Company. For example, the preparation of information and presentation in a suitable format (e.g. a BPEO assessment or Environmental Statement). The project schedule must then account for any periods of consultation and the time required by the Regulator or Governmental Department to make the decision.

Decision support tools for sustainable design which are systematic and transparent confer an important advantage in terms of meeting the expectations of the Regulators and the Client. When applied at the correct point in design, they prevent the late realisation during detailed design that there is insufficient information to produce a BPEO assessment or Environmental Statement, making it necessary to revisit the justification behind choosing the preferred option and the rejection of alternative design concepts. They will also help to avoid projects that may be unacceptable to society.

Research into environmental design by McAloone and Evans (1997) identified key success criteria as motivation, information flow, whole-life thinking and provision of decision support. This Sustainable Engineering Design framework satisfies these key success criteria and has formalised aspects of good practice identified in the investigation into current practice within LMTO companies. In addition, the framework shows how MADM can be integrated into the overall framework at the correct design stages to help identify the preferred design option.

Where many organisations have produced frameworks for environmental design, the framework presented here accounts for the complexities of the LMTO design process. Furthermore, it demonstrates how the input of society to LMTO product design can be introduced early and systematically in order to make real improvements to design in contrast to 'Decide Announce Defend' or communications-based approaches.

11 CONCLUSION

11.1 Conclusions

This thesis has demonstrated the need for the integration of environmental and societal factors into LMTO product design through the application of social research methods to case-studies. This provided evidence that there is a need for a variety of inputs, controls, mechanisms and outputs to ensure that environmental factors are adequately integrated into design. In particular, the need for decision support was identified as an opportunity for improvement which led to the investigation of two little known MADM methods, TOPSIS and CODASID. These methods were considered suitable for multiple attribute design selection problems where quantified data is available. It was found that both methods would help to encourage a systematic approach to design selection and made fuller use of the available information compared with the Simple Additive Weighting approach. However, it was recognised that CODASID in particular involved a complex series of calculations that would reduce the transparency of the decision. Therefore, this method may not be appropriate for decisions that need to be communicated to external Stakeholders, and especially the public.

The investigation into MADM methods was continued in order to manage early decisions associated with low data quality. Two useful methods were identified, which when combined with each other, could be used to aggregate weighted natural language expressions to compare design options (Herrera and Herrera-Viedma, 1997; Yager 1996). Linguistic expressions were captured and aggregated as fuzzy sets in order to determine the optimal design alternative and the results were compared with the intuitive results reached through group discussion. It was concluded that the use of MADM methods based on qualitative evaluation was more appropriate for decisions associated with low data quality. Furthermore, the combination of these two methods could provide an alternative to facilitated group decision making in addition to offering control over how optimistic or pessimistic the aggregation operation should be.

The same combination of methods was applied to indicators of risk perception to determine how acceptable a project would be to the public. It was established that this approach could provide a systematic approach for assessing public risk perception which could be used to guide design selection and public dialogue. However, is was concluded that criteria relating to perceived risk should be dealt with separately from other design selection criteria as they represent measures of safety, environmental. technical and economic criteria from the viewpoint of a different Stakeholder group. Therefore, to avoid double counting, risk perception should be dealt with as a separate exercise but integrated with the wider decision making framework as described in Chapter 10.

The Sustainable Engineering Design Framework presented in this thesis contributes to the existing body of research as it provides detailed guidance on how environmental and societal factors may be addressed, whilst recognising that the success of any proposed decision support is dependent on contractual arrangements, the presence of tangible and measurable objectives and the provision of incentives and awareness training.

11.1.1 Recommendations for Further Work

It would be useful to test the value of this framework by applying it to the development of new designs as a series of case-studies to determine how it improves the integration of environmental and societal factors. In conjunction with this, it would be beneficial to develop the sustainable engineering design aspects of an Environmental Management System to help monitor any improvements.

In terms of group decision making, it would be worthwhile applying the fuzzy MADM method to more case-study examples in order to make comparisons and generalisations between direct aggregation and the degree of optimism or pessimism achieved with an intuitive group consensus. This work could be used to test the efficacy of facilitators.

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ABBREVIATIONS

AHP	Analytic Hierarchy Process
ALARP	As Low As Reasonably Practicable
BAT	Best Available Techniques
BATNEEC	Best Available Technology Not Entailing Excessive Cost
BPEO	Best Practicable Environmental Option
BRE	Building Research Establishment
BSE	Bovine Spongiform Encephalopathy
CAD	Computer Aided Design
CAPEX	Capital Expenditure
CBA	Cost Benefit Analysis
CODASID	Concordance and Discordance Analysis by Similarity to Ideal Design
COSHH	Control of Substances Hazardous to Health
DFE (DfE)	Design for Environment
DFX	Design for X
DM	Decision Maker
ECP	Environmentally Conscious Products
EDO	Environmental Discharge Objective
EDP	Engineering Design Principle
EH&S	Environmental Health & Safety
EIA	Environmental Impact Assessment
EMS	Environmental Management System
ENVID	Environmental Identification
ENVOP	Environmental Optimisation

EPI	Environmental Performance Indicator
FMCG	Fast Moving Consumer Goods
GM	Group Member
GRI	Global Reporting Initiative
HAZOP	Hazard and Operability
HSE	Health, Safety and Environment
IPC	Integrated Pollution Control
IPPC	Integrated Pollution Prevention Control
LCA	Life Cycle Analysis
LMTO	Large Made-to-Order
MADM	Multiple Attribute Decision Making
MAUT	Multiple Attribute Utility Theory
MCDA	Multiple Criteria Decision Aid
MCDM	Multiple Criteria Decision Making
MODM	Multiple Objective Decision Making
NPV	Net Present Value
OWA	Order Weighted Averaging
P&ID	Piping & Instrumentation Diagram
POEMS	Product-Oriented Environmental Management
PROMETHEE	Preference Ranking Organization Method for Enrichment Evaluations
Q	Quantifier
QFD	Quality Function Deployment
QRA	Quantitative Risk Assessment
RIM	Regular Increasing Monotonic
SAW	Simple Additive Weighting
SEAMS	Safety & Environmental Actions Management System
SEDO	Sustainable Engineering Design Objective
TOPSIS	Technique for Order Preference by Similarity to Ideal Solution

UKOOA	UK Offshore Operators Association
WOWA	Weighted Ordered Weighted Averaging

APPENDIX I: INTERVIEW GUIDE

Then following guide was used to assist the semi-structured interviews presented in Chapter 5. The questions were not adhered to strictly as the interviews but served as a guide to steer the dialogue where necessary.

Introduction/Preamble:

Introductions; Name and position in company.

Firstly, thank you for taking part in this. The purpose of this exercise is to find out where environmental information is used in the design process, particularly at the conceptual design phase. This is a follow up to a questionnaire study that was previously circulated.

During the interview I will mention 'environmental information'. It is important that I describe now what I mean. My definition of Environmental information includes any information related in any way to environmental impacts; pollution, waste production and waste minimisation, energy loss/ efficiency, materials reduction, loss of containment, drainage, or safety incidents that have environmental consequences etc. The types of information could be legislation, data, guidelines, advice, events and conferences or informal conversations with environmental specialists.

FLIP CHART

So, even if you have little to do with environmental matters directly, we may find that some of your activities have an indirect effect on environmental performance of the project. We are looking at activities undertaken during conceptual design which affect the whole life-cycle, i.e fabrication to decommissioning and disposal. This will be confidential and the recording will only be for my data analysis, nothing else. Shall I begin? It should take about 20 minutes but take as long as you want.

If any questions are irrelevant feel free to say so...

What is your job title?

What projects have you been working on in the last 6 months?

Q1.

Can you describe the major design activities you undertake?

prompt:

material selection

equipment selection

optimisation (of what?)

what tools used?

Q2. Describe some typical design decisions you make during conceptual design.

Prompt:

design constraints - cost, safety, functionality...

material selection

structural optimisation

process design

concurrent engineering team

value engineering studies

project design

team structure

Q3.

Which disciplines or individuals do you regularly interact or exchange information with?

Q4. Keeping the introductory definition of environmental information in mind, **(indicate flip chart)** do you ever require environmental information during conceptual design? Often, occasionaaly, rarely...

PROMPT: *Can you give me some examples?*

legislation

energy usage/efficiency

flora/fauna

eco-toxicity / toxicological data

environmental performance of materials

loss of containment

Other:

Q5. ***(if negative to env. info go to Q11)***

What are your sources of environmental information? People, databases, documentation...

PROMPT:

Is there anyone apart from EHS that provide you with environmental information?

other engineers

other people on project

external sources

client

sub-contractors

suppliers

Q6.

Could you tell me how you get this information i.e what format?

Q7.

Can you give me your opinion of how effective environmental information transfer is between departments and disciplines?

Q8. Have you ever felt that you lacked sufficient information in this area? Is it easy or difficult to obtain when you need it?

Q9. Has it (the information) been accurate to your knowledge?

Q10. What general outputs do you produce in your design activities? Reports, diagrams, data...

Q11. Who receives these outputs?

Q12. Do any of these outputs require, contain or produce environmental information?

Anything that you deal with that could affect outputs of solid waste, emissions to air, wastewater, accidental spills, component lifetime, decommissioning related problems.

Describe the document/what was involved?

Format?

Who was it for?

What information did you need to gather for it?

Was there any outcome generated by it?

Q13.

In your Role, do you include environmental performance as a constraint during any of your design work?

PROMPT:

optimisation

targets / goals on **design brief / specification**

Q13.BACKUP

Is there any interaction between your activities and environmental/safety personnel?

Q14.

Tell me about any activities related to environmental issues which require the interaction between yourself and other disciplines/departments?

brainstorming

HAZOPs with env.

scenario prediction

Who was involved? Was it successful?

Q14. BACKUP

Although you are not directly involved with environmental activities, what do you know of the initiatives and procedures used in [Company name] to identify and reduce environmental impacts?

Can you see any benefits in becoming involved with these activities?

Q15. Have you been involved with the preparation of environmental statements? ES is part of EIA which is part of the planning application process for some projects.

Q16. Is there anything you would like to add?

Thank you for taking part in this study. If you are interested in the results I will send you a copy when I have processed them.

APPENDIX II: EXAMPLE OF FULL TRANSCRIPT

Interviewee: A

Function: Process Engineer

(Could you describe you design activities based on your work in the last 6 to 12 months?)

Ok? My job at the moment? Basically I joined the project at the beginning of last year in the process design team so a lot of conceptual work had already been [er] had been done to a greater ... greater rather than lesser extent. And [er] I joined as a process engineer ... a senior process engineer in the design team and I looked at well heads and [er] how we were gonna start up. Basically I looked at well heads and how we were gonna start up. The overall process ... the whole thing. And in the ... in the area of the starting up the overall process we had to [er] had to devise a route where we minimise flaring as much as possible. And that's really where I got involved and [Environmental Specialist] was involved as well as basically in the area of [er] flaring minimisation and that's ... that's by and large where I [er] I was involved if you like in the conceptual area and [er] cos even though I wasn't part of conceptual design it was still like with the concept of minimising flaring. And the other thing I did in the environmental area is I was to produce a quantification [er] report for how much they expect to flare during the operational phase of [er] the platform which again I had involvement with [Environmental Specialist] for that. So that is pretty ... that sort of summarises ...

(Is it possible in this sort of time scale to sort of talk to me about the options you consider for the minimisation of flaring and that sort of thing)

Yes... we [er] basically [er] we ... flaring is from ...I mean again I'm not sure how familiar you are with [Project Name] but I'll just carry on and you can stop me yeah whenever you like. Flaring basically from all these...from oil and gas installations tends to be two kinds. What we call continuous emissions and [er] intermittent emissions and what we did we listed down all of our potential emissions so like for the continuous emissions apart from small things like pilots and [er] some ... some off from low pressure sources and they were deemed to be very small. So firstly we split them into continuous and non continuous if they were there but we don't have any continuous emissions which is good. So then that non continuous or intermittent emissions we went through the list of them which is like equipment trips and [er] your start-up, spillage of control valves...control valves to flare ... things like that. So what intermittent ... and we basically looked at these in terms of intermittent emissions and quantify them but already we'd reduced our flaring quite a lot by reducing ... taking out our continuous emission by doing [er] the incinerator and now you must have heard about that so the incinerator has two ... does two things. One ... it prevents the need for acid gas that has to go to flare but it also takes a lot of gas at low pressure which we use to fuel it so whereas on other platforms they would have had to have flared gases at very low pressure because they don't have a source ... they don't have a sink to dispose of it. Because we had the incinerator we were able to do that. So we burnt ... the work that I did wasn't so much around...cos its all inextricably linked...we don't just say oh how do we minimise flaring then start...the thing has already progressed. We had the incinerator ... we had the mindset that we needed to reduce flaring so we came up with a start-up philosophy that minimises flaring as much as possible. We...the pressure control valves to flare we tried to set them up so we would minimise flaring as much as we could...in that area. The equipment unavailability obviously we tried to get the best...[er]...as reliable compressors as we possibly could get so...

(Did you have much conflict between selecting components for minimising flaring and the people that were trying to reduce CAPEX...where that was their primary goal. ?)

The only conflict I think was with the incinerator...you see I mean most things are fairly straight forward I mean the equipment that's more reliable will enable us to use compressors which are more reliable...will enable you to sell more gas. As well as to reduce flaring so really you would like something as reliable as you possibly could get. So there was no conflict there. The ...the major ...if there was a conflict in the design process it really cam with the incinerator...which is the most important sort of aspect as far as flaring and H_2S and every...probably the most...aside from the produced water and any other environmental context probably the most important piece of equipment.There was quite...some discussions we continually had as to its validity but [er]... over time we managed to convince [er] most people that [er] not only is it a good idea from an environmental perspective we are also economically better off using the incinerator cos...you know about this yeah?..[Environmental Specialist] must have gone through it cos you have these acid gases and in order to burn them in the flare you have to add a lot of supplementary fuel gas and if you don't...if you have the incinerator whilst you paid up-front for it you use less fuel gas...it turns out that fuel gas is a substantial saving that ...

(Is it easier to maintain the sorts of temperatures that you need in...presumably you don't need that high a temperature to incinerate these sorts of things.)

I presume... I have to say yes. I have not been involved in the detail design of the incinerator but we know the conditions and we know...we've gone to standard incinerators and...The thing that makes this unique is that it hasn't been used in an offshore environment but in so far as the concept of incinerating something is concerned I think its well proven...well proven.

(Onshore there are the old problems associated with dioxins, VOCs and things...but I mean they're not...they're usually extremely low. I wondered if it was something which had to be addressed)

I'm not fully familiar with the [er] detailed incinerator design but I presume that sort of thing has been addressed. So the summary...the answer to your question is that where my involvement has basically been...I'm more down the thrust of coming up with the concept of how we can start-up with minimal flaring and also going through and quantifying how much we are going to flare and sort of point out where our major flare is going to be coming from and where...

(Once you've quantified it who then receives that information?)

We found that we were...basically it was widely circulated and it's now part of our target I mean that quantification is in our...our target is 0.3% in energy terms should be flared...that's one of the Environmental Discharge Objectives. That quantification revealed that we were gonna be 0.25, so that 0.25 is in that target poster so that information has been...been...so basically the loop is there in terms of the flow of information. We had a target, we did a quantification which was below target so we stopped because we were below the target.

(How did you go .. I mean it's difficult for me to understand at conceptual phase of design it must be difficult to be assured of your level of accuracy when you are predicting these things.)

You never know...you never...I think this is a common myth is that you never know how much you're gonna flare till you actually flare it so between now and when the equipment is installed actually no new information comes to light...because if you think about it you know your system, you've gotta guess certain things and that...for that we have tools that do that now and they are just tools. Whether that is accurate or not we'll never know till the thing's operating. So it's easy...its as easy to do...to predict how much you're gonna flare and so on in the conceptual phase in the sense that once you know what equipment you're gonna install...whether you are going to have two compressors or one. Once you've done that sort of level of detail in your design you're as likely to know then as you are in the next two or three years.

(What sort of information have you taken from Environment, Health and Safety?)

In...in...in I don't follow the context of the question.

(Have you needed to go to the Environmental people here to request information whether it be on legislation, or environmentally related information...)

Not...not for this because if you think about it there I...no just in the area that I'm involved in now...there is no legislation that says you have to flare x% or y%. We know what our target was which was 0.3% of boe. We know who...so that was known. We don't see this information flow as...at least I don't see this information flow as I go to an environmental person to get this...its all a bit of a team effort really...you sort of feed off each other. That's how the information flow goes as far as I'm concerned. Not for something specific for legislation but obviously you're always looking for other people to throw in their ideas and experieinces...be their job environmental...the environmental officer or whatever you like....designer or managers of anybody. In theory everybody should be trying to reduce flaring, reduce discharges...everyone's opinion should be considered.

(Have you been involved in the ENVID?)

The ENVID...I was yes. I was involved briefly. That was...one of the things that came out of the ENVID...I'm trying to remember...there was something about start-up as well....at the ENVID at the ENVID the thing that I remember...the thing that I remember from that day was [er] at that time we didn't have a concept of how we were going to start-up so a lot of people talking about a lot of stuff and there was a lot of numbers being bandied about that we'd be flaring a lot of gas and so on. From that ENVID...well after that ENVID in terms of time this idea of how we were going to start-up came about and [er] we worked on a team and [Environmental Specialist] was part of that team on how to reduce flaring...I think that's all I remember about the ENVID.

(The ENVID is a big brainstorming thing really. When you are talking about flaring reduction with [Environmental Specialist] would it have been done as a small team doing a similar sort of brainstorming thing or was it one to one?)

I think the way we did the ... I don't remember that much of the ENVID so ... in terms of information flows if you look at it generically the fact that I don't remember that much about it possible suggests to me that I didn't consider it to be that important a step in what actually has happened here so that's one thing. Obviously others may disagree but [er] others will agree so that's one thing. In terms of your second question which was did we sit around and brainstorm how we were going to reduce flaring well...no...not really. What we did was come up with a method of how we were gonna start-up in terms of the start-up aspect again which is what I can talk about. And then that was discussed by the team in a ...and bearing in mind that reducing flaring was just one of the objectives of starting up. We have to actually get started in a safe and quick...it's got to be quick, it's gotta be safe and it's gotta minimise flaring. So what we did...we came up with a proposal from process engineering that this is how we'd start. We sat down with people from commissioning, from operations, [Environmental Specialist] was there as well and then over a period of months some comments were taken in and was slightly modified and so on...but the bulk of comments as I remember them...were not really to do with the reduction of flaring because that was by and large already reduced going down that road. It was more in the areas of [er] ease of start-up and [er] making it easier for the operators and more sequential and so on...

(Have you been invovled with any other environmental activities?)

Not again, not that I can remember. But again it's a bit...it's sort of doesn't work...I mean I don't think it works just setting off the thing for a minute. There's no...well I understand you are looking for a sort of formal process of you know... this is how information...this is how environmental information flows. I can see where you're coming from but of course in practice if you give it such a wide...if you give environmental discharge objectives and so forth such a wide sort of [er] publicity as they have done on this project you're likely that the system becomes less formalised which in a way I think is a good thing because everybody thinks about it all of the time and obviously at certain points in terms of the formal movement there are environmental audits which I'm sure [Environmental Specialist] must have told you about exactly what was done there. So I was working more...from a {er] didn't really work too much on setting these strategies as to why we should have 0.3% and what is...what was best in class what mainly I was working on given that we want to minimise our discharges preferably to zero in any given situation what can we do so for that there's a lot of things that go backwards and forwards...it's not mapped out put it that way. And maybe mapping it out will help future...help in the future...maybe we should go for that.

(I think it's been very effective in process. Generally through these discussions I mean...it's very accepted that to reduce emissions is of benefit to your normal objectives...some disciplines it seems less so. There's more of a conflict in selection of equipment between CAPEX and that sort of thing. So I mean this is probably the major thing that this has picked up...there's a very different attitude between disciplines).

Or it could be a different attitude also between individuals rather than disciplines.

(Yes...you could only take this as a case study and not as generic...)

One of the things that did come up was we were going to have two of one kind of compressor. I don't know if that came up but one of our low pressure compressors we were gonna have two 50% machines and that got changed to one 100% machine to reduce...basically to reduce cost...I don't know if you have come across that in your discussions...

(Yes...I spoke to someone that thought it was a shame that you went for the single option)

Yeah...so that did happen. But like I told you I wasn't really party to how information flowed backwards and forwards before that decision got made if you like. But [er] the only thing about that was you can't...again you can't look at these things...I think it's too simplistic to look at them in isolation because as I understand it two 50% machines...the problem with that was not so much cost but the thing was we couldn't actually lift the whole platform in place...it was another very pressing problem so if you...on the one hand it would be very easy to say ah yes when they had a problem the environmental requirements were sacrificed but you always have to ba a little bit careful because they had a...had a real problem in that we could not physically lift the whole thing and put it in place which would have...which would have...

(It hasn't been widely discussed as a problem anyway but you do have to look at the whole picture. I'm not just doing this for...not just coming in with the attitude that everything has to be done for the environment. One has to appreciate that things have to be feasible in every other sense of the word.)

Indeed, and because of that what because given that one appreciates that then you're left with and given lets say as you that everyone appreciates that everything has to be feasible in every possible way to use your words...once you appreciate that then you just talk about degrees of movement from a position that you would consider to be ideal and [er] it's not so much...I would argue that it's not so much between disciplines that you get this difference but between individuals. To me it's at that level so the thing that [Environmental Specialist] has done very well...that is her personally...and that this whole environmental sort of thrust on this project has done very well is that by starting from the beginning and publicising these targets this widely and giving them this sort of profile it's succeeded in winning the hearts and minds of people which means they are prepared to move further in the direction of emissions reduction than they otherwise may have in the absence of said initiatives. therefore it's...I guess where I'm coming form is it's not so much in the discipline...I would find it surprising if somebody had said to me there's a difference between disciplines as in groups of individuals in their attitude to this kind of thing. I would find that surprising if that were actually true from what I had experienced...it's more amongst individuals and even right in the management team there are some individuals that would be much more sort of...lets say amenable to [er] slight change of strategy to minimise emissions where a change may or may not cost more money or may not be perceived to cost more money. [Er] whereas others wouldn't. So a lot of it depends on whether you win peoples hearts and minds over and in order to win hearts and minds you have to have something like what we've done here which is publicise these things widely, give it priority, celebrate successes in that area and so on and so forth. Those were all really good things.

APPENDIX III: INTERVIEW SUMMARIES

COMPANY A

Interviewee A1

Design Role: Deputy Chief Safety and Environment Engineer

Diagram: A1-1

Interviewee A1 works in Safety and Environment and he begins by discussing the ENVID. He notes that it was restricted to key disciplines and would say that 70-80 % if the design team would not be responsible for the range of issues covered by this mechanism.

The subject's department have tried to set up an environmental champion for each discipline. The environmental champions were mostly lead engineers, however, the concept of environmentally champions was not taken very far on the project. Only the environmental champions from Mechanical and Process did some specific studies to improve environmental performance.

He adds that although the project gave very high consideration towards reducing environmental impact the team could have gone a lot further. He feels the reason for this is a lack of awareness of environmental issues amongst the design team.

Process is the main discipline who helps the Safety and Environment group to achieve environmental discharge targets. The client supplies much of the background information on the environmental regulatory framework and he also liaises with the Environment Agency. He also gathers information from journals, library resources and his past experience when undertaking his environmental activities within the design team.

The interviewee discusses the new Environmental Impact Assessment legislation which now applies to certain offshore projects. Although this research was carried out prior to this formal requirement, an Environmental Statement was produced voluntarily for this project. He relates that this activity drove environmental design and prompted a more thorough investigation of environmental impacts. He also hopes that the work in progress on the Environmental Management System (contractor's) will create an extra driver towards the consideration of environmental impacts as it will ensure that procedures are in place for the transfer of environmental information to the design team.

Actions and issues arising from the environmental brainstorming activity are logged on the safety and environmental management database which the design team can access. The subject is partly responsible for verifying that these actions have been addressed.

BPEO (Best Practicable Environmental Option) assessment was integrated with the Environmental Statement. BPEO assessment was used to address four key aspects of the project which could influence life-cycle environmental performance. A position paper was written for each, covering the possible impacts, evaluating these impacts and presenting design options.

The subject concludes by explaining that most engineers do not consider that environmental marionettes can lead to cost benefits and he is hoping to encourage life-cycle costing in the future. In general, he notes that young engineers are more motivated towards environmental design.

Interviewee A2

Design Role: Fire Risk Analysis Engineer

Diagram: A1-2

Fire risk analysis from a loss of life point of view is the subject's area of activity. This begins with the identification of process plant which may become a hazard in the event of a fire and a platform inventory is compiled to estimate the probability of a fire event or explosion. This information is gathered to identify the worst case scenario's are passed on to relevant design disciplines, such as layout and structural engineering. Risk minimisation parameters will then be incorporated into the layout and structural design.

Recommendations from fire safety are clearly seen as important. The subject says that occasionally a cast-benefit analysis is required to support a recommendation. One of the subject's main objectives is to satisfy the Safety Case Regulations and the main tool to support these activities is HAZOP. The subject mentions that 'environment' has been included as a HAZOP deviation (keyword) for the first time in the current project that she is involved with. The subject does not see the link between her role in fire safety and her influence on life-cycle environmental performance. However, her work will have a significant effect on reducing the risk of an out of envelope event which would have a high potential for environmental damage i.e. an explosion causing an unplanned emission to the marine environment.

Interviewee A3

Design Role: Senior Process Engineer

Diagram: A2-1

At conceptual design the subject looked at defining a start-up philosophy which would satisfy the client objective to minimise flaring. With others, identified potential emissions were split up between continuous and intermittent emissions. He added that start-up was constrained largely by safety and schedule aspects and that meeting the flaring objective was mainly carried out by the client prior to the alliance formation. However, the subject did remember participating in an environmental brainstorming session where the flaring objective was considered in the context of start-up philosophy. He remembered little about the activity and recollected that it contributed little to the decision outcome.

Interviewee A3 feels the most important contribution to improved life-cycle environmental performance was the well publicised environmental discharge objectives. The subject felt that this informal approach helped to formulate an environmentally aware culture within the design team. He felt that opposition to environmental design mainly came from individuals as opposed to design disciplines as some personalities were more likely to compromise than others.

Interviewees A4 (subject 1) and A5 (subject 2)

Design Role: Process Engineers

Diagram: A2-2

Two subjects attended the interview together although it is mainly one who spoke who is named subject 1. Subject 1 begins by describing the main drivers for his activities. He considers these drivers to be mainly CAPEX and OPEX, meeting regulatory standards and energy efficiency which is really tied in with OPEX. Process receive oil and gas specifications from the client and design the process required to reach these specifications. CAD and process simulation are used to achieve this. The process specification is strict and does not allow for much flexibility. Therefore, environmental objectives are not likely to be considered at this stage.

He obtains environmental information through the environment and safety group, such as discharge data, legislation and client environmental targets. It is mentioned that client targets are more stringent than legislation. Client goals are generally handed down in the Basis of Design document.

An economic and technical review is produced for the selected process technology which is reviewed by the client. The design is reviewed against criteria, such as CAPEX, OPEX and efficiency. Once the process is accepted the Process discipline will then prepare specifications for other disciplines, such as Control and Instrumentation. Process produce key documents which are handed down to other disciplines who make requisitions, such as process data sheets. Process are able to introduce environmental objectives are the level of machinery specification and material choice. The subject said that sometimes high grade materials would be chosen to reduce maintenance requirements during operations phase which may indirectly reduce out of envelope risks and the need for mid-life replacements.

Interviewee A6

Design Role: Mechanical Engineer

Diagram: A3-1

(subject requested not to be taped)

The subject works in the Mechanical discipline and his activities concern packaged equipment, such as heat exchangers, water treatment equipment, turbines, diesel engines, generators and compressors. The interviewee says that environmental impacts were addressed from two angles; compliance with legislation and satisfaction of client objectives. He felt that most of the equipment could be improved with respect to CAPEX and OPEX. He explains that each project begins with Value Engineering studies and that one of the key drivers is schedule. He has strong feelings about the formation of alliances and mentions an article which supports his opinion that they are becoming unpopular as concept. His reason is that it takes so long to negotiate the alliance initially and that it is more difficult to make decisions in an alliance. He adds that during equipment selection, the specification is mostly developed by the contractor.

The subject is not involved with the Environmental Statement and feels that the transfer of environmental information is adequate. He requires information on the expected composition of exhaust streams and evaluates equipment to ensure that it is performing within it's range. He is involved with Instrumentation Protection Functions and assesses complex equipment failure modes. He said that additional expenditure had been used to prevent venting of gases to atmosphere. Evaluation mainly considers CAPEX and technical feasibility. Although he adds that OPEX is secondary to these and there is more pressure to consider life-cycle costs.

He said the Mechanical discipline go through the motions of the environmental supplier assessment. However, he adds that when they deal with German suppliers they request the suppliers to drop their standards. He states that most cases of improved environmental performance leads to cost penalties. He adds that a reduced emissions unit may cost an extra million pounds. He also uses extra software in control systems as an example of increased costs.

In terms of mechanisms, he mentions HAZOP but notes that it is a cause and effect study which is not environmentally oriented.

Generally, the subject appeared negative to environmental objectives and the whole idea of the alliance. He specifically requested not to be taped.

Interviewee A7

Design Role: Spatial Layout Design Engineer

Diagram: A4-1

Interviewee A7 is involved in spatial layout and materials. He states that the main drivers are cost, weight and spatial layout constraints, however, he identifies many areas where these drivers act in synergy with environmental objectives. He gives examples where pipe length is reduced. He points out that this will save on materials, heat loss through piping and will lower risk of out of envelope spillage. He also designs for easy maintenance where possible and describes the new strategy where operators are included on the design team to advise on maintenance issues etc.

He mentions that any savings made on capital cost during requisitions will directly increase their profit as the contractor. He has been involved with the environmental supplier assessment. However, he says that the success of application is variable. Where small suppliers are concerned it is not taken too seriously and selection is rarely based on the supplier's environmental performance.

The subject feels that environmental objectives do not really drive his design activities but, as mentioned before, there are often indirect environmental benefits. He describes a safety-driven move towards welded valves instead of flanges. This was to reduce risk of emissions of the pipe contents which would have environmental gains.

In terms of mechanism, he has minimal participation in HAZOPs. The subject uses 3D CAD modelling to assist layout design and the client has a spreadsheet of failure probabilities to reduce risk and consequences of equipment failure.

Interviewee A8

Design Role: Electrical Engineer

Diagram: A5-1

Interviewee A8 works in the electrical department which covers power generation through to cabling and navigation aids. He does not receive an environmental remit from the client at conceptual design. Mechanical and Process are responsible for selecting and design the concepts, for example the power generation system The electrical engineers will then size the components and purchase the parts. The subject was responsible for selecting the alternators for the gearbox, however, efficiency was not an objective as he would select the standard 97% conversion factor. He did consider effulgence as an objective when selecting the high voltage motors. During purchasing activities the subject has been involved in the green supplier assessment. Once again it is confirmed that no supplier had been rejected due to poor environmental performance. He passes the supplier assessment forms to HS&E who convert the evaluation into a points system. The other interaction that the subject has with HS&E concerns the review of COSHH sheets.

There was a client led initiative to select low smoke zero halogen cables to improve visibility and worker safety during a fire event. He also considers that transformer oils are a fire risk and Electrical do try to select oils that reduce impact on the environment. However, he does not elaborate. It is also mentioned that Electrical have moved back to nickel-cadmium batteries from gas recombination vented lead acid cells. He did not discuss any environmental implications of battery disposal. The subject also recounts the selection of unarmoured cables instead of galvanised steel wire braid. The drivers for this decision were weight, cost and installation time. The subject did not indicate that these drivers were in synergy with resource efficiency.

generally, the subject gives the impression that his activities fit around those of Mechanical and Process, and therefore he has little influence upon the environmental performance of the design.

Interviewee A9

Design Role: Control and Instrumentation Engineer

Diagram: A5-2

Interviewee A9 designs control and instrumentation systems around the P&IDs produced by the Process discipline. His role is to put in detection systems and analysis equipment and can relate his activities to possible influences on life-cycle performance. For example, he talks about the influence that valve selection will have on fugitive emissions and his work on emission detection systems. However, he adds that he does not follow a specific green remit. He receives detailed emission limits from process which he writes into specifications during requisition activities. He also uses the environmentally data sheets supplied on the computer system for information on predicted environmental conditions of the operating platform (wind etc.) and client environmental objectives. The subject feels the supply of environmental information has been very satisfactory.

In terms of meeting environmental objectives, he does mention that sometimes the emission targets are not practical as the detection systems do not operate at such low levels.

He mentions his participation in HAZOPs as a separate activity from his general engineering rile. It appears that this is a traditional HAZOP methodology so there is no direct environmental keyword. In some cases, he says safety and environmental goals conflict. As an example he describes the shut-down process where the process of blow-down is initiated to protect the workforce which results in discharges to the environment. He has had some involvement with the green audit but this involvement is minimal and unclear.

Interviewee A10

Design Role: Operations Engineer

Diagram: A6-1

Interviewee A10 works within the operations group and begins by confirming how important it is to meet legislative standards and project objectives with regard to environmental issues. He has become particularly involved with looking at how systems operate from an environmental perspective and has a strong commitment to achieving environmental objectives. The subject has experience with produced water packages and he has been heavily involved with this aspect of the project in question. He mentions that it can be difficult to procure equipment that meets the stringent emissions targets that the client company has set. Initially when these targets were set the subject had close contact with the Process discipline to obtain fundamental data in order to meet these environmental discharge objectives.

The subject has been involved in ENVID studies and has been personally responsible for completing action items which he then logged in the environmental management database. He feels that the environmental aims of the project have been realised and that this has been encouraged by the alliance approach where the contractor mutually benefits from good performance at operations. However, he does feel some opportunities were missed and imparts that if anyone has an innovative idea, the responsibility falls to them in terms of costing the option. He also feels some opportunities have been driven out by engineers working for the contractor who artificially inflate the cost of novel solutions. The subject describes the great culture change required for an alliance team and feels that it has not been entirely successful in terms of interface management. As the subject is from client personnel, he recounts that were some initial minor problems familiarising himself with the contractor's information systems but now regards them to be robust information transfer systems.

Interviewee A11

Design Role: Operations Engineer

Diagram: A6-2

The subject investigates the impact of production deferment during operations phase and works on maximising availability through design for maintenance. He also has responsibilities for financial asset management and has experience of applying life-cycle costing to his job functions.

One of his key design criteria is design for accessibility of process plant and it's components. This will influence life-cycle environmental performance as high standards of maintenance will reduce equipment failures and risk of out of envelope events. The subject carries out availability modelling in order to minimise production downtime. He discusses the incentives for the contractor to design for operational efficiency due to the 'risk and reward' contract. Under this type of contractual agreement the design contractor will also benefit from savings in operational expediter. However, the subject does not feel that this is well understood or well publicised to the designers so opportunities for fuel efficient design for example, may be missed.

The interviewee discusses the low environmental awareness of the UK design business compared with other European countries. In terms of mechanisms. the subject is not directly involved in HAZOPs or environmental brainstorming. He explains that most of his work was very early in conceptual design before these mechanisms are implemented.

The subject mentions that the task of gathering data for life-cycle costing is time intensive and he feels that the design organisation lacks experience in this area and is too focused on CAPEX and schedule. He also feels that the design disciplines are not working in a fully integrated manner and that disciplines work to their own separate agendas. The subject feels that environmental design would benefit from a culture which share objectives and base decisions on life-cycle costs.

The subject is employed as Commissioning Manager which involves deriving a strategy which will take the fabricated design into service in accordance with the initial performance specification.

He divides the overall system into sub-systems and tests them for integrity and simulates equipment performance and inventory. Each component is checked and subjected to quality checks related to their mechanical, electrical or instrumental aspects. The subject will eventually work on the built offshore facility during hook-up, installation and commissioning and notes that it is beneficial to have continuity with respect to engineers working on the facility during it's life-cycle. He has also been involved in retrospective studies on loss of containment events from operating offshore facilities.

In terms of the environment, he talks about some extra processes which have been designed which will enable the gas to reach sales specification during commissioning. This will avoid flaring and the subject also confirms that it will increase revenue. He also discusses further strategies, developed by the client, to avoid blow-down during commissioning. When asked about his need for environmental information he answers that he discusses the need for containment of spillages and the existence of the COSHH database which logs all hazardous substances associated with the platform. The subject is responsible for writing commissioning procedures which include Health, Safety and Environment requirements. This includes a risk assessment of the systems with regard to safety and environmental issues. He had some input into the initial environmental brainstorming studies where he supplied information with respect to commissioning processes.

The interviewee is satisfied with the transfer of information and describes the electronic system which allows access to completed documents and documents in process.

Interviewee A12

Design Role: Operations Engineer

Diagram: A6-3

Interviewee A12 is concerned with designing and specifying the packages which are to be bought directly from vendors, such as pumps, compressors and generators. His experience as an offshore engineer has made him very aware of environmental discharges so he applies an environmentally conscious mindset to his design activities. The subject ensures that the discharges are met and usually exceeded. He comments that the client discharge objectives are far tighter than the regulatory framework. He has been involved in setting up a database which details the platform inventory in terms of waste, COSHH data and transportation requirements.

Interviewee A12 has investigated future legislation concerning compressed asbestos fibre gaskets and has presented a case to remove it. He undertook the information gathering himself and now he has informed engineers involved in procurement that they must look for alternatives. He suggests graphite. In order to gather information from the internet, relevant personnel within the client company, the manufacturers and he attended exhibitions.

He has not been involved in any environmental brainstorming activities.

Interviewee A13

Design Role: Commissioning Manager

Diagram: A7-1

The subject is employed as Commissioning Manager which involves deriving a strategy which will take the fabricated design into service in accordance with the initial performance specification.

He divides the overall system into sub-systems and tests them for integrity and simulates equipment performance and inventory. Each component is checked and subjected to quality checks related to their mechanical, electrical or instrumental aspects. The subject will eventually work on the built offshore facility during hook-up, installation and commissioning and notes that it is beneficial to have continuity with respect to engineers working on the facility during it's life-cycle. He has also been involved in retrospective studies on loss of containment events from operating offshore facilities.

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The interviewee is satisfied with the transfer of information and describes the electronic system which allows access to completed documents and documents in process.

Interviewee A14

Design Role: Quality / Verification Engineer

Diagram: A8-1

Interviewee A14 is involved in auditing and verification. One of his roles is to approve the placement of purchase orders and ensure suppliers have been asked to complete forms for the green audit. He points out that safety and environment personnel actually conduct the supplier assessment but the subject ensures that this step has been undertaken by the engineers during requisition. He feels that the main opportunity to improve life-cycle environmental performance is to influence the supply chain.

Another role which has an indirect influence on LCEP is his verification of HAZOP and ENVID actions. He checks the records to ensure all actions have been followed up satisfactorily. He is also aware of the implementation of the Environmental Management System and, although not directly responsible, he provides support to the Safety and Environment personnel who undertake this.

Interviewee A15

Design Role: Head of Verification

Diagram: A8-2

The subject deals with safety critical elements of the offshore platform, for example plant or component failure leading to a major accident. His activities include the organisation of independent, competent persons to review the engineers' design work in relation to the relevant codes and standards.

At conceptual design, verification perform a course major accident scenario which will progress to specific issues later in detailed design, such as potential for jet fires. The subject does not produce the documentation but he ensures that the documents are prepared by the engineers when relevant. For example, designs involving major hazard pipelines must include major accident prevention documentation. Any platform design must deliver an oil pollution prevention document. He is responsible for obtaining permits of consent and he discusses the problem of tracking and disseminating information on new legislation. He finds that the development of legislation towards a less prescriptive format is more difficult in terms of compliance.

The subject talks about the new initiative where verification activities during operations are fed back to the design process and to other operating platforms. The subject attends inter business unit verification meetings where problems with verification during operations are raised in an open forum. Problems raised during the forum can then effect the design of new offshore installations.

The interviewee's job by nature is driven by legislation, design standards and codes. His position has potential influence on the product life-cycle performance as most activities which reduces the risk of major accidents will reduce to risk of environmental damage.

<u>COMPANY B</u>

Interviewee B1

Design Role: Process Engineer

Diagram: A1-1

Interviewee B1 mainly discussed his current involvement in the new waste minimisation task BT407. This is one of several breakthrough tasks which aim to formulate Engineering Design Principles for waste minimisation, lifetime cost minimisation and energy efficiency. Interviewee B1 is the facilitator of BT407 and has just nearing completion of the framework. The task will largely entail information gathering from operators of existing plant and extracting generic heuristics with respect to waste minimisation which will provide the basis for waste minimisation Engineering Design Principles. This will be a continuous process and will be part of the revised design process.

The subject talks of the close interaction with the client engineer in an alliance type design situation. The client is a key figure in design reviews and optioneering studies and has been the main driver for these new Breakthrough Tasks. Waste minimisation is now often included in the client specification for projects.

Once the Process designer has produced the engineering flow diagrams and engineering drawings he presents these outputs at the Design Review. The Design Review is a group of people usually led by the Principle Engineer of that discipline and a representative from the client company is also usually present. The design is reviewed against a set of keywords:

Classification of areas:

Construction	Maintenance
Contamination	Operability
Decommissioning	Process

Environment	Waste minimisation*
Functionality	Health and Safety

Waste minimisation has recently been added to the design review keywords. The interviewee feels that further steps will be needed to change design culture in order to design for waste minimisation. He raised an issue to illustrate the sort of waste minimisation problem that arises where there is a tendency for a blanket categorisation of waste. In some instances a waste may be more strictly categorised than necessary due to the design not allowing for easy segregation.

Interviewee B2

Design Role: Lead / Senior Process Engineer

Diagram: A1-2

Interviewee B2 began by outlining the general activities of the Process function. After the initial client definition of requirement the Process function generates the process specification and equipment sizing to meet the requirement. This will involve producing chemical, product and waste flow sheeting which will be developed into the detailed specification involving pipework design etc.

The subject is involved with several projects as either a Lead or Senior Process Engineer. He discusses one project where routing the waste was a design issue. The waste source was a storage pond and the effluent from the pond purge was integrated with downstream operations so that the downstream discharge routing could be used. The subject talked about the heat removal systems in the context of energy efficiency but no obvious examples of design for energy efficiency were given.

On the subject of regulation and the need for environmental information the subject states that there are diverse sources, however, the Lead discipline Engineer is expected to know the basic regulatory issues associated with a project. Other sources are the Process and Technical files which identify key elements of legislation. Where more research is required, [named environmental specialists] become involved and undertake literature searches etc. The site will provide Process with information on discharge authorisations and sometimes it is necessary to communicate directly with the Regulators.

Interviewee B2 mentioned the Engineering Design Principles for decommissioning and said that these were kept in mind during the design of new plant. However, when asked about opportunities for re-use of plant the subject said that this had not been done and that there was little potential after the 20-30 year life-cycle especially where the majority of plant would be exposed to a degree of radioactive contamination.

Loss of containment was mentioned in the context of bunding systems which are designed between Process and Mechanical disciplines. The Process Engineers develop the flow sheets for estimated discharge data i.e. stack discharge, which is then the input information for the Safety Case which is undertaken by Safety and Risk Management personnel. As most discharge is contaminated by radiation the focus of the studies is to produce dose uptake figures and assess the radiological environmental impact. The main mechanisms used are ALARP studies (As Low As Reasonably Practicable) and cost-benefit analysis. The subject knew little of assessment procedures for non-radiological environmental impacts.

Where a decision must be made between design options, Kepner Tregoe analysis is a mechanism whereby a group scores alternatives individually, then the average score is taken to represent group consensus. A criteria weighting step is introduced which is derived by group agreement.

In the final stages of the interview the interviewee was asked if he had to contribute to the production of Environmental Statements. He answered that he did and told of involvement that he had with writing a BPEO assessment for a project, a job which usually is undertaken by the Lead Engineers. He also recounted his involvement with an ALARP assessment of aerial discharges where he had to decided how much capital was necessary to spend on improvement. He did not mention a contribution to an Environmental Statement specifically.

Interviewee B3

Design Role: Project Manager (Mechanical / Technical Design Manager)

Diagram: A2-1

Interviewee B3 is coming to the end of his involvement with one project and talked mainly of his involvement with a project based at [Site name]. He explains that projects operate within three frameworks which govern the limits that the design must achieve. The client framework will contain targets which often the reflect the national external regulations and, in the case of overseas clients, [Company name] must work towards the limits of that country. Client targets will usually go beyond compliance. There will be an internal framework within [Company name] and the external regulatory framework. The Safety and Risk Management group are the source of this type of information. The subject also says that company policy and past experience are sources of environmental information. The company is accredited for ISO 14001 and this is included in the company policy.

He illustrates an example where an assessment of dose uptake revealed that more shielding was required. This led to a brainstorming exercise where it was decided to increase the thickness of the steel wool. When asked if there were attempts to dematerialise in non-shielding situations the interviewee talks about corrosion assessment where vessel and pipework thickness is calculated according to the stream characteristics i.e. substance, temperature profile. In some cases where the corrosion behaviour is so unpredictable an excessive allowance would be required the designers design to replace. In situ monitoring of the corrosion shows when the vessel needs replacing. To facilitate this they design for upgradeability by designing access routes out of the cell (in the context of nuclear waste storage cells), easily demountable arrangements, for example flange pipework and lifting devices, such as in situ cranes may be required. The subject does not mention any tools or formal mechanisms by which the decision is made to design for replacement rather than adding corrosion allowance is made. This interviewee also engages in optimisation including optimisation to reduce material use.

The outputs are management related and most of the design output is through others on the design team. The subjects output is mainly decisions. He engages in Value Engineering and HAZOP mechanisms to reach these decisions and will contribute to the provision of documentation and instruction for the potential operators of the plant. Operating instructions are heavily influenced by the outcome of the Safety Case work undertaken by the Safety and Risk Management specialists. The subject has not had to write an Environmental Statement and is unsure who would have that responsibility.

Interviewee B4

Design Role: Mechanical Design Manager

Diagram: A2-2

Interviewee B4 is responsible for all aspects of mechanical design associated with the plant design including services and interfaces with other disciplines. There is a need to regularly interface with safety, Process, Civil and Architecture, Control and Instrumentation, specialists within Mechanical i.e. crane designers, as well as site operators and the client.

He must demonstrate that plant and associated waste can be decommissioned. As the function of the plant is to contain, process and export active waste the new plants are designed to 'eat their own waste' so failed components will be sealed in the waste drums and disposed of using the same route. Sometimes there is a need to separate high and low activity waste from waste streams. This represents a trade-off as the process of separation generates more active waste so it depends how on the proportions of low and high activity waste.

The subject is a key decision maker and is involved with KT studies. He describes a recent building layout review where the team aimed to optimise building layout and size with respect to functionality, operability, maintainability and through-life costing (TLC). No software is used for TLC and the subject does not favour size reduction of building designs as large buildings tend to be constructed quicker (more work faces), provide a better working environment and presents less conflict with safety due to access problems etc. It also increases the ease of retrofitting equipment. However, he adds that there is a driver by the company to minimise building size.

He describes Value Engineering studies as decisions based on 'musts'. Those criteria which must be fulfilled. The Kepner Tregoe analyses are describes as 'wishes' where the core criteria have been satisfied but design options are generated to account for less important attributes in. The interviewee is also involved in HAZOPs which can deal with environmental aspects. He gave examples of a service routing HAZOP where insufficient fire barriers were identified. A second example was the analysis of hazards associated with a hydraulic grab which could introduce flammable substances into the waste drums which led to substitution with a water based hydraulic power pack.

Outputs from the subject included mechanical building layout, service routing, machine specifications and drawings, electrical requirements for plant, ventilation flow diagrams and the production of the Safety Significance document with Electrical and Instrumentation which identifies parts of the control system which are safety significant.

The subject is heavily involved with group decision making exercises but there is no mention of software packages for decision support. The group mechanisms that are employed appear to identify problems in detail and generate successful, innovative solutions.

Interviewee B5

Design Role: Senior Mechanical Engineer

Diagram: A2-3

Interviewee B5 mainly acts as design manager and his current project concerns Caesium removal scheme. He is involved directly in design and the formulation of specifications. He mentions his involvement in conceptual design studies and when asked to elaborate he explains that they are studies on different design options. It is probable that these are Value Engineering or Kepner Tregoe studies described by others (discussion was interrupted briefly).

The subject describes his involvement in material selection where he states that functionality is the most important criterion followed by cost. In answer to my question regarding whether capital cost or whole life cost is used he says that whole-life cost it was they are supposed to look at but due to difficulties with making whole-life cost estimates, capital cost tends to be the focus. Other criteria that he mentions are ease of manufacture and material lifetime. He talks of selecting material for an ion exchange column. Stainless steel is inappropriate due to the requirement for 23 % sodium chloride solution. Duplex steels that might withstand these salt concentrations are not commercially available for this application due to the complex nature of the column. Sintered filter plates do not exist in duplex steels therefore polypropylene is used which presents a conflict with design life. Plastic would be less easy to decommission due to loss of strength.

In reply to my question of whether materials are selected for environmental performance he answers that he designs for long life in order to obviate the need to replace components mid-life which is a complex task due to radiation contamination. He points out that this is a form of waste reduction. The interviewee says that they think hard about waste minimisation and pollution prevention. They try to involve operators in the design process especially in the context of designing for decommissioning. He sources information for material selection from the Materials Technology department if the situation is unusual or complex and the Safety and Environmental department for discharge limits.

He does attend brainstorming sessions to decision on design options. He lists criteria such as cost and ease of building as well as environmental criteria. He mentions that waste minimisation is a highly weighted decision criterion as waste creation is heavily linked with cost due to the difficult nature of the wastes.

The interviewee is not involved with Environmental Impact Assessment but may contribute indirectly by supplying the safety department with data.

Interviewee B6

Design Role: Principle Systems Engineer

Diagram: A3-1

Interviewee B6 is currently involved in designing monitoring systems for emission and discharge outlets. As Principle Systems Engineer he is mainly involved with conceptual design and will take on a quality role in detailed design, for example checking that functions engineers have applied the correct standards and practice codes. He receives models of stack emissions etc. and incorporates this into monitoring design so that it can be demonstrated to the Environment Agency that the project will comply with site discharge consents.

He talks of selecting the best process option where he adds that environmental discharge issues may not necessarily enter into selection. However, issues regarding waste measurement and inputs and processes associated with waste storage will feature. This is purely with respect to radiological impacts. The subject begins to discuss criteria for option selection and states that safety is number one. Other criteria are product quality issues, cost and discharges. In answer to my question about his involvement with BPEO he answers that he would contribute indirectly by providing instruments support for a particular process option.

The subject represents the systems and monitoring function by developing the environmental monitoring policy. He gets involved with people who take monitoring samples and works on sample representativeness so that the stack design facilitating accurate sampling which is a major design issue. Once it has been identified which equipment will be requires, design standards and codes will show what support systems, monitoring arrangements and associated space envelope will be required. For example, when the ventilation philosophy and ventilation flow diagrams have been completed at the conceptual phase there is discussion with Civil Engineering and Architecture with respect to spatial layout. He did not mention that specific tools were used to assist these trade-offs and said that optimisation of layout is treated as a constraint alongside other design constraints. It appears that much of the decision work is based on experience and discussion. The only formal mechanism mentioned was Kepner Tregoe analysis. He has some involvement in HAZOP studies but it was not mentioned in detail.

The interviewee discusses outputs where he mentions BPEO and the decommissioning philosophy which focus on radiological waste minimisation. He reviews the environmental monitoring document produced by the Systems function. He also reviews Hazard Schedules and extreme environment information. The waste management philosophy document produced by the subject concerns the minimisation and categorisation of waste which will depend on whether the client is UK based or overseas. This will include option for decontamination and discuss trade-offs. Other key documents from Systems and Monitoring are the Basis of Control and Electrical Instrument Design document, the Control Philosophy which deals with safety issues and the Plant Service Schedule which will account for plant consumables.

He added that public opinion had been accounted for in the selection of cable casing where PVC cables would give rise to visible, black smoke which could cause loss of public confidence. However, the primary environmental aspect throughout the interview was radiological waste. For this environmental aspect there appears to be many procedures in place to deal with this and there are many outputs in terms of documentation and decision support from Kepner Tregoe analysis. There was no mention of designing out non-radiological environmental impact, such as material or energy efficiency.

Interviewee B7

Design Role: Head of Systems Engineering

Diagram: A3-2

Interviewee B7 ensures that where risks have been identified the correct protection systems are in place in accordance with the goals of Best Practice. His role deals with environmental aspects in the mitigation and protection sense which is particularly relevant to pollution prevention and loss of containment issues. Secondly, he is involved with equipment selection, such as the specification of motors to match plant machinery. Energy efficiency is a primary goal in this instance and over-specification is avoided.

This leads to the selection of energy savings products, such as energy saving switch-off mechanisms and low energy drives. Specific targets for energy efficiency are not written into the specification and vendors are not audited for environmental performance. Design life of systems components maybe for the full design life of the plant or for a 10 year refurbishment plan. His role requires assessment of novel technology and he may call upon a university or the National Engineering Laboratory to assist the Systems function.

The subject talks of the recent trend towards treating environmental issues as an additional requirement. In the past the environment was always considered in terms of pollution and safety but now wider issues are included. Formal procedures to identify risks are mentioned and the subject is sometimes called into reviews. It is unclear what these procedures are from the interview. He does mention some involvement in HAZOP and states that 'environment' has always been included in these studies.

Process engineers are responsible for determining waste limits which the interviewee will satisfy by his work on systems design. He will provide information on these systems to regulators. In answer to whether he is involved with Environmental Statements he says that he may sometimes be required to provide a section on energy efficiency, however, I am unsure if the subject is familiar with the specific process of EIA and maybe referring to a similarly named process.

Interviewee B8

Design Role: Senior Systems Design Engineer

Diagram: A3-3

Interviewee B8 describes three projects that he is involved with, generally at the conceptual design stage. The first is the design of an automated electricity metering system which currently uses 32 Megawatts of power per. year. The proposed system will save between 5 and 10% in power consumption leading to a major improvement in energy efficiency. He investigates new monitoring technology and discusses some advanced systems which email data on electricity usage to cost engineers and other functions with an interest in utility consumption figures.

The subject points out the need for through life costing with respect to systems monitoring design and he must demonstrate the financial savings for concept design monitoring technology. The second project concerns the design of a monitoring system for a pipeline. Water is taken from the local river and used in the plant cooling systems. The pipe which discharges the water back to surface waters is open and collects debris. The monitoring system will measure pipe flow at two points in order to identify that the pipe is clear and no solids are discharged along with the aqueous effluent.

The third project is based on waste retrieval. Waste must be moved from one site to another and therefore there are safety and critcality events which must be mitigated. The subject was involved in the production of a map of the movement of waste so inefficiencies can be designed out. Value Engineering is used as the mechanism for this and options are produced and assessed. His job is to provide information on ventilation systems and the radiometrics monitoring system and to produce cost estimates prior to procurement. The decision is based on objectives to minimise waste generation, comply with the safety case and complete the project within the time-scale. The nature of the project will require the involvement of the local Parish Council, the Environment Agency and local residents. He must also take into account that worker must operate the plant wearing full protective clothing which will introduce an ergonomic factor.

The subject returns to the subject of energy efficiency and explains that the use of variable speed drives are beneficial and good maintenance regimes increase the efficiency of plant. Interviewee B8 has been with the company for a substantial period and he informs me there has been a definite shift from the consideration of capital expenditure to through-life costs. He feels this is mostly due to the engineering function being part of the PLC so the success of the project trough the whole life-cycle affects the design subsidiary. Previously, engineering functions were separate business concerns which created a strong ethic of working to time schedule within estimated capital cost.

In terms of outputs, his work contributes to securing bids. He then works on the Basis of Design and Engineering Flow Diagrams. The subject is involved with the production of the environmental monitoring document and the pre-commencement safety report which is supported by HAZOP results which are entered on a risk register. The risk register is the Hazard Schedule and sometimes takes on the form of a database depending on project size. This will also include results from ALARP studies and other safety related information.

Interviewee B9

Design Role: Systems Department (Control and Instrumentation Engineer)

Diagram: A3-4

Interviewee B9 designs monitoring systems which concern all the safety systems that control workers conditions inside the plant. His work also runs into monitoring of plant discharges. He begins by talking about the strict company guidelines which underpin the design of stack discharge monitoring systems. The subjects design activities also receive input from a Radiation Protection Supervisor (usually one for each project) who looks at the potential for the plant to discharge and writes the safety case.

External regulation is brought into design activities by discussion with the Nuclear Installations Inspectorate who advise on how waste streams should be dealt with. There is some contact with the working party which sets discharge limits at the Environment Agency.

During design the interviewee will interface with the ventilation designers with regard to pipework. Layout issues require interaction with Civils and Architecture. He does not use any databases to acquire environmental information but he discusses HAZOP and Value Engineering studies which appear to be his main mechanisms for handling environmental design criteria. He described the Value Engineering studies that he had been involved with and said that the facilitator weighted the criteria. Although the group all came to a consensus score for alternatives it is unclear whether the weighting step was a consensus decision or determined solely by the facilitator. When asked about designing for energy efficiency he could see no application to his work and suggested it was more of a pipe distribution issues.

His outputs include the writing of specifications, the production of design drawings and project correspondence between different parties as mentioned above.

Interviewee B10

Design Role: Senior Architect

Diagram: A4-1

Interviewee B10 has completed work on a major waste re-packaging project and has recently been involved in bid support work. He works on material selection and adds that he tries to select materials which are less damaging to the environment in the production and operation stages of the life-cycle. There has been more effort to look at through life costs in design selection and the subject describes a design decision on paint systems which involved material substitution. One option was a water based epoxy paint which has been used frequently in the past. The new option is a non-water based polymer which enables off-site coating and is more durable so less requirement for reapplication mid-life, however, the first coating is more expensive. Life-cycle cost arguments are used but there is no TLC software to assist the problem. Currently figures are produced by the Cost Estimators.

He also talks of an example of material elimination, where they have purchased self-finishing materials i.e. concrete to eliminate the need for coating. An interesting example is given where a decision has accounted for public risk perception. A HAZOP study was the mechanism used to decide whether a lower performance insulation material should be chosen in place of a higher performance building cladding composite which was lighter, less expensive but would give off black smoke in the instance of a fire event. This would increase the perceived risk of plant operations in the minds of the public which is important to avoid.

In these examples, options have been assessed without life-cycle analysis or similar tools to assess the overall environmental / societal burden associated with the options. There is no formal decision making process. The designer will collect data from product manufacturers and use his or her experience and judgement in order to select the best option. Interviewee B10 has conducted some basic audits of suppliers and he recognises that although there is a commitment to addressing environmental issues with respect to product selection and design in the company policy, there is no formal system in place. Although this is not a full audit it is input for the documentation on environmental aspects. In his opinion the information is collected primarily to support decisions already made. It does not happen early enough in the design process.

Outputs include material and performance specifications and design drawings which form the basis of tender. He concludes by saying that tools to support decision making would be welcome as decisions are becoming increasingly complex.

Interviewee B11

Design Role: Project Architect

Diagram: A4-2

Interviewee B11 designs nuclear related buildings which includes service buildings and industrial plant. His departments has been taking on more bids and development work overseas which the subject has been involved with. The function integrates environmental criteria with building design and construction and they expect their contractors (suppliers) to account for this. This is in accordance with their corporate Environmental Statement which includes goals to achieve energy efficiency. The company have also been accredited for ISO 14001 and some projects have been reviewed for environmental aspects.

To achieve these goals energy efficiency targets are put directly into specifications. The subject hopes that all building designs will achieve excellent ratings on the BRE rating scheme known as BREAM.

The design must also meet Building Regulations, for example for insulation materials and the subject says that domestic housing regulations are used as guidelines for industrial buildings.

The interviewee is particularly interested in the management of buildings, for example the controls of room temperature and light levels according to requirements. He tries to look at energy demands of materials from manufacture through to operations and the function is beginning to collect data from suppliers. They are also beginning to request environmental mission statements from suppliers and the subject asks for information regarding the recyclability of the material. He mentions a government initiative aims to improve energy efficiency of construction.

The subject is a trained facilitator and holds brainstorming sessions which may be concerned with environmental issues. He would like to see procedures in place for the design of greener buildings, however, the function appear to making significant process in the absence of formalised procedures.

Interviewee B12

Design Role: Principle Architect

Diagram: A4-3

Interviewee B12 is accompanied by a student who is working in the department and involved in the energy minimisation task force. He will be referred to as subject 12b.

Interviewee B12 works as a principle architect in Civil Structure and Architecture Design. He is engaged in a laboratory building design for the parent company and he also is involved with bids for external work. He was the co-author of a paper on intelligent building design which was presented to Building Research Establishment (BRE). This reflects the subjects strong commitment to energy efficient buildings which he was interested in prior to formal company objectives being set in this area. He elaborated on his interest in eco-design by describing photocells to control light systems and the use of up-lighting. The subject leads a group tasked with designing for energy conservation.

The department have used external organisations to help increase energy efficiency. Consultants have been brought in to do studies and one company analysed their 3D architectural model for air movement, temperature differentials and light penetration.

In answer to my question regarding designing for decommissioning the subject mentioned designing structures composed of sections of steel which can be easily taken apart. They have previously purchased roofing form a manufacturer who will take the materials back at end-of-life as part of their contract. There was no particular financial gain associated with this. He also said that they try to maximise the use of recycled materials in new constructions. This type of activity is mainly in relation to service buildings. However, at the plant level old aluminium components have been decontaminated and smelted down for re-use. In general the interviewee tries to purchase green products (he mentions energy efficiency in the context of 'green'). The subject talks of looking at the 'total energy picture' and he has recently begun to ask suppliers for data to support this objective.

Interviewee B12 talks of the task force for energy minimisation. He also mentions an energy audit conducted by an external consultant used to find potential for energy conservation using a 'pathfinder' type document which suggests efficiency methods for various design functions. He added that they hope to create a similar assessment process specifically targeted at the nuclear industrial sector and they have a contract with BRE to develop a tool for this.He hopes that future buildings would achieve a good to very good BREAM rating. Other mechanisms mentioned during the interview are brainstorming and HAZOPs. The subject occasionally attends HAZOPs and is currently developing an Expert System with BRE for roofing and cladding materials which will be an intelligent question and answer list which will present an auditable decision trail. He comments that this should reduce the number of design decisions which are made because they were made in previous design projects.

For input he talks about extreme event data required for the Safety Case. Meteorological data will be given as part of the tender or will be accessible from the operations site. This is readily available. He also mentions the on-going company objective to protect the public from radiation at plant boundaries which will also protect the environment. Input also includes the external consultancy work, BRE projects and data gathering from manufacturers as previously mentioned.

Outputs include drawings, calculations, reports, safety cases, schedules and access databases. He is also occasionally involved with Environmental Impact Assessment and has published technical papers in his function area.

Interviewee B13

Design Role: Technical Manager

Diagram: A5-1

Interviewee B13 works on bids, proposals and projects in order to ensure the most appropriate technology is being applied. He also follows the projects through the design process and acts as a facilitator for feedback from operating plant to new design. He adds that although there are processes for this feedback they are not fully formalised and there are not review processes in place to ensure review in the correct time-frame. Furthermore, there are no formal processes to implement the findings in new project design. The subject has been working on a business plan for the last few months and has highlighted these areas for improvement.

The interviewee talks in depth about his part in selling company strategies to overseas clients. He helps them develop their criteria and needs and provides them with performance data from technology operating in the UK. During optimisation of waste processing and storage packages for clients he handles radiological and chemical composition data. He receives data from the modelling group regarding migration and geology characteristic of the proposed site and determines the need for shielding.

The subject talks about a development of technology and its impact on waste minimisation. The new technology removed a wet process step which involved solvent. They later removed further stages which resulted in less contaminated process equipment to dispose of, less exposure of workers to radiation doses and less direct waste i.e. no solvent to dispose of.

His design work has also improved energy efficiency in the instance of improving ventilation systems. However, he says that savings in utilities are 'small beer' compared with the capital spent on plant design and energy wastage is 'lost in the noise'. He adds that it is an area which they need to consider more but is not convinced focusing on these areas would yield any great improvement.

In terms of output he has produced environmental statements for some projects, however, they have been straight forward as the projects in question had virtually no environmental impact and therefore could be undertaken in-house.

Interviewee B14

Design Role: Technical Manager

Diagram: A5-2

Interviewee B14 is responsible for ensuring that the company uses the best or most appropriate technology in bids and projects and his involvement spans across the whole business. He says it is difficult to discuss how he deals with environmental performance during his work as it enters everything that he does and cannot be treated as a separate criterion. His function will either develop new technology or identify improved technology that exists within the market place. Sometimes he will receive information from the operators of existing plant with regard to new technological development and is aware that the mechanism for this type of feedback needs to be formalised. He will also consult with external suppliers with respect to new technology that they have to offer. There is not much novel technology in this industrial sector. Developments are usually an improvement of existing technology.

In terms of mechanism he participates in Value Engineering studies and Kepner Tregoe analysis. He also sits on design review meetings. He mentions that some clients will occasionally ask for a BPEO study which he will contribute too, however, he continues to say that they rarely mean BPEO in the full sense.

In response to my question regarding conflict between environmental objectives and other design criteria he cannot think of a particular example but this happens often as part of design. The interviewee suspects that 'many issues are done [resolved] subconsciously'. Kepner Tregoe analysis is also a mechanism for conflict resolution which he had already mentioned.

The subject says that the design process has not been affected since the introduction of ISO14001 but feels that the company policy goes beyond the standard requirements. When asked if suppliers are assessed for their environmental performance he said that he couldn't answer the question.

If the subject requires information regarding environmental legislation etc. he will go to [a named environmental specialist]. He generally interfaces with all engineering functions, Research and Development, Operations, Marketing and Business Development. When asked about his work outputs he replied that he was not formally responsible for the production of design documents. His main output is his influence on design through peer reviews.

Interviewee B15

Design Role: Technical Manager

Diagram: A5-3

Interviewee B15 is a project specific Technical Manager and comes from a Mechanical background. He co-ordinates work between Civils and Architecture, Mechanical and Systems and ensures that safety case requirements are met throughout all aspects of design. He is involved with HAZOP 1 studies (early HAZOPs, relatively high-level) which are attended by lead discipline engineers and authors of the safety case.

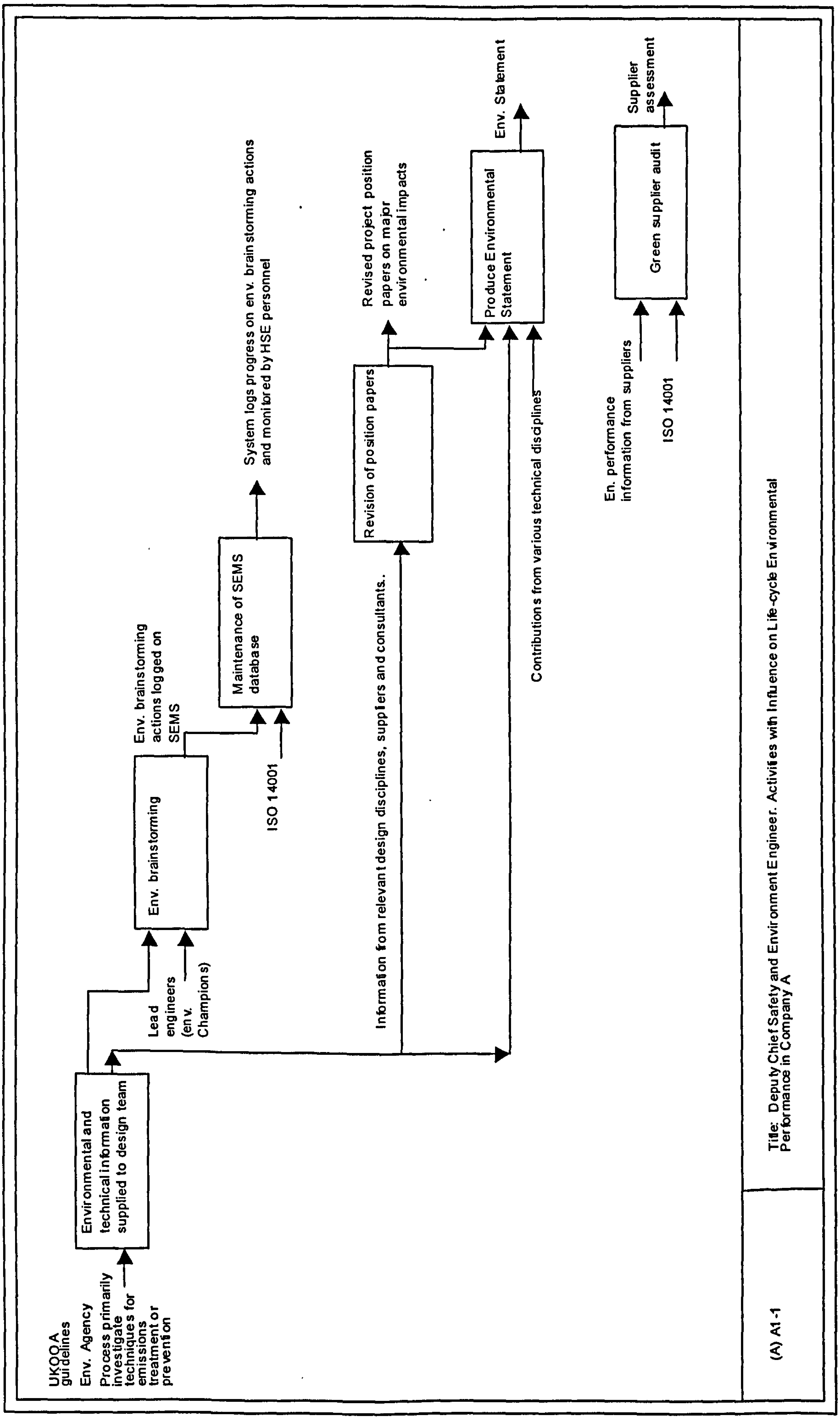
The project he is working on will deal with highly active waste and so shielding and containment are major requirements. He assesses the plant throughput to ensure that operations are compatible with up-stream and downstream operations. He receives modelling information from the Operational Research Department and will look at various scenarios.

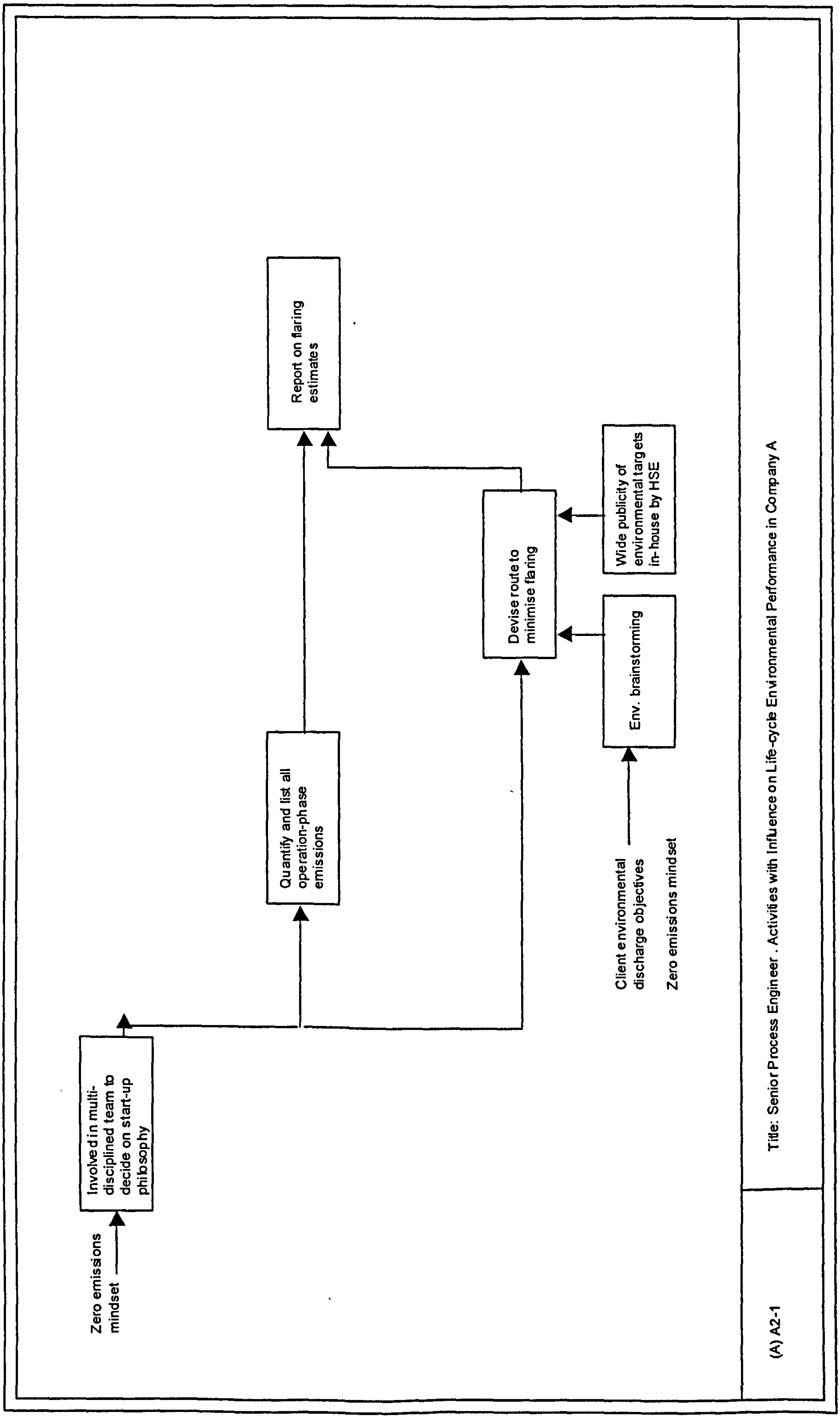
He has done a top-level optioneering study for the current project which addresses things like, should a new plant be built or should is be an extension on existing plant. He has no personal need for environmental information but he talks about general environmental requirements for the design process. As Technical Manager I asked the subject if he considered energy efficiency. He answered that it was not a big driver in his work. Due to the nature of the project most processes are operated remotely and the primary design criterion is reliability. It is important to design for minimal maintenance so components are designed with clean lines (to reduce radiation pick-up) and to minimise the amount of time human beings must be engaged in maintenance work. They try to design for modularity in the sense that if s component fails, the whole sub-system can be lifted out remotely as one unit. For example, a motor and gearbox will be designed as a complete unit which can be dropped onto the system remotely. Dowels are used to ensure correct alignment. If part of the system should fail either it is taken to an active workshop for repair or it is disposed of. There are high safety factors in the design and he describes it as 'battleship engineering'. That is to say, maximising reliability and safety by increasing shielding thickness, vessel thickness, enlarging and modularising components etc.

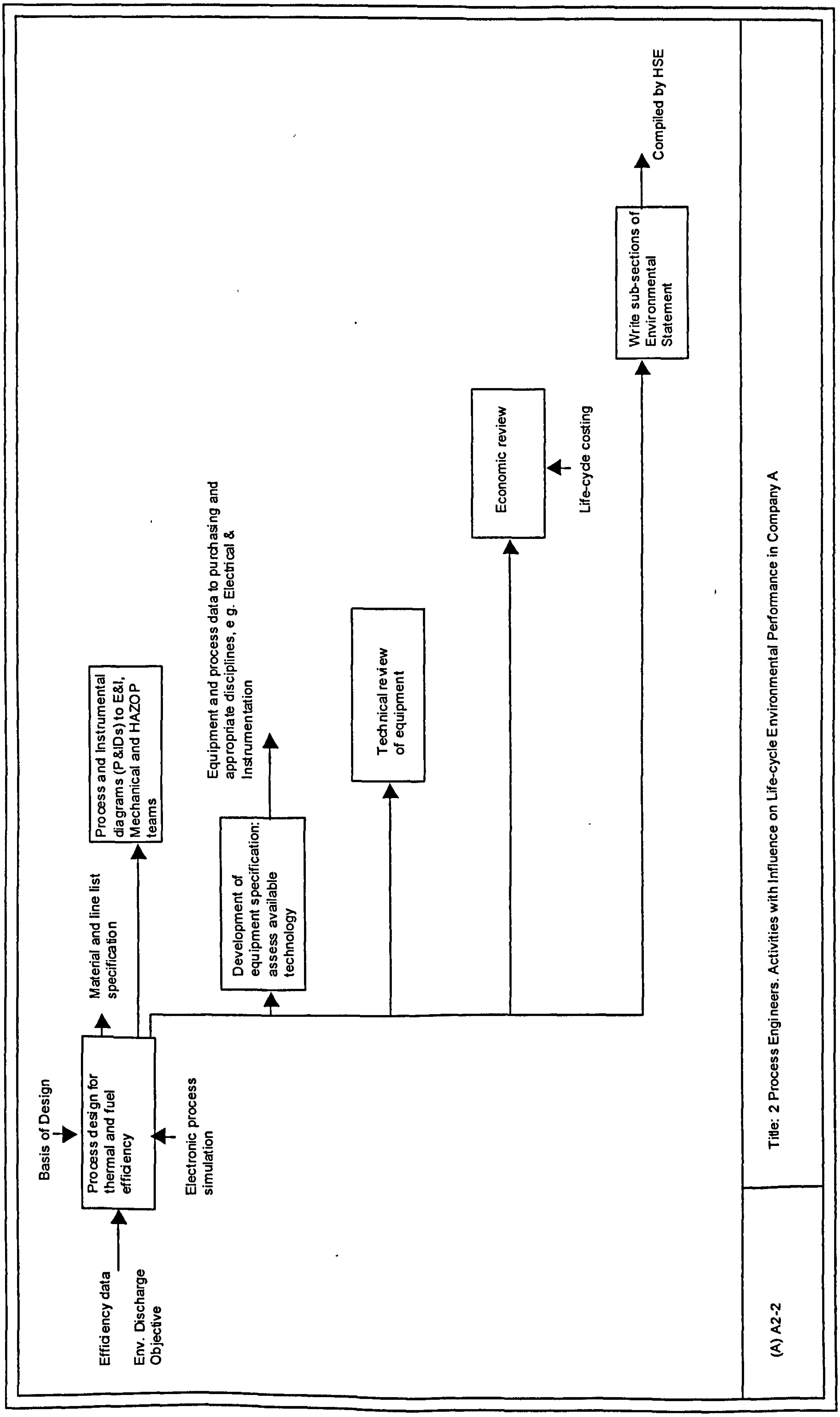
His outputs include the development of mechanical flow diagrams which show the sequential operation of equipment i.e. cranes. Design proposal drawings outline the general assembly and he will assist in the production of mechanical handling diagrams. He will receive information from the Safety advisor with respect to egress routes which the subject will build into design plans. The subject has been reviewing activities that need to be undertaken in order to produce all the underpinning documentation required when the Capital Expenditure Plan is presented. In terms of environmental objectives the client specification may well have environmental requirements and the Basis of Design which follows will take into account seismic data.

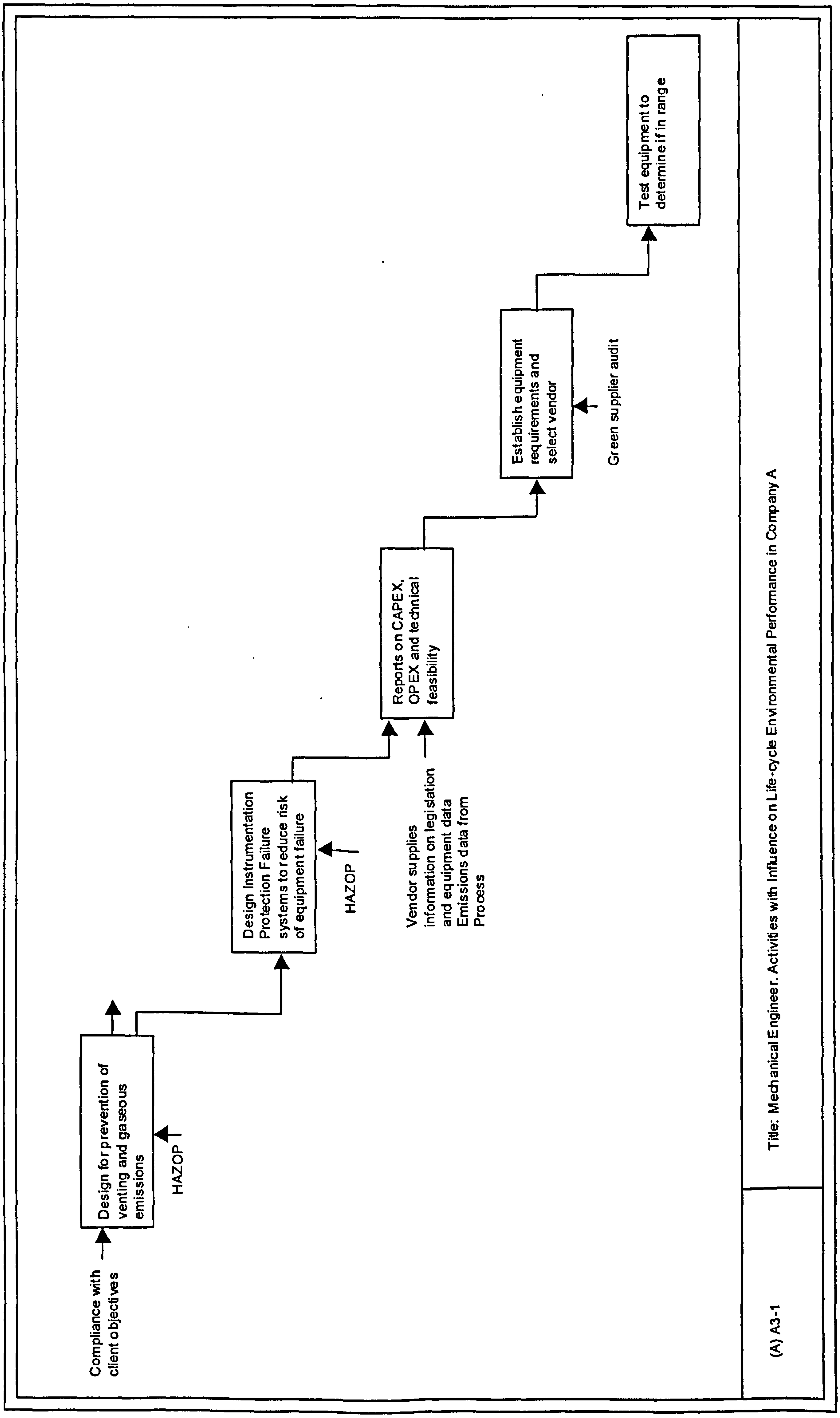
APPENDIX IV: IDEFO FIGURES

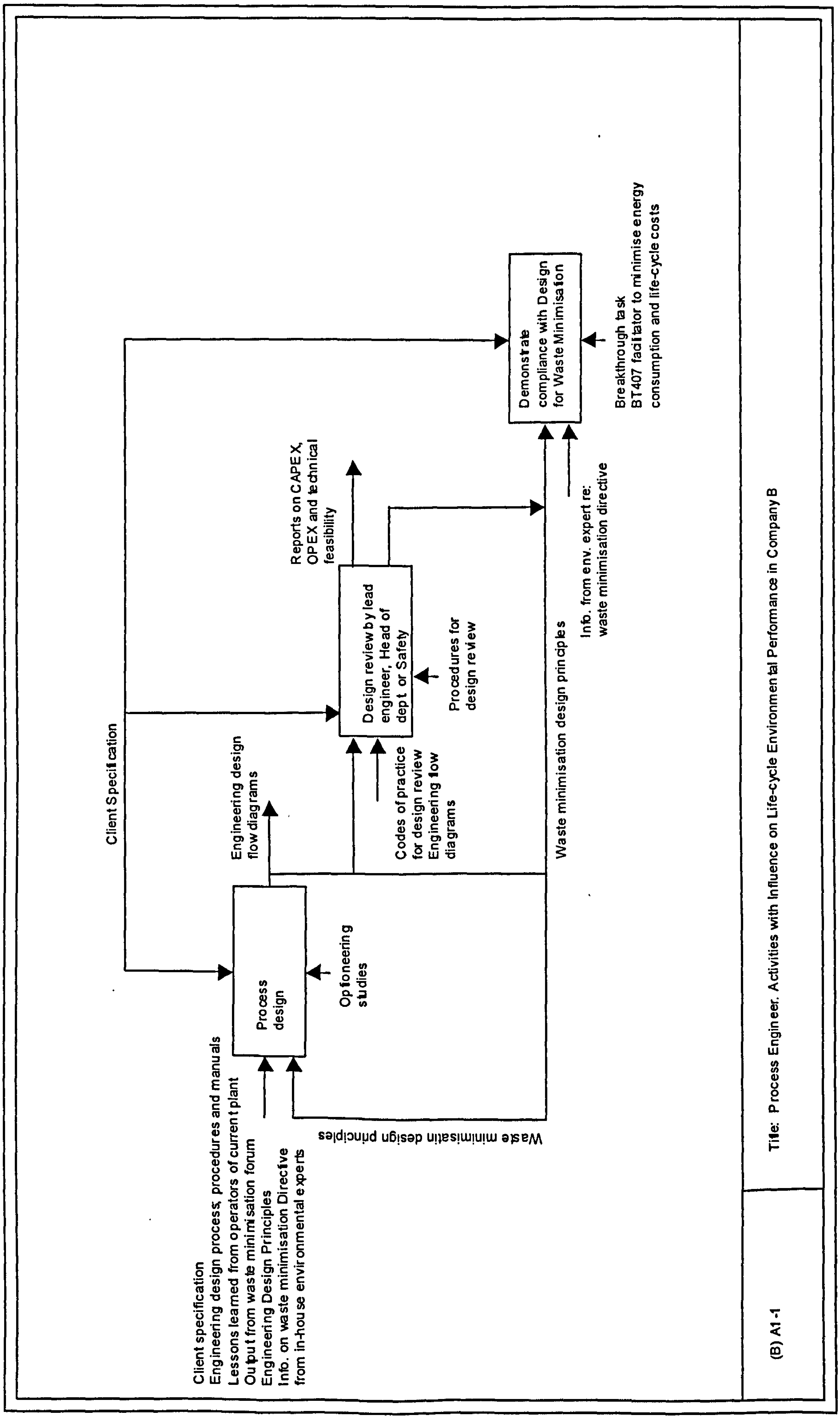
The following IDEF0 diagrams summarise the inputs, controls, mechanisms and outputs identified during the semi-structured interviews presented in Chapter 4. The Figures follow the IDEF0 modelling system (Mayer, 1990) and each diagram is referenced in the main thesis using its diagram classification label located on the bottom left-hand corner.

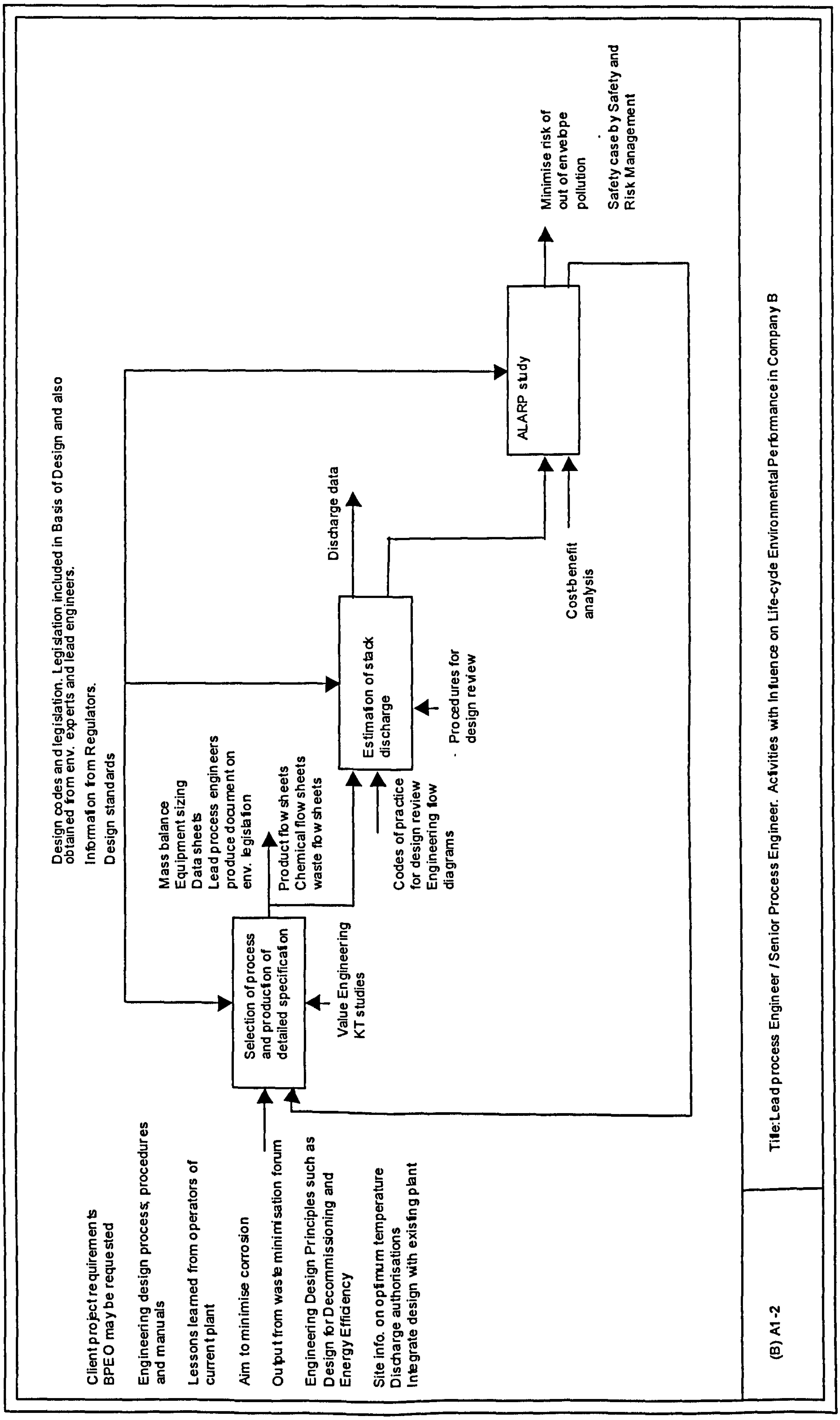

UKOOA guidelines
Env. Agency
Process primarily investigate techniques for emissions treatment or prevention
Environmental and technical information supplied to design team
Lead engineers (env. Champions)
Env. brainstorming
Env. brainstorming actions logged on SEMS
Maintenance of SEMS database
ISO 14001
System logs progress on env. brainstorming actions and monitored by HSE personnel
Information from relevant design disciplines, suppliers and consultants.
Revision of position papers
Revised project position papers on major environmental impacts
Contributions from various technical disciplines
Produce Environmental Statement
Env. Statement
En. performance information from suppliers
ISO 14001
Green supplier audit
Supplier assessment
(A) A1-1
Title: Deputy Chief Safety and Environment Engineer. Activities with Influence on Life-cycle Environmental Performance in Company A

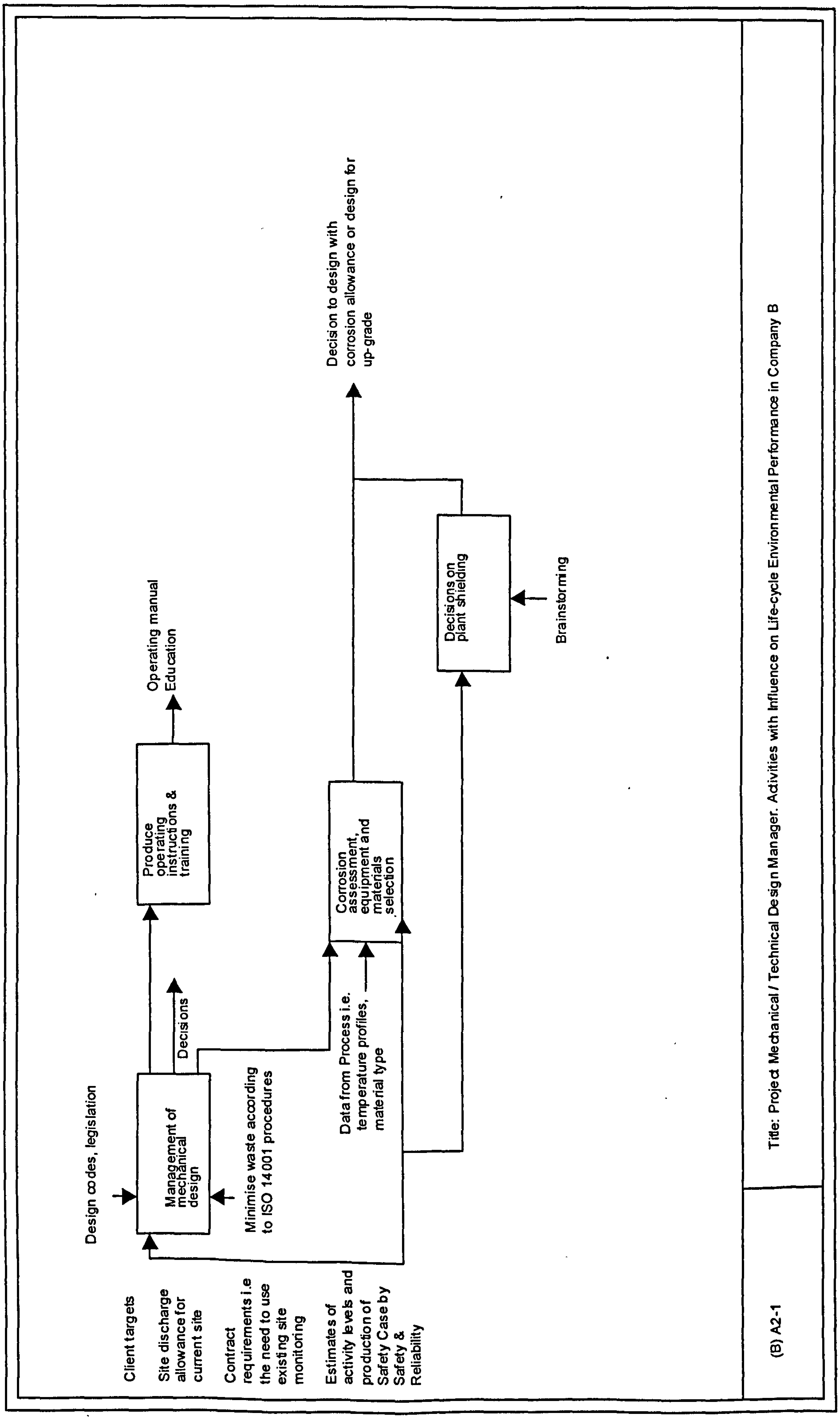

Zero emissions mindset
Involved in multi-disciplined team to decide on start-up philosophy
Quantify and list all operation-phase emissions
Report on flaring estimates
Devise route to minimise flaring
Env. brainstorming
Wide publicity of environmental targets in-house by HSE
Client environmental discharge objectives
Zero emissions mindset
Title: Senior Process Engineer . Activities with Influence on Life-cycle Environmental Performance in Company A
(A) A2-1

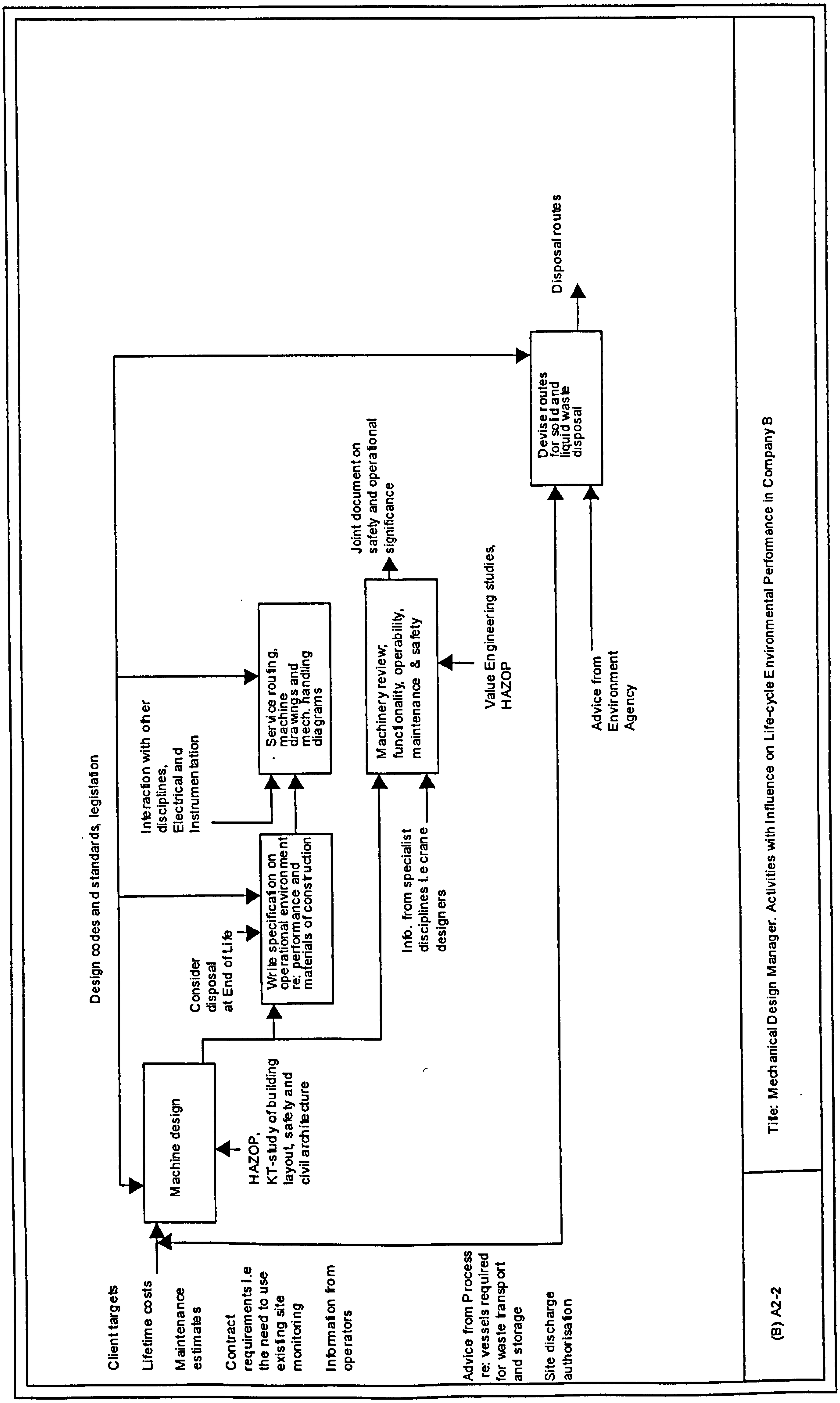

Efficiency data
Env. Discharge Objective
Basis of Design
Process design for thermal and fuel efficiency
Electronic process simulation
Material and line list specification
Process and Instrumental diagrams (P&IDs) to E&I, Mechanical and HAZOP teams
Development of equipment specification: assess available technology
Equipment and process data to purchasing and appropriate disciplines, e g. Electrical & Instrumentation
Technical review of equipment
Economic review
Life-cycle costing
Write sub-sections of Environmental Statement
Compiled by HSE
(A) A2-2
Title: 2 Process Engineers. Activities with Influence on Life-cycle Environmental Performance in Company A


Compliance with client objectives
Design for prevention of venting and gaseous emissions
HAZOP
Design Instrumentation Protection Failure systems to reduce risk of equipment failure
HAZOP
Vendor supplies information on legislation and equipment data Emissions data from Process
Reports on CAPEX, OPEX and technical feasibility
Establish equipment requirements and select vendor
Green supplier audit
Test equipment to determine if in range
(A) A3-1
Title: Mechanical Engineer. Activities with Influence on Life-cycle Environmental Performance in Company A

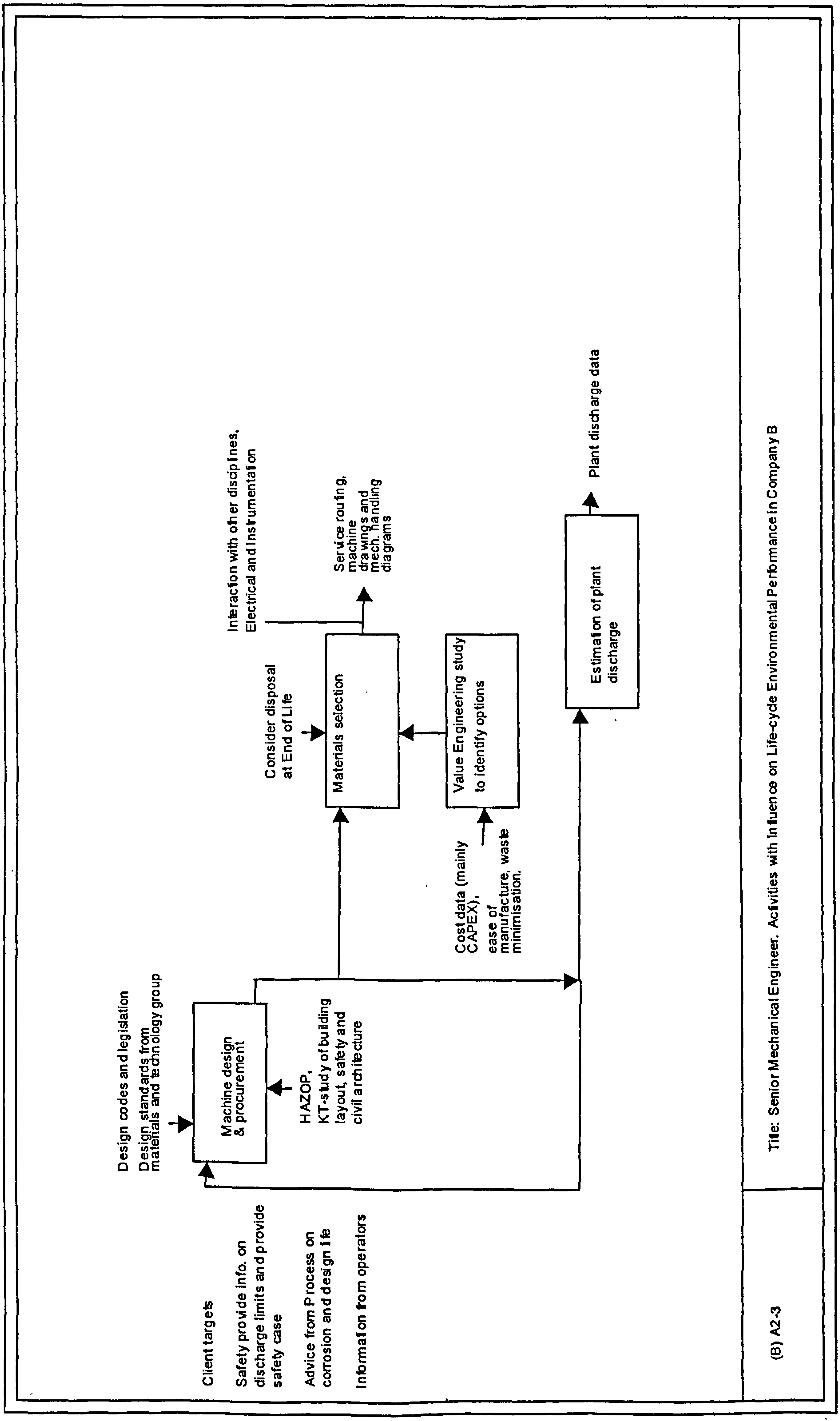

Client specification
Engineering design process, procedures and manuals
Lessons learned from operators of current plant
Output from waste minimisation forum
Engineering Design Principles
Info. on waste minimisation Directive
from in-house environmental experts
Waste minimisatin design principles
Client Specification
Process design
Optioneering studies
Engineering design flow diagrams
Codes of practice for design review
Engineering flow diagrams
Design review by lead engineer, Head of dept or Safety
Procedures for design review
Reports on CAPEX, OPEX and technical feasibility
Waste minimisation design principles
Info. from env. expert re: waste minimisation directive
Demonstrate compliance with Design for Waste Minimisation
Breakthrough task
BT407 facilitator to minimise energy consumption and life-cycle costs
(B) A1-1
Title: Process Engineer. Activities with Influence on Life-cycle Environmental Performance in Company B

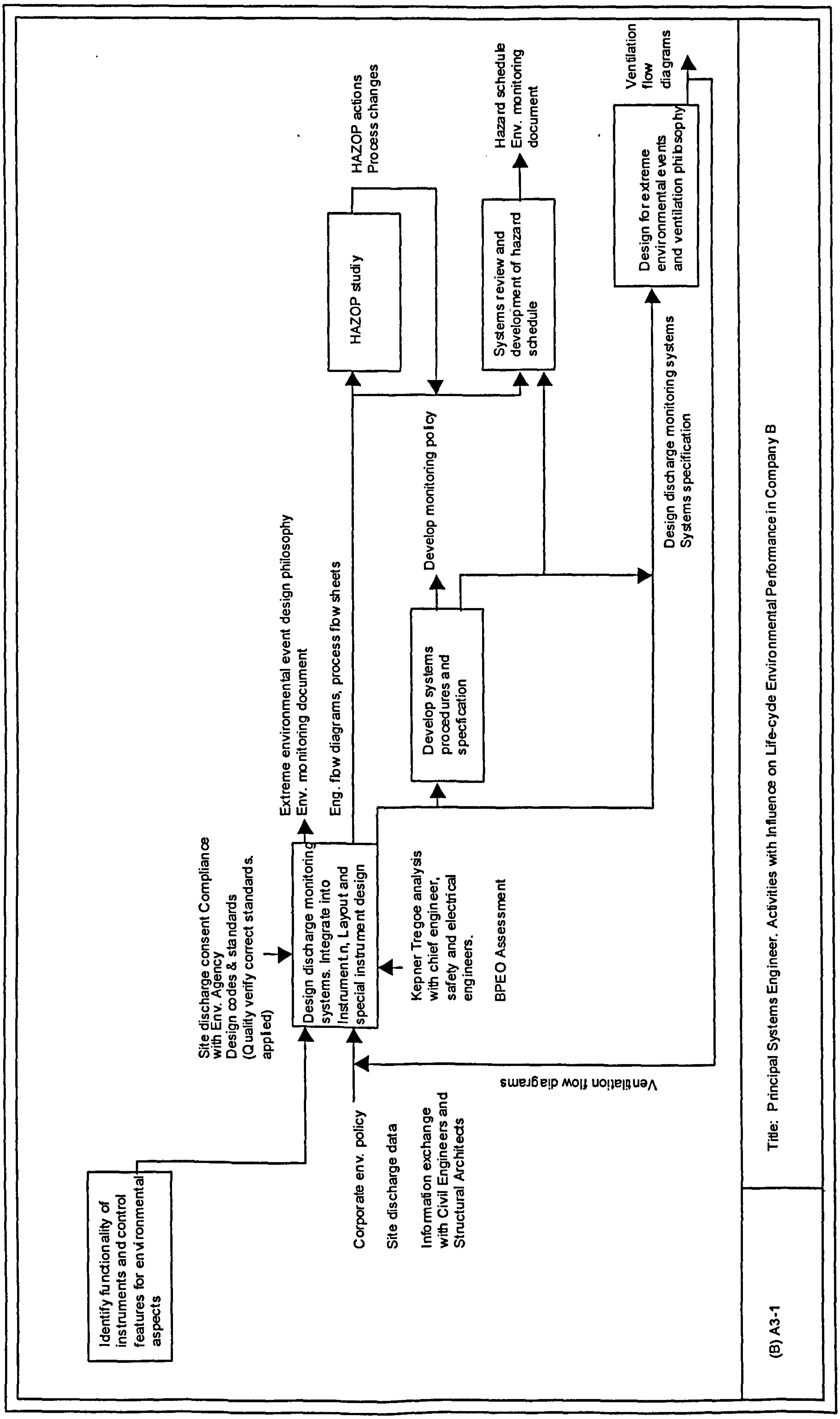

Client project requirements
BPEO may be requested
Engineering design process, procedures and manuals
Lessons learned from operators of current plant
Aim to minimise corrosion
Output from waste minimisation forum
Engineering Design Principles such as Design for Decommissioning and Energy Efficiency
Site info. on optimum temperature
Discharge authorisations
Integrate design with existing plant
Design codes and legislation. Legislation included in Basis of Design and also obtained from env. experts and lead engineers.
Information from Regulators.
Design standards
Selection of process and production of detailed specification
Value Engineering
KT studies
Mass balance
Equipment sizing
Data sheets
Lead process engineers produce document on env. legislation
Product flow sheets
Chemical flow sheets
waste flow sheets
Estimation of stack discharge
Codes of practice for design review
Engineering flow diagrams
Procedures for design review
Discharge data
Cost-benefit analysis
ALARP study
Minimise risk of out of envelope pollution
Safety case by Safety and Risk Management
(B) A1-2
Title: Lead process Engineer / Senior Process Engineer. Activities with Influence on Life-cycle Environmental Performance in Company B

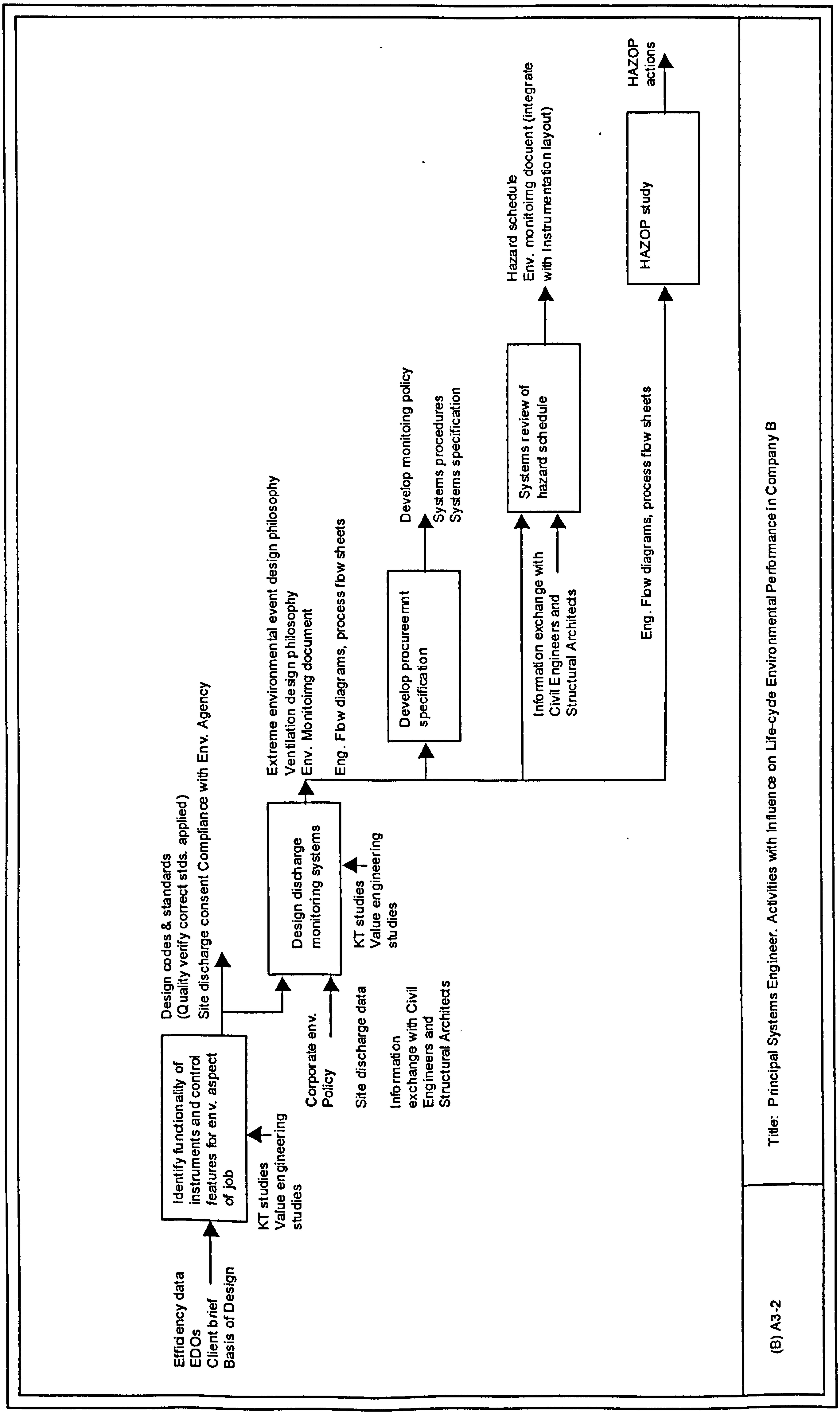

Client targets
Site discharge allowance for current site
Contract requirements i.e the need to use existing site monitoring
Estimates of activity levels and production of Safety Case by Safety & Reliability
Design codes, legislation
Management of mechanical design
Minimise waste according to ISO 14001 procedures
Decisions
Produce operating instructions & training
Operating manual Education
Data from Process i.e. temperature profiles, material type
Corrosion assessment, equipment and materials selection
Decision to design with corrosion allowance or design for up-grade
Decisions on plant shielding
Brainstorming
(B) A2-1
Title: Project Mechanical / Technical Design Manager. Activities with Influence on Life-cycle Environmental Performance in Company B



Title: Mechanical Design Manager. Activities with Influence on Life-cycle Environmental Performance in Company B

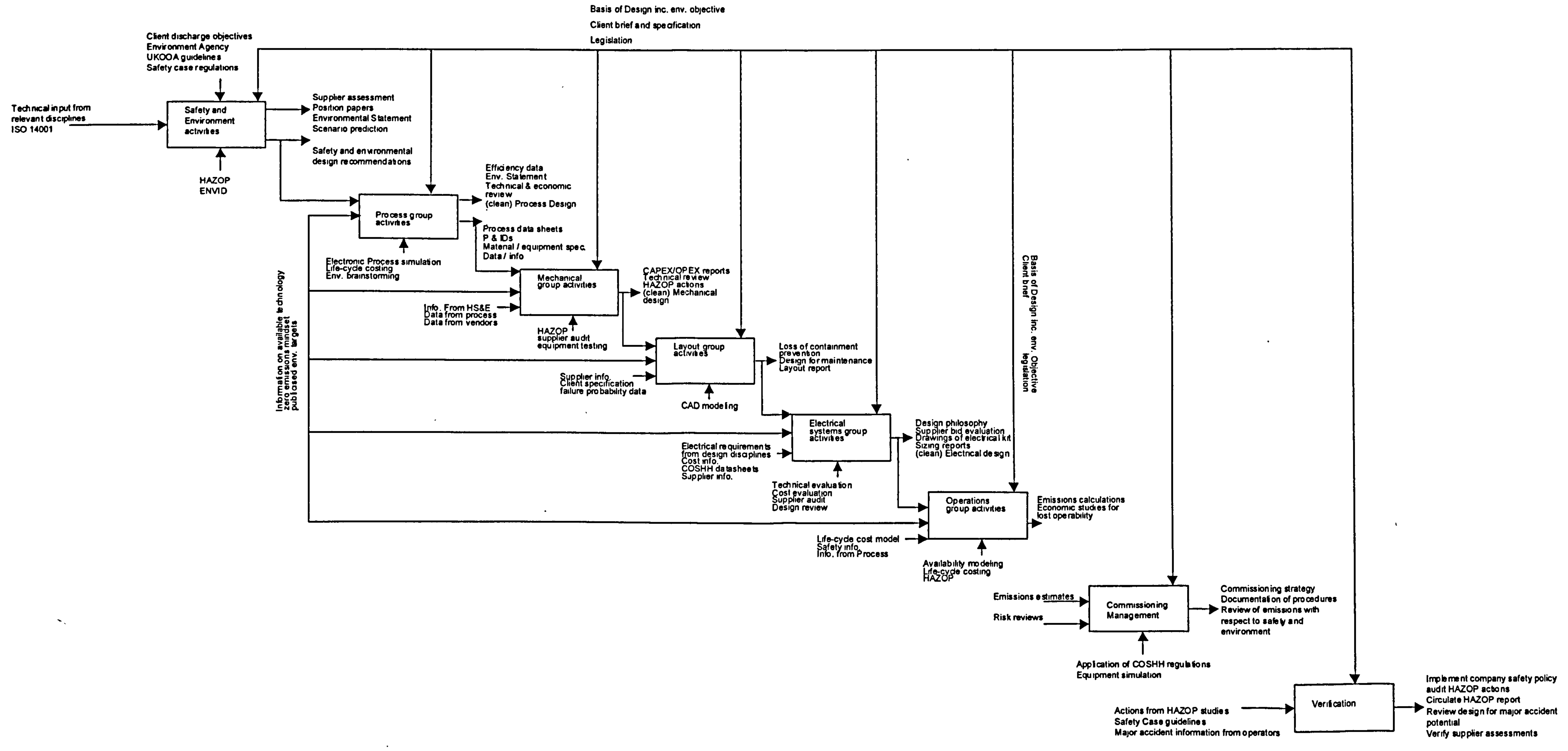

Client targets
Safety provide info. on discharge limits and provide safety case
Advice from Process on corrosion and design life
Information from operators
Design codes and legislation
Design standards from materials and technology group
Machine design & procurement
HAZOP, KT-study of building layout, safety and civil architecture
Consider disposal at End of Life
Materials selection
Interaction with other disciplines, Electrical and Instrumentation
Service routing, machine drawings and mech. handling diagrams
Value Engineering study to identify options
Cost data (mainly CAPEX), ease of manufacture, waste minimisation.
Estimation of plant discharge
Plant discharge data
(B) A2-3
Title: Senior Mechanical Engineer. Activities with Influence on Life-cycle Environmental Performance in Company B


Identify functionality of instruments and control features for environmental aspects
Site discharge consent Compliance with Env. Agency
Design codes & standards
(Quality verify correct standards. applied)
Design discharge monitoring systems. Integrate into Instrument.n, Layout and special instrument design
Kepner Tregoe analysis with chief engineer, safety and electrical engineers.
BPEO Assessment
Corporate env. policy
Site discharge data
Information exchange with Civil Engineers and Structural Architects
Ventilation flow diagrams
Extreme environmental event design philosophy
Env. monitoring document
Eng. flow diagrams, process flow sheets
Develop systems procedures and specification
Develop monitoring policy
HAZOP study
HAZOP actions
Process changes
Systems review and development of hazard schedule
Hazard schedule
Env. monitoring document
Design discharge monitoring systems
Systems specification
Design for extreme environmental events and ventilation philosophy
Ventilation flow diagrams
Title: Principal Systems Engineer. Activities with Influence on Life-cycle Environmental Performance in Company B
(B) A3-1



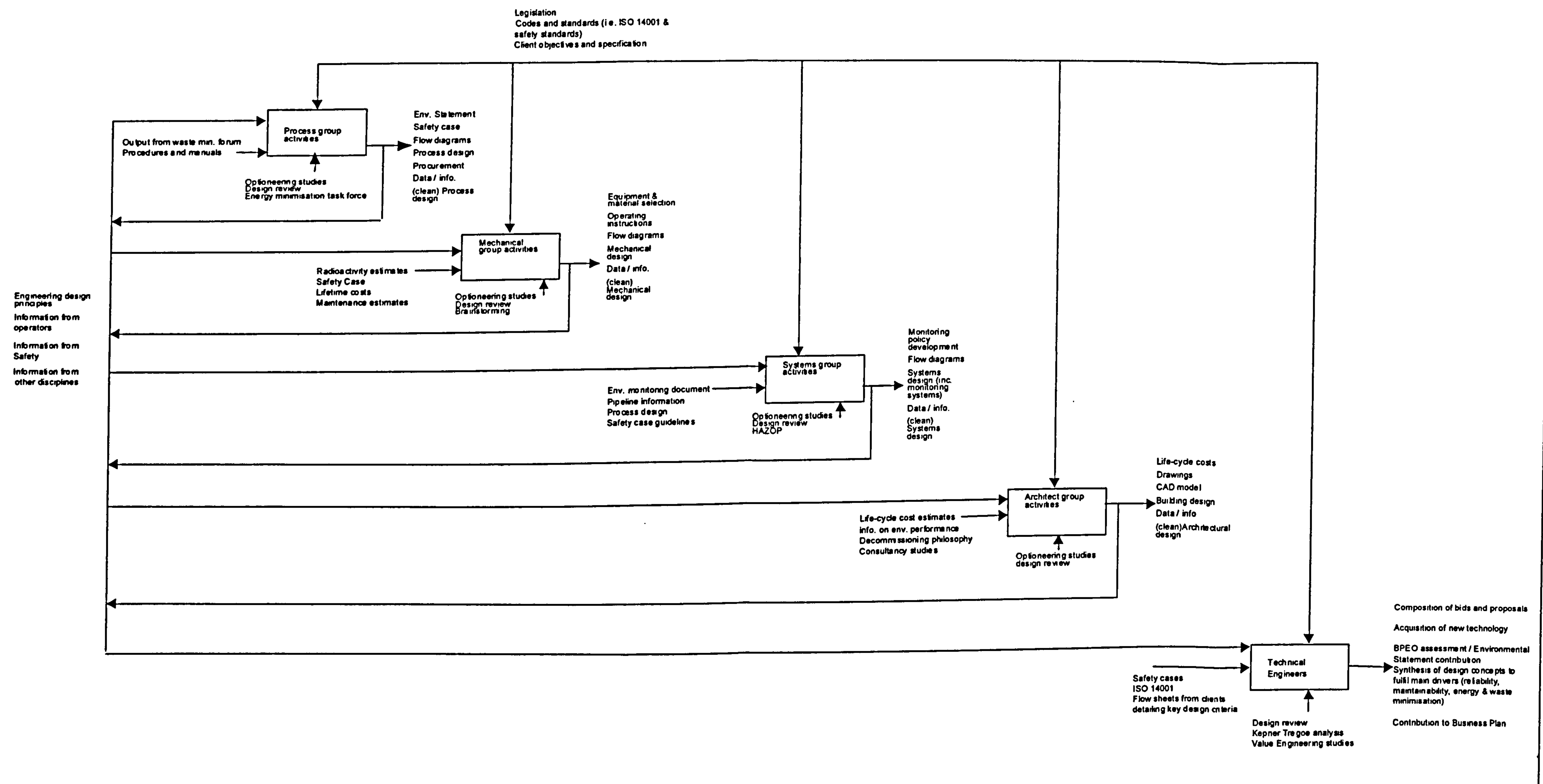
Title: Principal Systems Engineer. Activities with Influence on Life-cycle Environmental Performance in Company B

(B) A3-2



(A) A0

Title: Key Disciplines with Influence on Life-cycle Environmental Performance in Company A



(B) A0

Title: Key Disciplines with Influence on Life-cycle Environmental Performance in Company B

APPENDIX V: CURRENT PRACTICE QUESTIONNAIRE

NAME ....

POSITION ....

Q1. Are you under pressure from any of the following to incorporate environmental issues into the design process:

Driving Factors

Outside Regulation ❑
Internal Company Policy ❑
For ISO 14000 accreditation ❑
Customer Pressure ❑
Competitors ❑
Public Opinion ❑ *(any number of boxes may be ticked)*

Q1(a)	Outside Regulation	Company Policy	ISO 14000	Customer Pressure	Competitn.	Public Opinion
Company A (n=37)	28	26	24	22	8	6
% (Σ=114)	25.0	23.0	21.0	19.0	7.0	5.0
Company B (n=26)	18	23	5	15	6	17
% (Σ=84)	21.0	27.0	6.0	18.0	7.0	20.0

Q1b. If more than one box is ticked, please indicate the driving factor which has the most influence on the design process.

Q1(b)	Outside Regulation	Company Policy	ISO 14000	Customer Pressure	Competitn.	Public Opinion	None
Company A (n=37)	19	6	0	8	0	4	2
% (Σ=39)	48.7	15.4	0	20.5	0	10.3	5.1
Company B (n=26)	12	9	2	1	0	0	2
% (Σ=26)	46.2	34.6	7.7	3.8	0	0	7.7

Q2. To what degree is environmental impact considered in the design process at present:

It is not a consideration ❑ *(please go on to Q5.)*
It is a minor consideration ❑
It is a major consideration ❑

Q2	Major Consideration	Minor Consideration	Not a Consideration
Company A (n=37)	28	7	1
% (Σ=36)	77.8	19.4	2.8
Company B (n=26)	19	7	0
% (Σ=26)	73.1	26.9	0

Q3. If environmental impact is considered in the design process, what methods are currently used:

Discussion with Environmental personnel when required ❑
Organised brainstorming sessions ❑
Checklists to highlight potential environmental impacts ❑
Life cycle analysis tools ❑
Design for environment tools ❑
Other (please specify)

Q3	Discussion	Brainstorm	Checklists	LCA	DFE	Other
Company A (n=37)	30	12	20	11	4	3
% (Σ=80)	37.5	15.0	25.0	13.8	5.0	3.8
Company A (n=26)	18	7	7	4	1	7
% (Σ=44)	48.9	15.9	15.9	9.1	2.3	15.9

Q4. Have you seen any of the following tools used to minimise environmental impact at the design stage:

Design for disassembly ☐
Design for recovery ☐
Design for environment ☐
No ☐
Other ------------------------

Q4	Design for disassembly	Design for recycling / reuse	Design for environment	No	Other
Company A (n=37)	7	3	9	21	2
% (Σ=42)	16.7	7.1	21.4	50.0	4.8
Company B (n=26)	7	6	5	16	1
% (Σ=35)	20.0	17.1	14.3	45.7	2.9

Q5. Do you feel methodology to assist incorporating environmental issues as a design constraint would work best as;

A tool used by design engineers, integrated with the existing design process ☐
A tool used by environmental personnel followed by liaison with design engineers ☐

Q5	Tool used by design engineers, integrated with other design processs	Tool used by environmental personnel, followed by liaison with designer engineers
Company A	75	25
Company B	91.3	8.7

Q6. What format do you envisage for such a tool? *Rank the options, 1=best, 6=worst:*

A simple, diagrammatic aid to be worked through in structured discussions ☐
A concise, paper based referral manual ☐
A piece of software, separate from CAD packages ☐
Software integrated with existing CAD packages ☐
An environmental equivalent to HAZOP ☐
On-line referral manual ☐

Q6	Diagrammatic tool	Hard copy manual	Software	Software integrated with CAD	Environmental HAZOP	On-line reference guide
Company A	145	97	100	91	164	79
Mean	4.03	2.69	2.78	2.53	4.56	2.19
Rank Order	2	4	3	5	1	6
Company B	88	59	47	65	124	86
Mean	3.39	2.27	1.81	2.50	4.77	3.31
Rank Order	2	5	6	4	1	3

Q7. Environmental information affecting the design team, such as relevant legislation, is passed to design engineers by:

Meetings ❑
Informal verbal communication ❑
Memos ❑
Email ❑
Internet / On-line information system ❑
Reports ❑
Handbooks ❑
(please rank if more than one box is ticked, 1=mainly used, 7=least used).

Q7	Meetings	Verbal	Memos	E-mail	Internet	Reports	Handbook
Company A	153	119	143	139	12	176	66
Mean	4.14	3.22	3.86	3.76	0.32	4.76	1.78
Rank Order	6	3	5	4	1	7	2
Company B	84	71	73	25	45	67	35
Mean	3.23	2.73	2.81	0.96	1.73	2.58	1.35
Rank Order	7	5	6	1	3	4	2

Q8. Is the design team involved in the preparation of Environmental Impact Assessments:
Yes ❑
No ❑

Q8	The design team is involved with the EIA process	No design team involvement with EIA
Company A (%)	80	20
Company B (%)	87	13

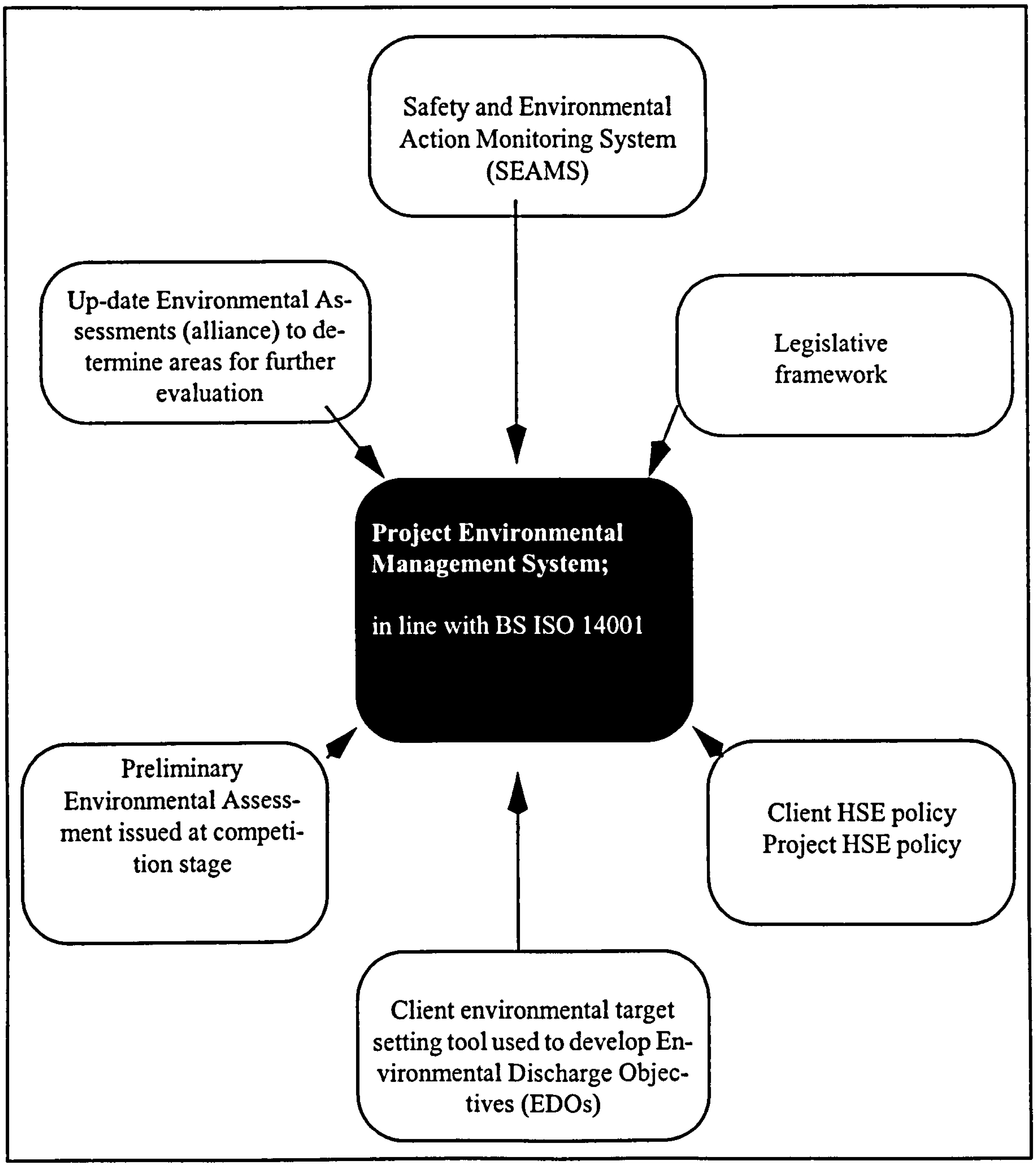
ANY ADDITIONAL COMMENTS:

APPENDIX VI: MULTIPLE ATTRIBUTE DECISION ANALYSIS (TOPSIS & CODASID)

Project Background

Company A has provided two case-studies upon which MADM methods may be evaluated. Figure 1 illustrates the environmental impact management structure employed by Company A. The project's quality management system includes ISO14001, which is supported by a project-specific HSE policy, procedures and environmental targets. The Safety and Environmental Action Monitoring System (SEAMS) is the information storage system which tracks progress on safety and environmental actions. This demonstrates the Client's commitment to improving environmental performance. However, the delivery of eco-design is dependent on the decision making undertaken by the alliance team, including the design contractor who will have strong business objectives.

Figure 1: Company A's Environmental Impact Management Model



Legislative Requirements of Case Study

Legislative requirements are complex as the project has a variety of sources of environmental impact spanning the project's life-cycle; fabrication, commissioning, operation, decommissioning, disposal and post-disposal. Listed below are the environmental impacts identified for the operations phase of the offshore facility which are controlled by legislation.

- *Flare and purge*; the key emissions are NO_x, SO_x, CO_2 and hydrocarbons. Consent to discharge is issued under the terms of the Petroleum Act 1998. In addition, discharges arising from flaring may soon be covered by the second phase of the EU Emissions Trading Scheme which will come into force in 2008. There are no plans to introduce an energy tax, however, this position could change.

• *Atmospheric vent*; the key emissions are unburnt hydrocarbons which are indirectly controlled by the DTI (Department of Trade and Industry) through issued consents.There are no plans for further legislation but greenhouse gases may become part of the EU Emissions Trading Scheme.

• *Power generation and gas compression*; the emissions involved are CO_2, CO, NO_x, SO_x and hydrocarbons. These emissions are controlled by the Offshore Combustion Installations (Prevention and Control of Pollution) Regulations 2001 which implement the IPPC directive offshore and introduce the concept of Best Available Technology (BAT). These Regulations require the operator to obtain a permit for power generation plant that exceeds 50 MWth. However, the permit does not cover carbon dioxide which is managed by Phase 1 of the EU Emissions Trading Scheme which will come into force in 2005.

• *Waste chemicals*; the disposal of waste or off-specification oils and chemicals is prohibited by the Prevention of Oil Pollution Act (1971) and Part II of the Food and Environmental Protection Act 1985, respectively. Routine operational discharges of oil must be exempted under the Prevention of Oil Pollution Act (1971) and chemicals must be subject to a permit under the Offshore Chemical Regulations 2002. Chemical discharges are controlled within these Regulations using a risk management tool called CHARM which replaces the voluntary Offshore Chemical Notification Scheme.

• *Produced water*; dispersed oil and dissolved oil containing heavy metals, organic compounds and production chemicals. Current legislation includes the Prevention of Oil Pollution Act (1971) which gives exemption to operational discharges below 40 ppm. However, it is considered Best Practice amongst members of UKOOA (UK Offshore

Operators Association) to work to 30 ppm. The lower limit will become a legal requirement in 2006 as part of the OSPAR initiative. In addition, new regulations are expected to replace POPA 1971 and introduce the concept of BAT. Industry is also considering a UK scheme to trade oil in produced water, as this would facilitate targeted investment to achieve an OSPAR target of 15% reduction in total discharges of oil in produced water. Production chemicals (e.g. corrosion protection agents, oxygen scavengers and biocides) in produced water and other oily waste streams are controlled under Chemical Regulations mentioned above and are being considered further by OSPAR.

Decision support systems are suitable for quantitatively defined legislative limits, such as oil and water concentrations. In this instance, these limits can be used as constraints and options that fail these limits can be deselected. However, the decision making process becomes more complex in the context of proactive regulation, such as Environmental Impact Assessment 97/11/EC or the Pollution Prevention and Control (PPC) Regulations (Environment Agency, 2000). In this case, it must be shown that an optimal solution has been reached, taking a wide range of factors into account that constitute the 'practicabilty' of an option or technique.

Project Environmental Policy

The client's environmental policy presents a set of requirements which must be integrated into design decision making. The document states that Health, Safety and Environmental objectives:

- Are of prime importance to [Company name].
- Have equal status with other primary business objectives.
- Are everyone's responsibility.

Specific environmental aims included in the policy are:

- To pursue the reduction of emissions and effluents from our operations, and where reasonably practicable, eliminate them.

• To establish and maintain high standards of environmental protection, pursue continuous improvement and integrate environmental protection into business processes.

The project-specific policy was written by the Development Alliance and was consistent with the client's policy, stating their commitment to:

• "Reduce harmful emissions and effluents by application of the best practicable environmental option and strive to continuously improve on past performance in all aspects of HS&E".

The client company used these aims to produce a set of tangible environmental discharge objectives which have been widely communicated throughout the design team, as shown in Chapter 4.

Environmental Target Setting and Environmental Discharge Objectives

A set of environmental discharge objectives (EDOs) were developed to define the volume or mass of a desired discharge level.

The following are particularly relevant to the case-study and applicable to the operations phase of the project or preferred design solution:

• *Gas loss through flaring and venting*: Less than 0.3 barrels of oil equivalent of annual production. Reduce flare emissions by selection of suitable processes and equipment.

• *Disposal of produced water by reinjection*: If reinjection is not BATNEEC then the concentration of oil discharged to sea is to be compatible with the surface environment. Remove dispersed oil using hydrocyclones.

• *Fuel Usage*: Minimise atmospheric emissions. Reduce fuel usage by selection of high efficiency processes and equipment.

Environmental design alternatives are generated to fulfil these EDOs. The Client gave priority to activities which are furthest from their discharge target, following a distance-to-target weighting approach. The minimisation of produced water discharges was considered to be one of these priorities.

Project Environmental Statement

Policy compliance is achieved by meeting the environmental requirements as set out in the Environmental Statement. This document details potential environmental impacts and evaluates their significance. The Preliminary Environmental Statement is issued to design contracting firms at the competition stage. Once Company A secured the design contract, up-dated versions of the Environmental Statement were produced by the alliance and environmental issues that required further consideration were identified. The first version of the Environmental Statement was produced within three months of Project Sanction. The final version was produced 2 years afterward. Therefore, the information gathering on alternatives and environmental impact identification was based primarily on work done during conceptual design, with continuation during detailed design. As a result, the preliminary environmental statement is subject to much uncertainty. An Environmental Statement was not a formal requirement for the case-study project and therefore the timing and integration of environmental impact assessment was not critical. However, since the ratification of the EC Directive 97/11 in April 1999, Environmental Statements became mandatory for certain offshore developments (Robertson-Rintoul, 1998) which must be submitted to the DTI before Project Sanction at the end of conceptual design. If undertaken beyond conceptual design, the production of the Environmental Statement will become a pinch-point in the critical path to achieving project authorisation. Therefore, this serves as an extra driver to undertake environmental decisions related to product design as early as possible.

Table 1: Normalised Matrix (TOPSIS Method)

$$D = \begin{bmatrix} 0.1053 & 0.1385 & 0.1584 & 0.1799 & 0.2330 & 0.3291 & 0.3772 & 0.7793 \\ 0.2763 & 0.2763 & 0.3812 & 0.3812 & 0.3400 & 0.5602 & 0.2522 & 0.2522 \\ 0.2068 & 0.2068 & 0.2068 & 0.2068 & 0.2068 & 0.7239 & 0.3620 & 0.3620 \\ 0.1302 & 0.1302 & 0.3906 & 0.3906 & 0.2604 & 0.3906 & 0.4694 & 0.4694 \\ 0.0000 & 0.0000 & 0.0000 & 0.0000 & 0.0000 & 1.0000 & 0.0000 & 0.0000 \\ 0.2763 & 0.2763 & 0.3812 & 0.3812 & 0.3400 & 0.5602 & 0.2522 & 0.2522 \\ 0.2068 & 0.2068 & 0.2068 & 0.2068 & 0.2068 & 0.7239 & 0.3620 & 0.3620 \\ 0.2068 & 0.2068 & 0.2068 & 0.2068 & 0.2068 & 0.7239 & 0.3620 & 0.3620 \\ 0.3780 & 0.3780 & 0.3780 & 0.3780 & 0.3780 & 0.0000 & 0.3780 & 0.3780 \end{bmatrix}$$

Table 2: Normalised Weighted Z Matrix (TOPSIS Method)

$$W\bar{D} = \begin{bmatrix} -0.0055 & -0.0073 & -0.0083 & -0.0095 & -0.0123 & -0.0173 & -0.0199 & -0.0410 \\ -0.0291 & -0.0291 & -0.0401 & -0.0401 & -0.0358 & -0.0590 & -0.0266 & -0.0266 \\ -0.0218 & -0.0218 & -0.0218 & -0.0218 & -0.0218 & -0.0762 & -0.0381 & -0.0381 \\ 0.0206 & 0.0206 & 0.0617 & 0.0617 & 0.0411 & 0.0617 & 0.0741 & 0.0741 \\ 0.0000 & 0.0000 & 0.0000 & 0.0000 & 0.0000 & -0.1053 & 0.0000 & 0.0000 \\ -0.0218 & -0.0218 & -0.0301 & -0.0301 & -0.0268 & -0.0442 & -0.0199 & -0.0199 \\ -0.0272 & -0.0272 & -0.0272 & -0.0272 & -0.0272 & -0.0952 & -0.0476 & -0.0476 \\ -0.0218 & -0.0218 & -0.0218 & -0.0218 & -0.0218 & -0.0760 & -0.0381 & -0.0381 \\ -0.0597 & -0.0597 & -0.0597 & -0.0597 & -0.0597 & 0.000 & -0.0597 & -0.0597 \end{bmatrix}$$

Table 3: Normalised Matrix (CODASID Method)

Table 3: Normalised Decision Matrix R

	a1	a2	a3	a4	a5	a6	a7	a8
j1	1.0000	0.9508	0.9213	0.8893	0.8106	0.6679	0.5966	0.0000
j2	0.9219	0.9219	0.5812	0.5812	0.7152	0.0000	1.0000	1.0000
j3	1.0000	1.0000	1.0000	1.0000	1.0000	0.0000	0.7000	0.7000
j4	0.0000	0.0000	0.7677	0.7677	0.3839	0.7677	1.0000	1.0000
j5	1.0000	1.0000	1.0000	1.0000	1.0000	0.0000	1.0000	1.0000
j6	0.9219	0.9219	0.5812	0.5812	0.7152	0.0000	1.0000	1.0000
j7	1.0000	1.0000	1.0000	1.0000	1.0000	0.0000	0.7000	0.7000
j8	1.0000	1.0000	1.0000	1.0000	1.0000	0.0000	0.7000	0.7000
j9	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000	0.0000	0.0000

Table 4: Normalised, Weighted Z Matrix (CODASID Method)

	a1	a2	a3	a4	a5	a6	a7	a8
j1	0.0526	0.0500	0.0485	0.0468	0.0427	0.0352	0.0314	0.0000
j2	0.0970	0.0970	0.0612	0.0612	0.0753	0.0000	0.1053	0.1053
j3	0.1053	0.1053	0.1053	0.1053	0.1053	0.0000	0.0737	0.0737
j4	0.0000	0.0000	0.1212	0.1212	0.0606	0.1212	0.1579	0.1579
j5	0.1053	0.1053	0.1053	0.1053	0.1053	0.0000	0.1053	0.1053
j6	0.0728	0.0728	0.0459	0.0459	0.0565	0.0000	0.0789	0.0789
j7	0.1316	0.1316	0.1316	0.1316	0.1316	0.0000	0.0921	0.0921
j8	0.1053	0.1053	0.1053	0.1053	0.1053	0.0000	0.0737	0.0737
j9	0.0000	0.0000	0.0000	0.0000	0.0000	0.1579	0.0000	0.0000

Table 5: Preference Concordance Index Matrix (CODASID).

	a1	a2	a3	a4	a5	a6	a7	a8
a1	0.0000	1.0000	0.8421	0.8421	0.8421	0.6842	0.6579	0.6579
a2	0.9474	0.0000	0.8421	0.8421	0.8421	0.6482	0.6579	0.6579
a3	0.7632	0.7632	0.0000	1.0000	0.8158	0.8421	0.6579	0.6579
a4	0.7632	0.7632	0.9474	0.0000	0.8158	0.8421	0.6579	0.6579
a5	0.7632	0.7632	0.7895	0.7895	0.0000	0.6842	0.6579	0.6579
a6	0.3158	0.3158	0.3158	0.3158	0.3158	0.0000	0.2105	0.2105
a7	0.6052	0.6052	0.6052	0.6052	0.6052	0.7895	0.0000	1.0000
a8	0.6052	0.6052	0.6052	0.6052	0.6052	0.7895	0.9474	0.0000

Table 6: Evaluation Concordance Index Matrix (CODASID)

	a1	a2	a3	a4	a5	a6	a7	a8
a1	0.0000	0.0055	0.0845	0.0880	0.0670	0.6862	0.1449	0.2112
a2	0.0000	0.0000	0.0790	0.0826	0.0615	0.6807	0.1394	0.2057
a3	0.0853	0.0853	0.0000	0.0036	0.0550	0.6018	0.1361	0.2024
a4	0.0853	0.0853	0.0000	0.0000	0.0514	0.5982	0.1326	0.1989
a5	0.0427	0.0427	0.0298	0.0298	0.0000	0.6192	0.1238	0.1901
a6	0.1964	0.1964	0.1111	0.1111	0.1538	0.0000	0.1190	0.1853
a7	0.1285	0.1285	0.1189	0.1189	0.1318	0.5924	0.0000	0.0663
a8	0.1285	0.1285	0.1189	0.1189	0.1318	0.5924	0.0000	0.0000

Table 7: Discordance Index Matrix (CODASID)

	a1	a2	a3	a4	a5	a6	a7	a8
a1	0.0000	0.0000	0.1212	0.1212	0.0606	0.2791	0.1723	0.1723
a2	0.0026	0.0000	0.1212	0.1212	0.0606	0.2791	0.1723	0.1723
a3	0.0669	0.0643	0.0000	0.0000	0.0247	0.1579	0.1138	0.1138
a4	0.0686	0.0660	0.0017	0.0000	0.0247	0.1579	0.1138	0.1138
a5	0.0480	0.0455	0.0664	0.0647	0.0000	0.2185	0.1497	0.1497
a6	0.6347	0.6321	0.5678	0.5661	0.5867	0.0000	0.5656	0.5656
a7	0.1239	0.1213	0.1198	0.1181	0.1140	0.1616	0.0000	0.0000
a8	0.1553	0.1527	0.1512	0.1495	0.1453	0.1930	0.0314	0.0000

Table 8: CODASID Preference Evaluation Matrix

	p(a)	e(a)	d(a)
a1	0.7631	0.6206	-0.1734
a2	0.6579	0.5769	-0.1527
a3	0.5528	0.6273	-0.6070
a4	0.4476	0.5989	-0.5945
a5	0.2634	0.4259	-0.2739
a6	-0.3161	-3.2978	2.6715
a7	0.3682	0.4892	-0.5601
a8	0.2630	-0.0411	-0.3091

Sensitivity to Weight Scenarios (Chapter 6, Section 6.5.6 and Section 6.5.10)

The change of attribute weight from the original weight vector will be described using + for increased importance and - for decreased importance, using the following symbols:

Cost	C	End of life solid waste	S
Weight	W	Global warming potential	G
Fuel	F	Acidification potential	A
Abatement	Ab	Ecotoxicity	E
Operational solid waste	O		

Weight vector variants represent different value-set scenarios. Scenarios can be based on the variation expected between an internal group of decision makers. In addition, scenarios can be set to capture external stakeholder viewpoints. The following weight vector variants were used to assess the robustness of the TOPSIS and CODASID results in the face of five alternative value-sets:

- E++: 20% of the total weight has been placed on ecotoxicity, in comparison with the 5% allocated to cost. Overall, this scenario represents a strong viewpoint in support of reducing heavy metal discharges and would generate the highest Ci value for Option 6 as it is the only option that removes heavy metals from the aqueous waste stream.

- E+: This value-set represents the same viewpoint as E++, but the weight allocated to ecotoxicity has been moderated. Both E+ and E++ could indicate the view of external stakeholders who would prioritise discharges of heavy metals to sea relative to capital cost or solid waste issues. This scenario could be appropriate if new research showed that heavy metals from offshore oil and gas facilities were having a major impact on the local environment. It may also provide an indicator on pressure group viewpoints.

• C+F+: in this value-set, a greater proportion of the weight has been allocated to capital cost and fuel consumption. This represents a moderately economics-based argument.

• C-W-Ab+G+A+E+: This weight variant increases or maintains the weight allocated to environmental impacts, whilst reducing the weight allocated to the cost and weight. It should be noted that the relationship between weight and solid waste produced at end-of-life means that some weight is indirectly lost from end-of-life solid waste.

• C+: This represents a value-set which places an additional 2% weighting on cost, strengthening the economic argument. None of these cases represent an extreme economic-argument as the case-study is aligned with the balanced objectives of BPEO. However, this method of producing value-set scenarios could look at extreme weighting systems if the decision makers feel that it is useful.

Table 9: Modified Weight Vectors

Modified Weight Vectors	W
[0.0526, 0.1053, 0.1053, 0.1579, 0.1053, 0.0789, 0.1316, 0.1053, 0.1579]	Original weight
[0.0500, 0.1000, 0.1000, 0.1500, 0.1000, 0.0750, 0.1250, 0.1000, 0.2000]	E++
[0.0513, 0.1026, 0.1026, 0.1538, 0.1026, 0.0769, 0.1282, 0.1026, 0.1795]	E+
[0.0750, 0.1000, 0.125, 0.1500, 0.1000, 0.0750, 0.1250, 0.1000, 0.1500]	C+ F+
[0.0250, 0.0750, 0.1000, 0.1750, 0.1000, 0.0750, 0.1500, 0.1250, 0.1750]	C- W- Ab+ G+ A+ E+
[0.0770, 0.1030, 0.1030, 0.1540, 0.1030, 0.0770, 0.1280, 0.1030, 0.1540]	C+

APPENDIX VII: FUZZY MULTIPLE ATTRIBUTE DECISION MAKING

Worked Examples

The Calculation of Ordered Weights for Each Recursive Step

The following example demonstrates the application of Equations 8.1 to 8.4 (Chapter 8):

Assume we have a vector A={VL, L, VL, M}

Vector A is reordered to produce vector B, shown with associated weights;

B = {0.3 M, 0.2 L, 0.4 VL, 0.1 VL}

1. C4 {(0.3 M), (0.2 L), (0.4 VL), (0.1 VL)}

So, for the term 0.2 L, 0.2 is divided by the weight of the remaining elements *k*. As the sum of the weights must always equal 1.0, the remaining weight is 1.0 - 0.3. The calculation is therefore, 0.2 / 0.7 = 0.29:

C4 = $0.3 \otimes M(C^3\{(0.29L),(0.57VL),(0.14VL)\})$

2. C3 {(0.29 L), (0.57 VL), (0.14 VL)}

= $0.29 \otimes L \oplus C^2\{(0.80VL),(0.20VL)\}$

3. C2 {(0.80 VL, (0.2 VL)} = $0.8 \otimes VL \oplus (1-0.8) \otimes VL$

The Calculation of Weights (Prior to Recursive Combination)

Table 1 shows a worked application of Equation 8.6 (see Chapter 8), where weights are calculated from the evaluations given by six decision makers for the attribute 'cost'.

Table 1: Generation of Quantifier-Guided Weights for the Attribute 'Cost'

	GM1	GM2	GM3	GM4	GM5	GM6
aj	M	H	L	H	M	M
uj	3	2	6	2	2	5
Reordering step	Highest score					Lowest Score
vjbj	2H	2H	2M	3M	5M	6L
Si, i=1, ...,6	2	4	6	9	14	20
Si - 1[a]	0	2	4	6	9	14
wj	0.01	0.03	0.05	0.11	0.29	0.51

a. The expression Si refers to the partial sum of the ordered weight. Si - 1 refers to the partial sum of the previous ordered weights. In the case of the first weight, v_1, there are no previous terms in the vector so Si-1 is equal to zero.

Option Descriptions

Option 1:

The 'Do Nothing' option risked the breakthrough of contaminated water through the heat exchanger plates and potential contamination of the cooling water system. The seals on the heat exchanger plates were known to be overdue for replacement, however, direct replacement was not possible due to the levels of radioactivity.

If the heat exchangers were left, short-lived radionuclides such as Cobalt-60 would naturally decay, and therefore minimise any dose uptake to the intervention team upon eventual exposure. However, the advantages of such a time delay must be balanced against the consequences of breakthrough.

Option 2:

The risks of the 'do nothing' approach could be reduced if an interim spare cooling circuit was added. The option would involve the placement of shielding around the existing heat exchangers whilst a new exchanger, twice their size, was connected to the reserve location at the east end of the cell. The existing exchangers would need to be drained and the valves locked out to avoid accidental opening. Associated risks would be the lack of reserve capacity if the replacement exchanger failed, and the potential for breakthrough and leakage of contaminated effluent to the cell floor if the drained exchangers were accidentally reflooded.

Option 3:

This option would involve *in situ* decontamination of exchanger and pipework with recycling of the decontaminant. This could be combined with other options to reduce dose uptake during dismantling (see options 4a and 4b). Modification to the heat exchanger inlet / outlet would be required to allow the connection of the recirculation equipment's flexible hoses. Pipe fitters would incur dose uptake.

The recirculation equipment would require special design and manufacture. The holding/ heating tank for the recirculating decontamination system would require shielding and a ventilation system to remove hydrogen generated by the decontamination process. The tank would also require a steam or electrical heating system and heat insulation.

It is not envisaged that this process would totally decontaminate the exchanger. This is mainly due to the expectation that some of the channels in the exchanger plates could have become blocked, prohibiting complete dissolution and removal of contaminated material. It is known that most preferred decontaminants operate in the range 70 - 90 °C and that the decontamination process is temperature and concentration dependent. An increase of 10 °C would approximately double the level of decontamination. However, the design of the heat exchanger and the relatively low volume of decontaminant would make it difficult to sustain the optimum temperature. If the decontaminant temperature exceeds the temperature of the pond water there would be a risk of damaging plate seals and therefore, increased possibility of leakage.

Decontaminant would be held in a tank which would require lead shielding. It is not known at this stage what type of decontaminant would be used, however, water or nitric acid are possibilities. The volume of decontaminant depends on the volume of crud. An early estimate indicates that a tank of 1.5 m^3 would be necessary. After decontamination, the heat exchanger would require further flushing which would generate liquid effluent for disposal.

The risks associated with *in situ* decontamination are:

- The initial dose incurred in making connections to the heat exchanger system to allow decontaminant recycling. Dose implications are manageable once adequate shielding is put in place.

- The possible deterioration of the heat exchanger plate seal could lead to a spillage of active decontaminant to the cell floor with the associated dose-uptake that would be incurred during clean-up.

• Disposal and handling of used decontaminant would incur dose uptake. There is also potential for leakage of radioactive acid into the heat exchanger plant room.

This option would facilitate the removal and replacement of the heat exchanger plate and the original heat exchanger would be transported to an appropriate disposal facility. A suitable disposal route for the contaminated effluent must be identified.

Option 4: Complete Removal

This option would be carried out in addition to *in situ* decontamination (option 3). By removing the heat exchanger to an appropriate off-site location, the heat exchanger could be stripped and disassembled and parts of the heat exchanger could be re-used. Off-site facilities offer a wider and better choice of decontamination processes. Option 4 was split into sub-options **4a** and **4b**. The following risks are associated with <u>both</u> sub-options.

Complete removal options give rise to the following safety issues:

• Radiological dose uptake to workers.

• Potential for entrained fuel crud to be displaced from the inlet and outlet pipe connections when the heat exchanger is broken. Displacement would be to a stainless steel cladded floor therefore there would be no problem with containment but there would be an issue of dose uptake during clean up.

• There would be potential for dropping the unit whilst lifting above the main operating floor (~13m lift) and subsequent lifts back to the plant room and during final export. Removal of the heat exchanger would risk an accidental drop on to significant safety related plant or radioactivity source i.e. the fuel elements in the container pond.

The heat exchanger would then be transported to a decontamination facility where the workforce are experienced in the decontamination of one-off items. Two stainless steel wash-down enclosures enable high power water jetting, chemical decontamination and size reduction.

Option 4a:

This option involves complete removal of the heat exchanger and exchange plates to a decontamination facility. The heat exchanger would be decontaminated using high pressure water jetting. The exchange plates could be decontaminated using ultra high pressure jetting and subsequently dismantled so that the seals and gaskets could be replaced. Reassembly would be complex and the workforce has little prior experience. Due to previous problems encountered during the resealing of gaskets, any stripping down of the plates would necessitate gasket replacement. Old gaskets and cement would be removed either through a heat process (blow torch or steam), or by cooling with nitrogen. The new gasket would be bonded using a vinyl adhesive and reassembly would require hot water or steam to cure the adhesive.

Jetting of the individual plates would incur less dose uptake to the workforce than dismantling of the heat exchangers.

Option 4b:

The contaminated plates would transported to a disposal facility. The rest of the exchanger would be transported for decontamination using high pressure water jetting as for 4a.

Option 5:

In situ decontamination would be undertaken to a level that permits dismantling and plate removal. The exchangers and pipework would be taken away for chemical decontamination. This process may use nitric acid or picolinic acid plus a variety of reducing agents and oxidants. The process would dissolve the corrosion products and oxide layer containing the Cobalt-60. The process has been well proven in the US and Europe and would have the following requirements:

- A purpose built rig would be required to hold, heat and circulate the chemicals around the pipework.
- An engineered return from the pipework to the recirculation rig would be required to form

the closed loop.

• Large volumes of chemicals would be required, causing handling, holding and final disposal problems.

• Effectiveness is temperature dependent and would require heating of the pipework.

The exchanger plates would be jet cleaned at the same facility or removed for disposal and replaced by new ones.

The Influence of Ordered Weights on Aggregation

Table 2 shows the extent to which V values can affect the final linguistic decision in relation to the performance of Option 1 for the attribute *cost*. The performance of Option 1 is represented by the A vector, [VG, VB, VB, VG, E, M].

Table 2: The Order of the V Vector and its Affect on *D(x)*

V values	W based on the application of $Q(r)^2$	Label
[2,2,2,2,2,6]	[0.016, 0.047, 0.078, 0.109, 0.141, 0.609]	VB
[2,2,2,2,6,2]	[0.016, 0.047, 0.078, 0.109, 0.516, 0.234]	VB
[2,2,2,6,2,2]	[0.016, 0.047, 0.078, 0.422, 0.203, 0.234]	B
[2,2,6,2,2,2]	[0.016, 0.047, 0.238, 0.172, 0.203, 0.234]	B
[2,6,2,2,2,2]	[0.016, 0.234, 0.141, 0.172, 0.203, 0.234]	M
[6,2,2,2,2,2]	[0.141, 0.109, 0.141, 0.172, 0.203, 0.234]	M
V values	W based on the application of $Q(r)^{1.5}$	Label
[2,2,2,2,2,6]	[0.044, 0.081, 0.105, 0.124, 0.141, 0.506]	VB
[2,2,2,2,6,2]	[0.044, 0.081, 0.105, 0.124, 0.465, 0.182]	VB
[2,2,2,6,2,2]	[0.044, 0.081, 0.105, 0.420, 0.169, 0.182]	B
[2,2,6,2,2,2]	[0.044, 0.081, 0.369, 0.155, 0.169, 0.182]	M
[2,6,2,2,2,2]	[0.044, 0.309, 0.141, 0.155, 0.169, 0.182]	G
[6,2,2,2,2,2]	[0.230, 0.124, 0.141, 0.155, 0.169, 0.182]	G

Group Dynamics and Decision Making

Some important parts of the group discussion were transcribed in order to see how the consensus decision was achieved and what the key influences were. Below is an excerpt pertaining to the weighting of 'confidence in technology'.

Excerpt 1

- **(facilitator)** technology... I thought it [information regarding technology of options] was quite technical... a lot of analysis on what you can do and what you can't do...

- **(GM 1)** I assumed we'd offer nothing that was particularly bad on confidence so... as I say I didn't see it as a main driver... I thought scoring it as medium.

- **(GM 2)** medium to high, sort of veering towards high so... so yeah [watching the facilitator mark the scale on the flip chart]... spot on.

- **(GM 3)** I scored it as medium... but following the discussions we've had I might push it slightly higher than medium now.

The next excerpt from the transcript regards Option 4a where knowledge was contributed by GM 3.

Excerpt 2

- **(GM 3** with background knowledge of project) there's quite a big job in re-using... the cleaning... [heat exchange plates]

- **(GM 2)** as opposed to throwing them?

- **(GM 1)** yeah...

- **(GM 3)** I wouldn't make it any more than medium

- **(GM 2)** yeah...

- **(facilitator)** medium?

[all agree]

The two excerpts demonstrate how an individual's opinion is open to the influence of other members. The first passage shows how an individual changes his opinion due to hearing how others had evaluated the importance in 'confidence in technology'. The second passage shows how one individual introduces his additional knowledge [his experience of the difficulties with respect to cleaning and reusing active heat exchanger plates] which influences the other group members. Reaching a consensus is a process of compromise and psychological studies of group behaviour show a tendency to conformity in a group. One explanation for the shift in an individual's judgement in a group environment is given by Davis (Beach, 1997). Davis' theory is based on the frequent emergence of a dominant faction during discussion which causes opposing group members to subordinate their views.

Excerpt 3

- **(facilitator)** resource?

- **(GM 1)** low

- **(facilitator)** low?

- **(GM 2)** I put medium to high

- **(facilitator)** right...

- **(GM 3)** I put a wide range on it actually... medium to high

- **(GM 2)** yes! [laughs]

- **(GM 4)** I put low [laughs]

- **(GM 5)** it's between low and medium... so about midway... between low and medium

- **(GM 6)** I was a low coming up to medium ... but I put the cross on low

- **(facilitator)** so you're down here then

- **(GM 6)** yeah

- **(facilitator)** a bit of a spread there ... we've got two medium ... you're almost midway there ... you've got three that pulls you down ... put around low to medium ... are we happy with that?

[The group agreed after further discussion. Those who originally gave a higher evaluation did not assert their opinion.]

In some cases, discussion helped to clarify the full meaning of the decision attribute. For instance, an excerpt follows on the discussion of 'resource':

Excerpt 4

- **(facilitator)** low to medium... everyone happy with that?

- **(GM)** I'm happy with that as long as it comes in lower than the ones we've done so far

- **(GM 3)** I'd agree with that...

- **(facilitator)** is a lot of design involved in this... site work?...

- **(GM)** it's not those resources, it's the environmental resources....

- **(facilitator)** sorry

- **(GM)** but my argument is... if the world was a fair and reasonable place, that should really be reflected in costs.

A discussion follows regarding the cost of Option 1 and the implication of risk.

Excerpt 5

- **(GM)** I don't know... I don't know where you'd cover that... whether you'd cover that here or risk...

-**(GM)** We haven't got risk [included in the attribute list in a purely financial sense]. Normally... your actual capital cost is zero but your risk cost...

- **(GM 1)** is enormous

- **(GM)** is enormous so it's very bad... if that cost is supposed to cover the risk cost

- **(GM 4)** it's absolutely true... we would normally split... somehow... er... capital costs and life-time costs

- **(researcher)** right... but for the cost attribute I would say include financial risk costs... risk [the attribute] is more engineering risk... for out of envelope...

- **(GM 3)** yeah, that's how I'd read it

- **(GM 2)** oh... that wasn't how I'd read it

[all laugh]

The comment of GM 2 in this excerpt ties in with the revised rank order shown in Chapter 8, Table 8-9.