School of Mechanical, Materials and
Manufacturing Engineering

A MULTI-ATTRIBUTE DECISION MAKING METHODOLOGY FOR SELECTING NEW R&D PROJECTS PORTFOLIO WITH A CASE STUDY OF SAUDI OIL REFINING INDUSTRY

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ABSTRACT

Energy is a resource of fundamental importance and if there is one thing that the world is going to need more in the future, it's energy. Increased energy demand is a major factor for the energy industry to invest in innovative technologies by developing processes and products that deliver improved efficiency and environmental performance. With oil continues to satisfy a major part of the energy needs, it is important for oil companies to invest wisely in Research and Development (R&D) projects.

Literature is full of methods that address the problem of R&D portfolio selection. Despite their availability, R&D portfolio selection methods are not used widely. This is due to lacking several issues identified by researchers and practitioners. As a result, R&D portfolio selection is still an important area of concern. This research proposes a multi-attribute decision making methodology for selecting R&D portfolios with a case study of implementation of the methodology in the Saudi oil refining industry. Driven by the research question and some gaps identified in the related literature review, the methodology has been modified and improved. The methodology includes methods and techniques that aim to give insights to decision makers to evaluate individual projects and select the R&D portfolio.

The methodology is divided into three stages with different steps in each stage by combining and modifying two well-known multi-attribute decision making methods: the Simple Multi-Attribute Rating Technique (SMART) and the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS).

The case study describes further methods such as Integer Linear Programming (ILP) and Monte Carlo simulation for generating data to test the validation and operationality of the methodology. It is designed in a step-by-step, easy to apply way and considers the decision making type in a national oil company. It includes the preferences of the decision makers and takes into consideration the multiple, monetary and non- monetary, attributes that ought to be considered to satisfy not only the objectives of the Saudi national company (Aramco), but the strategic goals of the Saudi government as well.

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LIST OF PUBLICATIONS

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ARMAN, H., KABLI, M. and GINDY, N.N.Z., 2008. Integer Linear Programming Model to Optimise the Decision-making in R&D Investments. *In*: *EuroMOT, Nice, France, 17 - 19 September 2008*.

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ABBREVIATIONS

ADNOC	Abu Dhabi National Oil Company
AHP	Analytic Hierarchy Process
ANP	Analytic Network Process
ELECTRE	Elimination Et Choix Traduisant La Réalité
GOSP	Gas Oil Separation Plant
GP	Goal Programming
ILP	Integer Linear Programming
IOCs	International Oil Companies
KPC	Kuwait Petroleum Corporation
LP	Linear Programming
LPG	Liquefied Petroleum Gas
MADM	Multiple Attribute Decision Making
MCDM	Multiple Criteria Decision Making
MODM	Multiple Objective Decision Making
NIOC	National Iranian Oil Company
NOCs	National Oil Companies
OPEC	Organisation of Petroleum Exporting Countries
OR	Operational Research
SABIC	Saudi Basic Industries Corporation
SMART	Simple Multi-Attribute Rating Technique
TOPSIS	Technique for Order Preference by Similarity to Ideal Solution

1 INTRODUCTION

1.1 Background and the Importance of the Subject

Energy is a resource of fundamental importance and if there is one thing that the world is going to need more in the future, it's energy. With an average annual growth rate of 1.6 percent, the world's energy needs are estimated to be more than 50 percent higher in 2030 than 2007 (Birol 2007). Increased energy demand as a result of economic growth of some developing countries (e.g. China and India) and concerns about climate change are major challenges for the energy industry. Companies in this industry must now respond to these global challenges by increasing their production capacity, improving the efficiency of their current products and investing in innovative technologies to develop processes and products that deliver improved efficiency and environmental performance.

Fossil fuels such as coal, oil and gas will continue to satisfy a great portion of the world's energy needs for the next 20 years (International Energy Agency 2005) while other alternatives suffer from limitations and significant technical challenges. The world will continue to rely on that kind of fuel, and oil in particular, with alternatives complementing oil but not replacing it. Therefore, the role of research and development (R&D) is highly important for oil companies and the need to wisely select R&D projects is more essential than before.

Companies operating in the oil industry can be classified into National Oil Companies (NOCs) and International Oil Companies (IOCs). Holding about ninety percent of the world's oil reserves, NOCs are state-owned companies that provide economic fortunes for their respective countries. Many of them are emerging on the international level to compete with oil majors, which left when the host countries nationalised their oil sector, by developing new oil reserves overseas and investing in international activities such as oil refining and retailing. In order to encourage competitiveness, some NOCs are being partially privatised while other countries maintained full control over their oil companies. All oil companies share the same goal of reaching commercial success through maximising revenue but NOCs, that carry the flag of their countries, have more responsibilities than private-owned IOCs in order to satisfy national expectations, for example, through employing and training young people, developing local technological capabilities, creating opportunities for the private sector and developing the country's infrastructure.

In her study of five NOCs, Marcel (2006) shows that NOCs are generally distinct from IOCs in many ways:

- They have a strong domestic reserve base with a monopoly (or near monopoly) over their countries' resources without a majority of shareholders.
- Middle Eastern NOCs do not necessary need to develop internationally since they have very large size reserves.

- They have an obligation to satisfy the domestic demand with affordable energy.
- Finances of NOCs are not independent form their government.
- Their operations and strategy are restricted by government directives.

The study also shows that each company from the five NOCs (Saudi Aramco, the Kuwait Petroleum Corporation (KPC), the National Iranian Oil Company (NIOC), Sonatrach of Algeria, and the Abu Dhabi National Oil Company (ADNOC)) is unique although they have common cultural, historical, and political references. Nevertheless, all NOCs and IOCs face the same major industry challenges and need to find solutions to beat those challenges. Table 1-1 and Table 1-2 shows similarity in the classification of oil operations for some famous companies of both IOCs and NOCs. The empty cells in the tables denote that the relevant operations are not currently carried out by the company.

Table 1-1: Operations of IOCs

	Upstream Operations			Downstream Operations			
Company	**Exploration**	**Production**	**Development**	**Refining**	**Petrochemicals**	**Distribution**	**Marketing**
ExxonMobil							
Shell							
Chevron							
BP							
ConocoPhillips							
Total							
Sinopec							
ENI							
Pemex							
Marathon Oil							
Repsol YPF							
Lukoil							

Table 1-2: Operations of NOCs

		Upstream Operations			Downstream Operations			
Company	**Country**	**Exploration**	**Production**	**Development**	**Refining**	**Petrochemicals**	**Distribution**	**Marketing**
ARAMCO	Saudi Arabia							
SONATRACH	Algeria							
Rosneft	Russia							
KPC	Kuwait							
NIOC	IRAN							
ADNOC	UAE							
CNOOC, CNPC	China							
PETRONAS	Malaysia							
NOC of Libya	Libya							
Petrobras	Brazil							
Pertamina	Indonesia							
PDVSA	Venezuela							
Statoil	Norway							

As the world's leading oil producer and exporter, Saudi Aramco (Arabian American Company) is an oil company fully owned by the Saudi Arabian government and provides most of the state's income. Saudi Arabia is regarded as a key player in the oil industry and central to steadily, more interdependent global economy, with high influence on decisions related to the Middle East, Arabic area and Islamic world. As a member of the Organisation of Petroleum Exporting Countries (OPEC), the country produces about 33 percent of OPEC's total crude oil production and continues the policy of coordination among member countries to maintain their common interests. The responsibility of Aramco towards the country is very high not only because of economic profitability but also because of other internal and external factors that influence the Saudi oil industry (see section 6.2).

Aramco is the world's largest crude oil producer with production capacity of 10.5 million barrels per day and holds 259.9 billion barrels of crude oil reserves, which equal one-quarter of the world's proven oil reserves (Saudi Aramco 2008). In 1980, the Saudi Government acquired 100 percent participation interest in Aramco, purchasing almost all of the company's assets from major U.S. oil companies known now as Texaco, ExxonMobil and Chevron. Aramco is also the discoverer and producer of Ghawar Field, the world's largest onshore oil field, and Safanyia Field, the world's largest offshore oil field. Similarly to other oil companies, oil operations at Aramco are classified mainly into upstream and downstream operations (see Figure 1-1).

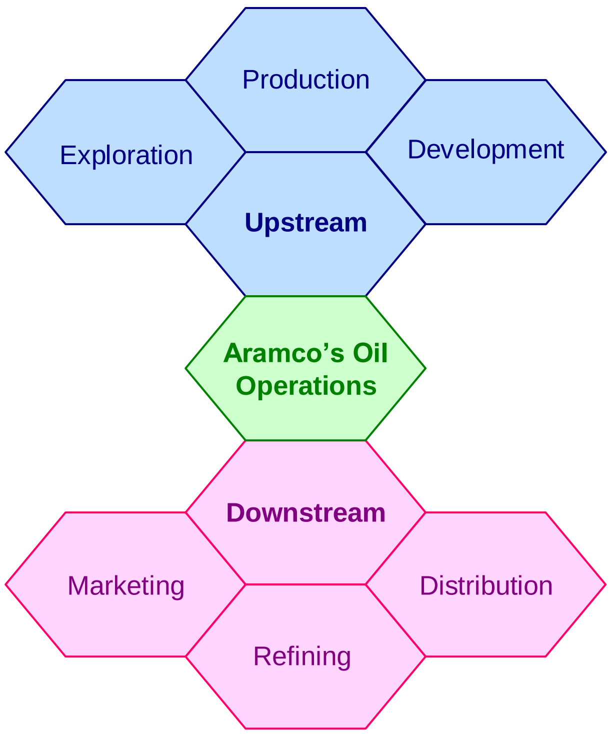

Figure 1-1: Classification of Aramco's Oil Operations

Upstream operations are responsible of oil exploration, development of oil wells and oil production. *Exploration* is the first step to make oil and its products available to the world with the aim of finding oil fields hidden deep underground. After geologists and geophysicists of exploration teams locate oil trapped in geological environments using advanced technologies, *development* begins by studying oil reservoirs to determine exactly the amount of oil available and how it can be safely and effectively extracted or produced. *Production* starts after drilling oil wells with oil free-flowing from most of oil-producing wells. Oil is then piped to a Gas Oil Separation Plant (GOSP) where water and the majority of dissolved gases are extracted. Oil is then transported to major stabilising facilities for final gas separation and removal of hydrogen sulphide and delivered afterward to refining or distribution.

Downstream operations, on the other hand, consist of oil refining, distribution and marketing. In order to be used, crude oil must be *refined* (or broken down) into products with the specific characteristics to handle certain jobs well (e.g. diesel to power cars) (Conaway 1999). Oil refining is an essential operation to provide markets with important products such as gasoline, kerosene diesel and asphalt. Aramco is regarded as number 10 in worldwide refining capacity and operates five domestic refineries and two domestic joint-venture refineries. More than half of the company's refining capacity is at international equity and joint-venture refineries. A broad network of bulk plants and air-fuelling units strategically located throughout the Kingdom supplies thousands of bulk customers with products ranging from gasoline and jet fuel to fuel oil and liquefied petroleum gas. Added to this are gigantic tank farms that enable terminal exports of crude, natural gas liquids and refined products through the Arabian Gulf and the Red Sea. Interconnected with these storage facilities are extensive delivery systems that enable timely and reliable delivery of product. In a continually evolving world, the Saudi Aramco supply and distribution operations strive to surpass customer expectations by providing state-of-the-art facilities run by a world-class workforce.

One downstream operation that is not of Aramco's current interest is production of *petrochemicals* (e.g. plastics, chemicals and fertilizers) which is under the responsibility of another company, partially owned by the Saudi government, called SABIC (Saudi Basic Industries Corporation). The feedstocks for petrochemical plants are provided largely by refineries and include naphtha, kerosene, and light gas oil. Natural gas processing plants are also a source of feedstock, providing natural gas, ethane and LPG (Liquefied Petroleum Gas).

Aramco has a strong national focus but it runs like a private oil company. Decision making in all five NOCs tends to be slow and careful because managers in those companies want to protect themselves from the consequences of a bad decision. In Aramco specifically, managers are more involved operationally due to their concerns about any wrongdoings or inefficiencies being uncovered under their watch.

1.1.1 R&D Portfolio Selection

R&D is an important activity and some companies invest heavily in R&D due to the challenges of the new millennium and the future effect of R&D on the continuity (and sometimes the existence) of companies. In 2004, it was estimated that the five largest companies in the US oil refining market (ConocoPhilips, Exxon Mobil Corp., BP plc, Valero Energy Group and Chevron Texaco Corp.) spent a total of US$1.7 billion in R&D, with Exxon Mobil spending US$649 million alone (Euromonitor International 2005a). In the UK, the total R&D activity for the major companies in the same year reached a value of around US$3 billion (Euromonitor International 2005b).

The common problem of selecting R&D projects comes from the existence of more projects to be carried out than the available resources (e.g. money, staff and equipment) (Martino 1995). Many methods and techniques are available in literature with the aim of selecting R&D portfolios.

In reality, R&D portfolio selection methods are not used widely. The methods highlighted in chapter 3 lack one or more of the following issues (see for example Baker & Freeland 1975, Martino 1995, Cooper et al. 2001; Stummer & Heidenberger 2003):

- Treatment of multiple, often interrelated, criteria.
- Treatment of risk and uncertainty.
- Treatment of project interrelationship with respect both to value contribution and to resource utilization.

- Recognition and incorporation of the experience and knowledge of the R&D manager.
- Recognition and treatment of non-monetary aspects
- Perceptions held by the R&D managers that the models are unnecessarily difficult to understand and use.
- Treatment of the time variant property of data and criteria and the associated problem of consistency in the research program and the research staff.
- The portfolio reflects the enterprise's business strategy.

1.2 Research Outline

This research attempts to develop some remedies of the problems and gaps identified in literature and practice which are highlighted in section 1.1.1 and 3.5, within the boundaries and limits stated in section 1.2.3.

The topic of this research is R&D portfolio selection, and the research object is the Saudi oil company: Aramco. Based on this topic, research questions have been formulated and research aim and objectives have been identified.

1.2.1 Research Questions

Based on literature review in chapters 2 and 3, needs identified in practice and interviews with people working in the area of R&D, the research questions were designed and further modified. Research aim and objectives were formulated to answer the research questions.

The main research question was formulated as follows:

- **How can an appropriate decision making methodology be designed and implemented for R&D project evaluation and portfolio selection at government-owned oil enterprises?**

The following additional questions have been derived to explain the main research question in depth:

1. How can enterprises evaluate and select R&D portfolios?
2. How will R&D portfolio selection help enterprises to achieve their business goals and objectives?
3. What are the characteristics of government-owned and private oil enterprises?
4. How can the decision making style of enterprises affect the process of evaluating and selecting R&D portfolios?

1.2.2 Research Aim and Objectives

In order to answer the main research question of designing and implementing a decision making methodology for selecting R&D portfolio, research aim was identified and research objectives were formulated.

The aim of this research is to develop a decision making methodology to enable enterprises to identify, evaluate and select R&D projects that form the enterprise's R&D investment portfolio. Detailed research objectives are explained below:

1. To explore methods and techniques of R&D project evaluation and portfolio selection.
2. To investigate the differences between private and government-owned oil enterprises.
3. To study project attributes and preferences used by decision makers to evaluate and select R&D portfolios.
4. To provide tools and methods that can give the decision maker insights and help to select R&D portfolio.
5. To incorporate different project attributes, R&D portfolio selection methods, and decision making methods and tools in a decision making methodology, and to test this in an industrial scenario (Saudi oil company: Aramco)

The decision making methodology introduced in this research aims to address the research objectives described above by providing the tools and methods that will enable decision makers to evaluate and select R&D portfolios in a form of a step-by-step procedure. The case study demonstrated the application of the methodology at the Saudi oil company 'Aramco' for selecting oil refining R&D portfolio.

Within the context of the research outline, the research key components are highlighted below:

- Literature review on decision making and its different approaches (chapter 2).

- Literature review on R&D project evaluation and portfolio selection (chapter 3).
- Development of the proposed decision making methodology for selecting R&D portfolio (chapter 5).
- Application of the methodology on selecting oil refining R&D portfolio at Aramco (chapter 6).
- Revision and modification of the methodology based on the case study as well as further academic and industrial research (chapter 6).

1.2.3 Research Boundaries and Limits

Within the boundary of project management, this research attempts to address the process of identifying R&D projects, setting the attributes to evaluate projects and selecting the investment portfolio. It does not go beyond to the project execution phase where projects could continue going, halt or terminated.

Many portfolio selection methods and techniques deal with the result of project evaluation as the final portfolio without making sure whether it is aligned with the enterprise's objectives and decision maker's preferences. The proposed methodology separates project evaluation from portfolio selection in a different stage to enable balancing of the final portfolio.

This research assumes the involvement of the decision maker in all the stages and steps of the methodology. Most of the steps of the methodology require the input of the decision maker applying easy-to-use methods and techniques that have been used and tested in other related researches.

Finally, the case study was carried out to demonstrate the application and evaluation of the decision making methodology in oil refining operations at Aramco, therefore generalisation would be adequate for any other cases of the same type (Kumar 2005; Yin 2009) assuming that the case is typical of cases of government-owned companies.

Aramco supplied the researcher with many important information about the company and its R&D oil refining activities but, due to security and confidentiality issues from Aramco, numerical data was produced using simulation instead of real data despite a gentlemen agreement of providing real data with senior decision makers in the Saudi Ministry of Petroleum and Mineral Resources, and the Saudi Ministry of Economy and Planning. This is a common concern in NOCs since oil issues are dealt with as a political issue rather than an economic one (Marcel 2006). Applying simulation gave the researcher insights about the operationality of the methodology and how to modify it to reasonably suits R&D portfolio selection.

Further assumptions and limitations are related to the methods and techniques used in the different stages of the decision making methodology.

1.3 Research Design and Methodology

The methodology used for this research can be described as an applied, explanatory, exploratory, and mixed (quantitative and qualitative) type, with the method of case study is applied to develop and test a decision making methodology for R&D portfolio selection in the Saudi oil refining industry.

Choosing case study method is to address the ‘how’ research question for selecting R&D portfolios that is related to a real-life problem. The decision making methodology for R&D portfolio selections applies different methods and techniques to help R&D decision makers to implement them at their enterprises.

The overall research design is illustrated in Figure 1-2. Further discussion of research design and methodology is presented in chapter 4.

1.4 Structure of the Thesis

The thesis consists of seven main chapters. Figure 1-3 illustrates an overview of the structure of the thesis. Following the introduction chapter, chapter 2 contains relevant literature and background in the field of the theory of decision making. Chapter 3 covers the literature of R&D portfolio selections and its various methods used. Chapter 4 presents in details the research design and methodology used in this particular research.

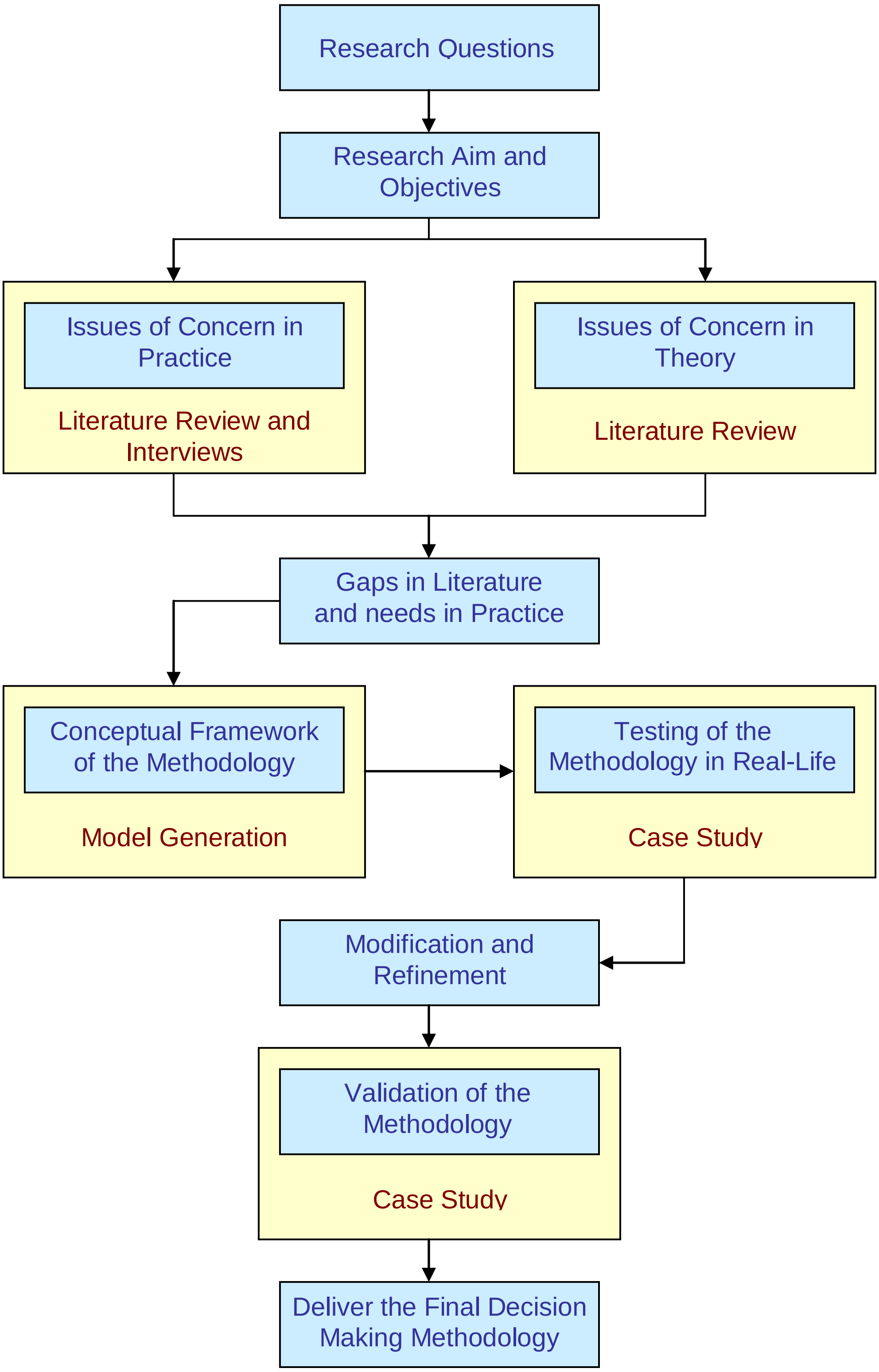

Figure 1-2: Overall Research Design

Chapter 5 introduces the multi-attribute decision making methodology for selecting R&D portfolios. The methodology comprises three main stages formed of steps which are described thoroughly in this chapter. The preparatory stage includes forming the decision maker(s) who will go through the different steps of the methodology to select the final R&D portfolio. This stage identifies the objectives and constraints of the current selection period, and the different attributes that R&D projects and portfolio will be judged against. The project evaluation stage assesses alternative projects to realise their benefit to the enterprise. Choosing the final group of R&D projects to be funded is done in the portfolio selection stage.

In chapter 6, an industrial case study is illustrated. The industrial case study reports the way of applying the methodology in Aramco. It goes through the different stages of the methodology with considering two different scenarios of R&D projects being homogeneous or not. The case study shows how Monte Carlo simulation was used to represent the numerical responses of decision makers.

Finally, chapter 7 presents a discussion and conclusions about the methodology and the case study; with research contributions and suggestions of future work are discussed at the end of this chapter.

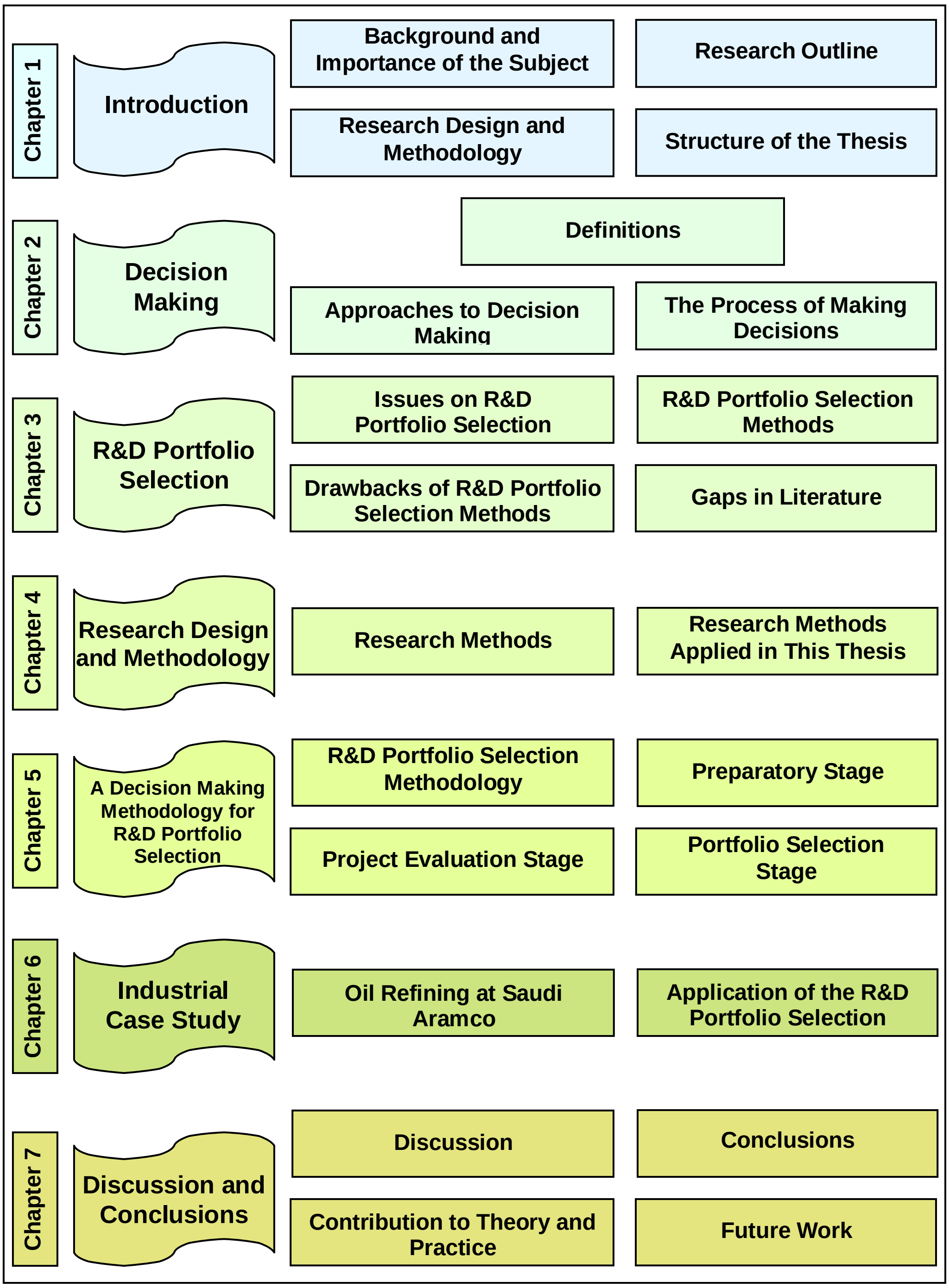

Figure 1-3: Structure of the Thesis

2 DECISION MAKING

2.1 Introduction

Every individual in his life will face occasions that he/she needs to make decisions about. Some of the decisions will have a small effect on life and some will affect the whole life. Decisions are so important that they may lead to success or failure for managers and organisations.

This chapter is a literature review of the theory of decision making. Section 2.2 discusses the different definitions of the term ‘decision’ and the nature of decision making. The process of making decisions is covered in section 2.3, while section 2.4 presents the different approaches of decision making and representative methods of some decision making approaches.

2.2 Definitions

Before discussing the process of decision making, it is important to explore the different definitions of the term ‘decision’. Ofstad (1961) stated three alternative definitions: “To say that a person has made a decision may mean:

1. that he has started a series of behavioural reactions in favour of something, or it may mean
2. that he has made up his mind to do a certain action, which he has no doubts that he ought to do. But perhaps the most common use of this term is this: to make a decision means

3. to make a judgment regarding what one ought to do in a situation after having deliberated on some alternative courses of action."

Baron (2000) defines a decision as a choice of actions to achieve goals based on beliefs about those actions and their ability to reach goals. Harrison (1999) expands that definition to describe a decision as "*a moment in an ongoing process of evaluating alternatives for meeting an objective, at which expectations about a particular course of action impel the decision maker to select that course of action most likely to result in attaining the objective*".

Other authors argued about decision-making as a process. Simon (1960) deals with decision making as a process of three phases. First: finding occasions for making a decision, second: finding possible courses of action, and finally: choosing among courses of action.

Bunn (1984) splits decisions into three types as follows:

1. Intuitive decisions are those choices that individuals make almost instinctively and people just know what to do in certain situations.
2. Programmed decisions occur when a defined set of guidelines or instructions is present when making a decision.
3. Analytical decisions are those important ones about which one must think carefully.

Decision making could be normative, descriptive or prescriptive. According to Bell et al. (1988), if the decision maker prefers alternative A to B, and prefers B to C, then the *normative* decision making means that he/she will also have a preference for A over C. This shows how the decision maker ‘ought’ to make a decision. Sometimes in reality, a decision maker may have cyclical preferences: A over B, B over C, and C over A. This is *descriptive* decision making that shows how a decision ‘is’ made. If the decision maker have two alternatives: A and C, and he/she must choose one of them, introducing a hypothetical alternative B for which the decision maker finds it comfortable to say that he/she prefers A to B and B to C may help the decision maker to believe that A is better than C. This sort of decision making is not normative (A is preferred to C if and only if there exists B) or descriptive (the decision maker could do this for himself). It is called *prescriptive* decision making.

Before making any decision, the decision maker must have a clear grasp of the context surrounding a decision problem. It is important to explore in detail the context in which managerial decision problems arise. Ignoring the nature and environment of decision problems result in poor planning, fire fighting and crisis management. Jennings and Wattam (1998) states four aspects that are almost always important in determining the nature of a decision problem as follows:

1. *The level of decision-making.* There are three levels of decision-making. *Strategic* decision making where decisions are likely to have a significant impact on the whole system over time, and *tactical* decision making where only elements of the system are likely to be affected.

Between these two levels there is a whole range of *operational* decision making in most management environment which is often associated with particular management functional areas such as finance or production. The effects of *tactical* or *operational* decisions may affect the whole system over time and there are links between the three levels of decision-making and the other factors discussed below.

2. *The time horizon*. There are two phases for time horizon: the period available for decision making and the planning period over which decision making is effective. Considering the period available for decision-making, it is one of the resources available to aid decision making. Some decisions must be made *immediately*. These are usually tactical decisions that will not affect the whole system but managers should not make such decisions if they are strategic decisions.

   The categoraisation into *short, medium,* and *long term* is frequently made when considering the planning period. Exact length of each category depends on the nature of business but rough estimation might be less than 6 months for short term, between 6 and 24 months for medium term, and more than 24 months for long term periods. Long term periods are very difficult because of the difficulty of forecasting future needs and changes in the market.

3. *Frequency*. There are two types of decisions based on frequency: *one-off* and *recurrent* decisions. Higher level longer term courses of action at the strategic level are the association of one-off decisions. Recurrent decisions are associated with lower level tactical decision making and shorter time horizon. If the important decisions are recurrent, it is important to develop strategies and solution approaches that are rational, effective and consistent.

4. *Resources*. These are the resources available for decision making not the resources about which decisions may be made. Resources such as personnel, budget, information, analytic skills, and consultants must be available to make the quality of decisions much better.

2.3 The Process of Making Decisions

Most of the decision-making approaches deal with decision making as a process. Clemen and Reilly (2001) describe this process as a six-phases process assuming that the decision maker develops the alternatives. These phases are shown in Figure 2-1.

The first phase for a decision maker is to identify the decision situation and understand the objectives in that situation. The trouble is not in finding the problem; the decision maker sometimes has trouble with identifying the exact problem and verifying its boundaries, and may, therefore, treat the wrong problem.

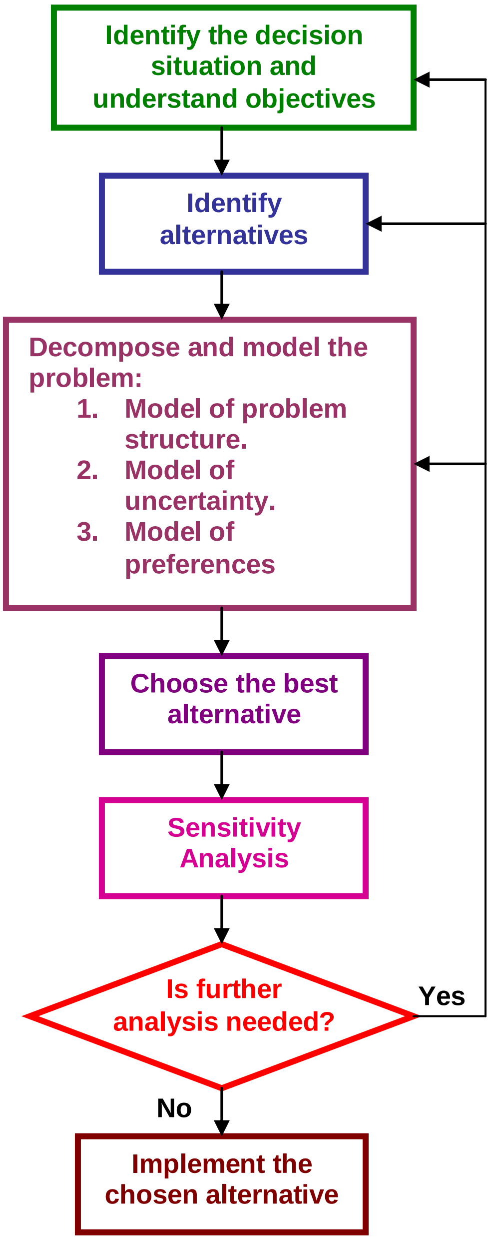

Figure 2-1: Decision Making Process (Source: Clemen & Reilly 2001)

Objectives must be defined and expressed in broad terms. It is also needed at this phase to establish some performance measures to test the effectiveness of the process to solve the problem. Factors, variables, and data relevant to the problem are also identified at this phase.

After establishing the decision situation and objective, the second phase is to discover and create alternatives. Understanding objectives and careful examination of them help the decision maker to identify different alternatives.

Modelling is an important feature of the process of decision making. Analogue and symbolic models are used widely. Mathematics has a role to play in modelling, and the development of computers and computer systems has had a big impact on decision making. The decision maker can use decision trees and hierarchies to structure the problem and represent relationships between different objectives and performance measures. Models of uncertainty use probabilities to inherent the uncertainty in the problem. Mathematical representation of subjective preferences can help indicating a 'preferred' alternative. The decision maker implements decision models in the next phase to choose the best alternative.

The fifth phase is to apply sensitivity analysis, which answers 'what if' questions. It shows the consequences of selecting an alternative solution if the decision maker applied small changes to some aspects of the decision model. If these changes lead to changing the selected alternative, the decision is considered sensitive and the decision maker may need to reconsider more carefully those aspects to which the decision is sensitive. The process allows the decision maker to return back to the first, second and/or third phase to make modifications. If the decision maker reaches satisfaction about an alternative, the final phase is to implement the chosen alternative.

This decision process is iterative. The decision maker may develop or change his/her perception of the decision problem, objectives or models while going through the different phases of the process. However, returning back to some phases, like redefinition of the problem after modelling, may be costly and may cause negative consequences.

The basic idea for a decision making process is similar for most of the authors. Elbing (1978) suggested five steps for a decision-making process:

1. *Perception* of the environment or situation: observing and becoming sensitive to potential problem situations.
2. *Diagnosis*: attempting to understand what is happening in a particular problem situation.
3. *Definition* of the problem to be solved: identifying and stating a problem in relation to organisational and personal goals.
4. *Determination* of alternative methods and solutions and choice of the best solution: selecting a course of action from a series of alternatives.
5. *Implementation* of the chosen solution: the entire process of actualising the chosen solution.

All the decision makers prefer a decision making process that will guide them directly to the solution of their decision problem, which does not exist. The process of decision making has some limitations to be straightforward due to several factors that influence the decision maker, information needed, and the organisation.

Clarity of the problem and objectives is very important. The decision maker may decide the suitability of an alternative over other alternatives based on a wrong understanding of the problem. Some problems involve a group of people to make decisions and the compatibility of the understanding of the problem and objectives between these people is also very essential.

Decision makers always set time limits to each step in the decision making process. It is important to set these time limits accurately and also, accomplish each step in its scheduled duration. If the decision maker could not meet the scheduled time for any step, the following step and the whole process will be affected. Decisions will be made based on intuition because the decision makers do not have enough time.

Cost is another factor that may limit the decision making process. It is not easy to obtain information needed to make decisions within organisations and the only way is to ‘buy’ this information from those who have it. If the information is very costly and the decision makers cannot acquire it, the decision making process is surely affected.

2.4 Approaches to Decision Making

There are many approaches to decision making and they depend on the ideas and opinion of researchers and authors. In this research, some approaches will be discussed such as: behavioural, organisational, operational research, and multiple-criteria decision making.

2.4.1 Behavioural Decision Making

This approach is based on the behaviour of the decision maker. There is always a motivation force generated by some causes and purposes that can tell why a person makes a particular decision. The basic aim of modeling human behaviour is to model a business process that increases workforce enthusiasm considering all aspects of human behaviour including group dynamics, project work climate, and organisational culture.

Behavioural decision making is to understand how people make decisions and how they can make the decision making process more effective and efficient. The behaviour sciences are applicable to decision processes from both quantitative and qualitative viewpoints to improve a stronger foundation for making better decisions. The decision maker's style and characteristics can be classified as: the thinker, the cowboy (snap and uncompromising), Machiavellian (ends justifies the means), the historian (how others did it), the cautious (even nervous), etc.

2.4.2 Organisational Decision Making

This approach says that the decision making process is not based on the individual’s behaviour acting in isolation as the behavioural decision making approach claims. The organisational theory has been focused on examining how the task the individual is engaged in or the environment in which it operates influences the decisions made by the organisation.

Type of information, environment of the decision problem, training, skills, resources, and organisational goals have as much influence on the organisational decisions as the behaviour of the individuals does. The organisational approach does not neglect the factor of human's behaviour but at the same time it gives importance to facts, figures, and information structure and applies some numerical and mathematical models to aid the behavioural decisions. Neural networks, genetic algorithms and simulation are examples of computational methods used by the organisational decision making approach.

2.4.3 Operational Research (OR) and Decision Making

OR is a relatively recent discipline having its origins in Britain in the World War II. The British military leaders asked scientists and engineers to analyse several military problems related to the war effort such as maximising efficiency in war supplies, optimal usage of resources, logistical support for military operations and provision of goods and services to the general population under the restrictive conditions of war.

Winston (1994) defines OR as a scientific approach to decision making, which seeks to determine how best to design and operate a system, usually under conditions requiring the allocation of scarce resources. It is the discipline that uses rational methodologies and solution approaches for management decision problems. In the US the term Management Science is the more common term used instead of Operational Research.

The discipline was influenced significantly by the discovery of Simplex algorithm, developed by George Dantzig in 1947, to optimise limited resources to achieve a specific objective under constrained conditions. It was applied in the oil industry to solve the problem of achieving optimal production.

At the beginnings of OR, it was often criticised as too mathematical and too academic although it made remarkable contributions in business, industry, government and economics. In the 80's the discipline had its revival especially after the development of personal computers which helped the decision makers to model and solve their own problems. Business Process Re-engineering in the 90's concentrated in using methods from OR and many industrial organisations made account of OR and its continually developing decision support software.

Examples of the methods of OR are: Linear Programming (LP), Network Analysis, Simulation, Queuing Systems, and Goal Programming. This thesis will give highlights on some of the OR methods such as Linear Programming and Goal Programming.

2.4.3.1 Linear Programming (LP)

A *Linear Programming* problem is a special case of a *Mathematical Programming* problem. From an analytical perspective, a mathematical program tries to identify an *extreme* (i.e., minimum or maximum) point of a function $f(x_1, x_2, \ldots, x_n)$, which furthermore satisfies a set of constraints, e.g.

$g(x_1, x_2, \dots, x_n) \geq b$. LP is the specialisation of mathematical programming to the case where both function *f*, to be called the *objective function*, and the problem constraints are *linear*.

From an applications perspective, mathematical (and therefore, linear) programming is an *optimisation* tool, which allows the rationalisation of many managerial and/or technological decisions required by contemporary techno-socio-economic applications. An important factor for the applicability of the mathematical programming methodology in various application contexts is the computational tractability of the resulting analytical models. Under the advent of modern computing technology, this tractability requirement translates to the existence of effective and efficient algorithmic procedures able to provide a systematic and fast solution to these models. For Linear Programming problems, the *Simplex* algorithm provides a powerful computational tool, able to provide fast solutions to very large-scale applications, sometimes including hundreds of thousands of variables (i.e., decision factors or attributes).

Two families of solution techniques are in wide use today. Both visits a progressively improving series of trial solutions, until a solution is reached that satisfies the conditions for an optimum. The first is called the *graphical* solution where the objective function and constraints are plotted and then the optimum solution that satisfies the equations is identified from the graph. This method will become more complex when the functions have more than two decision variables. In fact, the *Simplex* algorithm was one of the first

Mathematical Programming algorithms to be developed, and its subsequent successful implementation in a series of applications significantly contributed to the acceptance of the broader field of OR as a scientific approach to decision making.

As it happens, however, with every modelling effort, the effective application of Linear Programming requires good understanding of the underlying modeling assumptions, and a pertinent interpretation of the obtained analytical solutions. The Simplex method is beyond the scope of this research and a simple example is presented in Appendix A that illustrates the use of graphical solution in LP.

2.4.3.2 Goal Programming (GP)

As shown in the previous section, LP has always one goal to be achieved within a set of constraints. In many cases the decision makers try to satisfy more than only one goal which the LP method cannot solve. To overcome this problem, the Goal Programming method is a useful tool for decision makers when facing multiple goals problem. It has the same concept of LP with some modifications and the best way to describe this method is through an example as presented in Appendix A.

2.4.4 Multiple Criteria Decision Making (MCDM)

MCDM provides a structured (organised) approach to decision making. It involves describing a decision problem with six elements (Malczewski 1999), which are as follows:

- *Value*: Something a person cares deeply about.
- *Goal*: Formulation of values in a given problem context.
- *Objective*: Specification of goal in terms of the desired property of problem solution.
- *Decision Maker*: A single person, a group of people, or the whole organisation responsible for making decisions.
- *Decision Alternatives*: Feasible solutions to a decision problem.
- *Criteria*: Basis for evaluating decision alternatives. It may be used as attributes or objectives. An attribute measures the performance of an objective. An objective is a statement about the desired level of goal achievement.
- *Outcomes*: Achievement or performance of each decision alternative on criteria.

There are two basic approaches to MCDM problems: Multiple Attribute Decision Making (MADM) and Multiple Objective Decision Making (MODM). The MADM approach requires that the selection be made among decision alternatives described by their attributes. It assumes that the problem has predetermined number of decision alternatives. In the MODM approach, it assumes that the decision alternatives are not given. Instead, MODM provides a mathematical framework for designing a set of decision alternatives. Once identifying the decision alternatives, each alternative is judged by how close it satisfies the objective.

There are three generic types of MCDM problems as follows:

- *Selection*. Given a set of decision alternatives, the selection task involves finding the alternative (or alternatives) judged by the decision maker as the most satisfying.
- *Sorting*. It consists of assigning each alternative to one of the predefined criteria. Assignment is often based on relative differences of decision alternatives along a criterion.
- *Ranking*. It involves establishing a preference pre-order on the set of decision alternatives. The pre-order represents a priority list of the alternatives.

Solving MADM problems involves sorting and ranking while solving MODM problems involves selection only.

In this research, it has been decided to follow the attributes approach in MCDM because the scope of this research is to select from a predetermined number of investment projects based on a set of criteria (attributes) for a defined set of objectives.

The process of MCDM begins with the recognition of the decision problem. After identifying the problem, a series of steps is applied. Malczewski (1999) presents a flow chart describing these steps (see Figure 2-2).

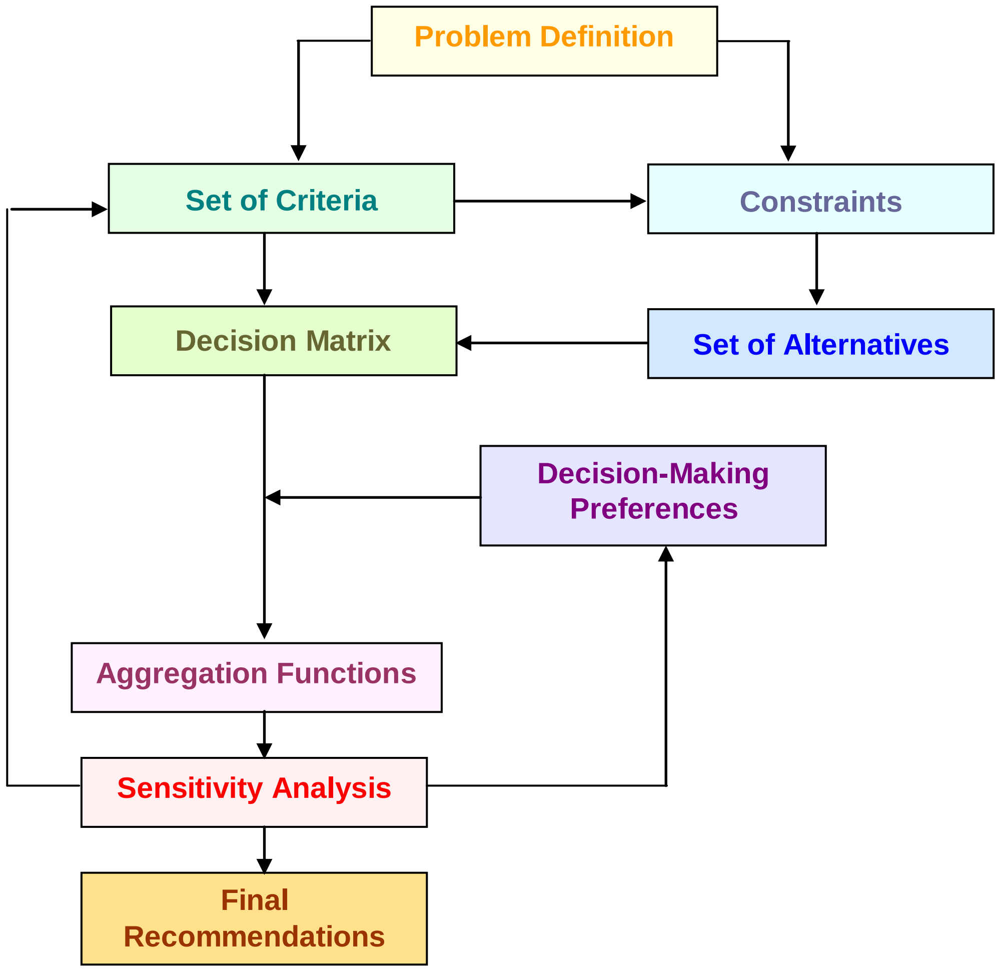

Figure 2-2: Steps of Decision Process in MCDM Approach
(Source: Malczewski 1999)

- *Set of Alternatives*. The nature of decision-making involves choice. It can be exercised if there are decision alternatives to choose from. It is the matter of testing whether or not these potential alternatives satisfy the basic decision problem in order to be admitted as feasible decision alternatives.
- *Set of Criteria*. Evaluation criteria represent measures for achieving those criteria.

- *Criterion Scores*. These scores represent achievements of decision alternatives on evaluation criteria.
- *Decision Table*. It represents the collection of criterion scores and thus provides the basis for the comparison of decision alternatives.
- *Decision Maker Preferences*. They are expressed in term of weights. These weights (ranging between 0 and 1) express relative importance of the evaluation criteria under consideration.
- *Aggregation Functions*. Sometimes called decision rule. It computes an overall assessment measure of each decision alternative by integrating decision maker's preferences with criterion scores.
- *Sensitivity Analysis*. It tests the stability of assessment measure of each decision alternative when weights and criterion scores are varied. The ranking of decision alternatives is said to be sensitive if small changes in the weights or criterion scores produce significant changes in the order of ranked decision alternatives.
- *Final Recommendation*. The choice of the most appropriate decision alternative(s).

There are several methods that use the MCDM approach to make decisions. The following sections describe some of the commonly known MCDM methods.

2.4.4.1 Analytic Hierarchy Process (AHP)

Saaty (2000) defines AHP as: "*a framework of logic and problem-solving that spans the spectrum from instant awareness to fully integrated consciousness* *by organising perceptions, feelings, judgements and memories into a hierarchy of forces that influence decision results*".

AHP is used to derive ratio scales on a variety of dimensions both tangible and intangible from the application of paired comparisons in multilevel hierarchic structures. The comparisons are either actual measurements or taken from a fundamental scale that reflects the relative strength of preferences and feelings. Arranging these dimensions in a hierarchic structure allows for breaking down the decision problem into its smaller parts that will lead from simple paired comparison judgements to the priorities in the hierarchy. Table 2-1 shows the fundamental scale of absolute values for representing the strength of judgements.

Often the decision alternatives are associated with costs and benefits. In this case it is useful to construct separate costs and benefits hierarchies, with the same decision alternatives on the bottom level of each. The benefit/cost vector is obtained by taking the ratio of the benefits priority to the costs priority for each alternative, with the higher ratio indicating the preferred alternative. An example of using benefit/cost ratio in AHP is presented in Appendix A.

Many decision problems involve tangible and intangible criteria or attributes. Tangibles are the criteria that are physical (can be numerically measured), as they constitute some kind of objective reality outside the individual conducting the measurement. Intangibles are the psychological criteria that comprising the subjective ideas, feelings, and beliefs of the decision maker. The AHP is a method that can be used to establish measures in both the physical and the psychological domains. An example is provided in Appendix A about the AHP method.

Table 2-1: The fundamental Scale (Source: Saaty 2001)

Intensity of Importance	Definition	Explanation
1	Equal importance	Two activities contribute equally to the objective
2	Weak	-----between Equal and Moderate
3	Moderate importance	Experience and judgement slightly favour one activity over another
4	Moderate plus	-----between moderate and strong
5	Strong importance	Experience and judgement strongly favour one activity over another
6	Strong plus	-----between strong and very strong
7	Very strong or Demonstrated importance	An activity is favoured very strongly over another, its dominance demonstrated in practice
8	Very, very strong	-----between Very strong and Extreme
9	Extreme importance	The evidence of favouring one activity over another is of the highest possible order of affirmation
Reciprocals of above	If activity *i* has one of the above nonzero numbers assigned to it when compared to activity *j*, then *j* has the reciprocal value when compared with *i*	If x is 5 times y, i.e. x = 5y, then y = x/5 or y = 1/5x
Rationales	Ratios arising from the scale	If consistency were to be forced by obtaining *n* numerical values to span the matrix

Decision makers consider the favourable and unfavourable concerns (attributes) when making a decision. Some of these concerns are sure things and others are less certain. The favourable sure concerns are called *benefits* while the unfavourable ones are called *costs*. The decision may create less certain concerns that are the positive *opportunities* and negative *risks*. Each of these concerns contributes to the merit of a decision and must be evaluated (rated) individually on a set of prioritised elements that is used to also evaluate any other decision. The prioritised elements are called *key factors* of the four attributes.

The key factors must be prioritised for frequent use of all decisions. The pairwise comparison of the attributes and their key factors is based on the fundamental scale (Table 2-1) and then applying the following expression to calculate the overall priority of each decision alternative:

$$\text{Priority} = \frac{(\text{Benefits}) \times (\text{Opportunities})}{(\text{Costs}) \times (\text{Risks})}$$

The way of computing the priorities is complex and will take time to convert a super matrix to a stochastic matrix. The computer programme for the ANP does these calculations automatically after all the comparisons have been made. This programme is called *Super Decisions* and it implements the Analytic Network Process developed by Dr. Thomas Saaty. The ANP Team, working for the *Creative Decisions Foundation*, wrote the programme and this report used this programme in comparing the decision attributes and their key factors.

The AHP method has proved its powerfulness in the predictions of the outcome of US presidential elections, the results of sports contests and the winner of chess matches (see Saaty 2000). AHP has been applied by decision makers in many areas, including accounting, finance, marketing, energy recourse planning, microcomputer selection, sociology, architecture, and political science (Triantaphyllou 2000). Although, AHP has its own critics regarding the theory behind it (see Appendix A).

AHP is a theory of measurement concerned with deriving dominance priorities from paired comparisons of homogeneous elements with respect to a common criterion or attribute. Such measurement can be extended to non-homogeneous elements through “clustering.” In a multi-criteria setting, the AHP can be used to scale elements in a hierarchy (feed forward) structure with mutually independent elements in each level, or in a network (feed forward – feed back) system of components allowing for dependence within and between components. Thus a hierarchy is a special case of the more general system formulation, the network.

2.4.4.2 Analytic Network Process (ANP)

Many decision problems cannot be structured as a hierarchy because they involve the interaction and dependence of higher-level elements on lower-level elements. In hierarchies, the importance of the criteria determines the importance of alternatives but sometimes, the importance of the alternatives determines the importance of the criteria. For example, if anybody wants to choose between two cars and both are reliable. One car is beautiful and the other is more reliable but vulgar. That may lead to choose the most reliable and ugly one unless the criteria themselves are evaluated in terms of the cars and reliability receives a smaller value and appearance a larger value because both cars are reliable. For this reason, the need for networks rather than hierarchies to represent all multiple criteria decision problems.

The feedback structure takes the shape of a network rather than the top-to-bottom form of a hierarchy, with components of elements (or levels) connected by cycles, and loops that connect a component to itself. The structure has *source* and *sink* nodes. The node that is an origin of path of importance and never a destination of such paths is called a *source* node while the node that is a destination of paths of importance and never an origin of such paths is called a *sink* node. The nodes that fall on paths from source nodes, lie on cycles, or fall on paths to sink nodes are called *intermediate* nodes (see Figure 2-3).

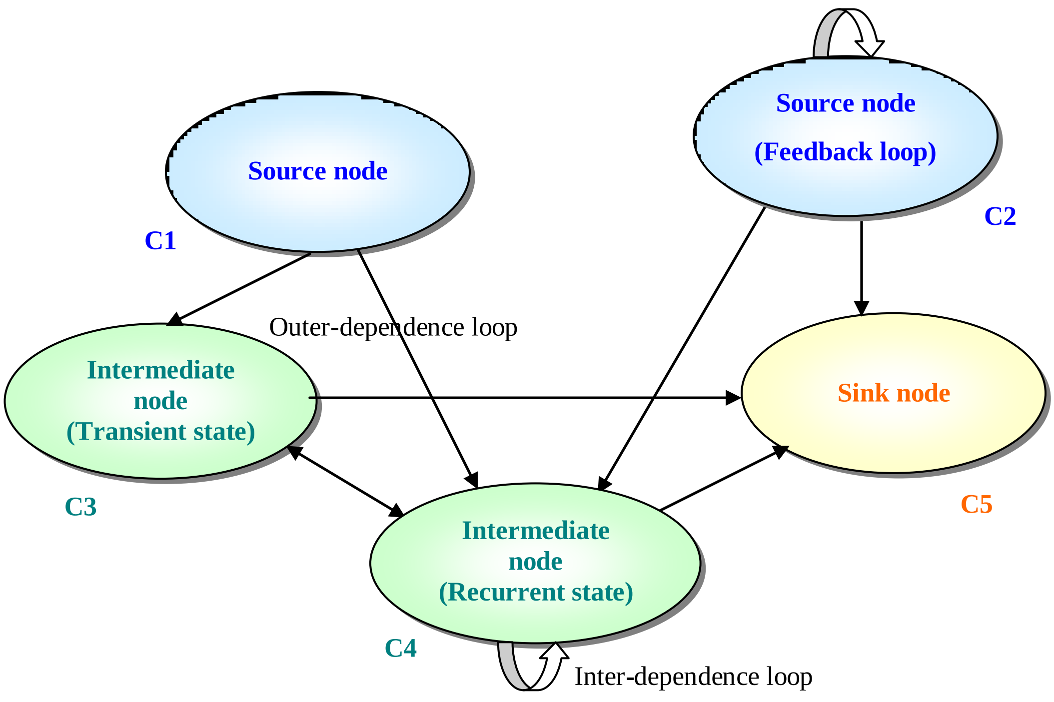

Figure 2-3: Feedback Network
(Source: Saaty 2001)

Those components that no arrow enters from any other node are source nodes. Those from which no arrow leaves are sink nodes, and those that arrows both enter and leave are intermediate (or transient) nodes. C3 and C4 form a cycle of two components because they feed back and forth into each other. The loops that connect C2 and C4 to themselves are inner-dependence loops and all other connections represent dependence between components are outer-dependence loops.

In general, a network consists of nodes where each node is made up of elements. The nodes are sometimes called ‘components’ or ‘clusters’. “A component in the ANP is a collection of elements whose function derives from the synergy of their interaction and hence has a higher-order function not found in any single element” (Saaty 2001). The influence of elements in the network on other elements in that network can be represented in the following *super matrix*:

$$W = \begin{array}{cc} & \begin{array}{cccc} C_1 & C_2 & \cdots & C_N \\ e_{11}e_{12}\cdots e_{1n_1} & e_{2}e_{22}\cdots e_{2n_2} & & e_{N1}e_{N2}\cdots e_{Nn_N} \end{array} \\ \begin{array}{cc} C_1 & \begin{array}{c} e_{11} \\ e_{12} \\ \vdots \\ e_{1n_1} \end{array} \\ C_2 & \begin{array}{c} e_{21} \\ e_{22} \\ \vdots \\ e_{2n_2} \end{array} \\ \vdots & \vdots \\ C_N & \begin{array}{c} e_{N1} \\ e_{N2} \\ \vdots \\ e_{Nn_N} \end{array} \end{array} & \begin{bmatrix} W_{11} & W_{12} & \cdots & W_{1N} \\ W_{21} & W_{22} & \cdots & W_{2N} \\ \vdots & \vdots & \vdots\ \vdots\ \vdots & \vdots \\ W_{N1} & W_{N2} & \cdots & W_{NN} \end{bmatrix} \end{array}$$

A typical entry W_{ij} in the super matrix, is called a *block* of the super matrix as follows:

$$W_{ij} \quad = \quad \begin{pmatrix} w_{i1j1} & w_{i1j2} & \cdots & w_{i1jnj} \\ w_{i2j1} & w_{i2j2} & \cdots & w_{i2jnj} \\ \vdots & \vdots & \vdots\vdots\vdots & \vdots \\ w_{inj1} & w_{inj2} & \cdots & w_{inijnj} \end{pmatrix}$$

Each column of W_{ij} is a principal *eigenvector* of the influence (importance) of the elements in the *ith* component of the network on an element in the *jth* component. Some of its entries may be zero corresponding to those elements in a component that have no influence.

The super matrix must be reduced to a matrix, each of whose columns sums to unity, known as a *column stochastic* or a *stochastic matrix* to derive limit priorities of influence from the super matrix. The limiting priorities in the super matrix will not depend on the reducibility, primitivity, and cyclicity of the matrix unless the matrix is stochastic. This stochastic matrix is called a *weighted matrix* and is obtained by multiplying the elements of the super matrix by the appropriate component weight which comes from comparing each component with the other. Finally, from the weighted super matrix, a matrix called the *limit super matrix* is obtained by raising the weighted super matrix to powers by multiplying it times itself. When the column of numbers is the same for every column, the limit super matrix has been reached and the matrix multiplication process is halted.

The influence represented in all the derived eigenvectors of priorities entered in a super matrix must be measured according to a single criterion, such as social influence. Another super matrix may represent economic influence, and so on. Such criterion with respect to which influence is represented in individual super matrices is called *control criteria* and the structure of control criteria is called a *control hierarchy*. So, the criteria in the control hierarchy that used for comparing the components are usually the major parent criteria whose sub-criteria are used to compare the elements in the component.

Saaty (2001) identifies the generic question to be answered by making pairwise comparisons as: "Given a control criterion (sub-criterion), a component (element) of the network, and given a pair of components (elements), how much more does a given member of the pair influence that component (element) with respect to the control criterion (sub-criterion) than the other member?"

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

The basic concept of TOPSIS is that the selected alternative should have the shortest distance from the ideal solution and the farthest distance from the negative-ideal solution in some geometrical sense (Triantaphyllou 2000). It defines an index called "similarity index" (or relative closeness) to the positive-ideal solution by combining the proximity to the positive-ideal solution and the remoteness from the negative- ideal solution. Then the method chooses an alternative with the maximum similarity to the positive-ideal solution. TOPSIS assumes that the larger the attribute outcome, the greater the preference for benefit attributes and the less the preference for cost attributes (Yoon and Hwang 1995). The idea of TOPSIS can be expressed in a series of steps:

Step 1: Obtain performance data for *n* alternatives over *m* attributes. Raw measurements are usually normalised by converting raw measures x_{ij} into normalised measures r_{ij} as follows:

$$r_{ij} = (x_{ij}) / \sqrt{\sum x^2_{ij}}, \qquad i= 1, \ldots, m, \quad j= 1, \ldots, n$$

Step 2: Calculate weighted normalised ratings:

$$Weighted\ r_{ij} = w_j\, r_{ij}$$

where w_j is the weight of the jth attribute. The basis for these weights can be anything, but, usually, is *ad hoc* reflective of relative importance. Scale is not an issue if normalising was accomplished in Step 1.

Step 3: Identify the positive-ideal alternative (extreme performance on each criterion) A^+.

Step 4: Identify the negative-ideal alternative (reverse extreme performance on each criterion) A^-.

Step 5: Develop a distance measure over each criterion to both positive-ideal (S_i^+) and negative-ideal (S_i^-).

Step 6: For each alternative, determine a ratio C_i^+ equal to the distance to the negative-ideal divided by the sum of the distance to the negative-ideal and the distance to the positive-ideal,

$$C_i^+ = S_i^- / (S_i^- + S_i^+)$$

Step 7: Rank order alternatives by maximizing the ratio in Step 6.

Yoon and Hwang (1995) presented a good example that illustrates the TOPSIS method (See Appendix A).

2.4.4.4 Elimination Et Choix Traduisant La Réalité (ELECTRE)

The basic concept of the ELECTRE (also for *Elimination and Choice Translating Reality*; English translation from the French original) method is to deal with 'outranking relations' by using pairwise comparisons among alternatives under each one of the attributes separately. This method is most popular in Europe, especially among the French-speaking community.

Suppose that there are two alternatives A_p and A_q, the notion (A_p **R** A_q) or ($A_p \rightarrow A_q$) means that A_p outranks A_q. Formally, an outranking relationship of (A_p **R** A_q) states that even though two alternatives A_p and A_q do not dominate each other, it is realistic to accept the risk of regarding A_p as almost surely better than A_q. Accordingly, the outranking relationship **R** is not required to be transitive. For example, the following assessments (A_1 **R** A_2) and (A_1 **R** A_3) do not necessary imply (A_1 **R** A_3). Yoon and Hwang (1995) describe this kind of outranking relationship as "both ambiguous and practical".

The basic idea of the ELECTRE method comes from pairwise comparisons of alternatives under each attribute. The decision maker then declares that he is indifferent between the alternatives under consideration, that he has a weak or a strict preference for one of the two, or that he is unable to express any of these preference relations. This means that the set of outranking relationships produced may be complete or incomplete. The steps of the ELECTRE method are shown below (the first two steps are the same as the first two steps of TOPSIS):

Step 1: Obtain performance data for n alternatives over m attributes. Raw measurements are usually normalised by converting raw measures x_{ij} into normalised measures r_{ij} as follows:

$$r_{ij} = (x_{ij}) / \sqrt{\sum x^2_{ij}}, \qquad i= 1, \ldots, m, \quad j= 1, \ldots, n$$

Step 2: Calculate weighted normalised ratings:

$$Weighted\ r_{ij} = w_j\, r_{ij}$$

where w_j is the weight of the jth attribute. The basis for these weights can be anything, but, usually, is *ad hoc* reflective of relative importance. Scale is not an issue if normalising was accomplished in Step 1.

Step 3: Calculate the *concordance* and *discordance* sets. For each pair of alternatives A_p and A_q ($p, q = 1, 2, \ldots, n$ and $p \neq q$), the set of attributes is divided into two distinct subsets. The concordance set, which is composed of all attributes for which alternative A_p is preferred to alternative A_q. In other words, the concordance set $C(p, q)$ is the collection of attributes where A_p is better than or equal A_q. The complement of $C(p, q)$, which is called the discordance set $D(p, q)$, contains all attributes for which A_p is worse than A_q.

Step 4: Calculate the concordance and discordance Indexes. The relative power of each concordance set is measured by means of the concordance index. The concordance index C_{pq} represents the degree of confidence in the pairwise judgments of ($A_p \rightarrow A_q$). The concordance index of $C(p, q)$ is defined as:

$$C_{pq} = \sum w_{j*}$$

Where $j*$ are attributes contained in the concordance set $C(p, q)$.

On the other hand, the discordance index measures the power of $D(p, q)$. The discordance index of $D(p, q)$, which represents the degree of disagreement in ($A_p \rightarrow A_q$), can be defined as:

$$D_{pq} = \left(\sum \left| v_{pj^\circ} - v_{qj^\circ} \right| \right) / \left(\sum \left| v_{pj} - v_{qj} \right| \right)$$

Step 5: Find the outranking relationships. The method defines that A_p outranks A_q When $C_{pq} \geq C$ and $D_{pq} < D$, where C and D are the averages of C_{pq} and D_{pq}, respectively.

A detailed example of ELECTRE is shown in Appendix A.

2.4.4.5 Simple Multi-Attribute Rating Technique (SMART)

SMART is based on Ward Edwards' work which he introduced in 1971. It has been widely applied because of the simplicity of both the responses required of the decision maker and the manner in which the responses are analysed. The method went through many modifications and improvements (see Edwards and Barron 1994). The main stages of the SMART technique are eight stages (Goodwin and Wright 2004) as follows:

Stage 1: Identify the decision maker (or decision makers).

Stage 2: Identify the alternative courses of action.

Stage 3: Identify the attributes which are relevant to the decision problem.

Stage 4: For each attribute, assign values to measure the performance of the alternatives on that attribute.

Stage 5: Determine a weight for each attribute.

Stage 6: For each alternative, take a weighted average of the values assigned to that alternative.

Stage 7: Make a provisional decision.

Stage 8: Perform sensitivity analysis to reach the final decision.

This method went through several changes and it can be found in different forms. The main stages described above remain as the backbone for all versions of SMART available in literature. More details about SMART are discussed in chapters 5 and 6.

After reviewing the literature of MCDM, the researcher highlighted the strengths and weaknesses of the different MCDM methods at the end of Appendix A. This helped in identifying the methods that the researcher used in developing the multi-attribute decision making methodology for selecting new R&D projects as will be shown in chapter 5.

The next chapter describes the methods available in literature about R&D portfolio selection, with gaps in literature discussed at the end of the chapter.

3 R&D Portfolio Selection

3.1 Introduction

In this chapter, a review of the available literature on the methods of R&D project evaluation and portfolio selection is presented and discussed. Section 3.2 addresses the importance of portfolio selection and the need for careful investment in R&D projects.

Methods used for portfolio selection are discussed in section 3.3. It shows methods used for evaluating and selecting R&D projects grouped into families of methods, such that all the methods in any family have similar features. Due to the large number of applications in the area of portfolio selection, representative models are highlighted to give a clear understanding of the general method.

A discussion of the disadvantages and drawbacks of the methods is highlighted in section 3.4, while gaps in the literature of R&D portfolio selection methods are presented in section 3.5.

3.2 Issues on R&D Portfolio Selection

The problem of R&D portfolio selection is not a new one. There are many articles describing portfolio selection methods since the 1960s (Martino 1995), with the aim of answering the question: Are we doing the right R&D?

Globalisation enabled enterprises to open markets in parts of the world which were difficult to access before and new competitors enter the markets from new regions. Current trends such as environmental concern, shorter product life cycles, cost reduction, and developments in information technology and computer power have increased the importance of R&D which, therefore, increased the interest in R&D portfolio selection methods. Nowadays, investment in R&D project if not done properly could lead to wasting large amount of resources or even ruin the enterprise (Heidenberger & Stummer 1999).

The term 'portfolio' is used synonymously with the expression 'collection of assets' or, even more generally, 'collection of prospects'. A portfolio could consist of financial assets as well as real estate, paintings, or other collectables (Zeleny 1982).

This research is concerned with portfolios that contain new R&D projects. Therefore, the aim of R&D portfolio selection is to assess the overall benefit from investing in R&D project, for a given period of time, relative to the resources needed and the likelihood of achieving the goals and objectives set by the investing enterprise. In other terms, the aim is to make sure that the selected portfolio is balanced.

3.2.1 Factors for Portfolio Balancing

The objective of portfolio selection is to choose from the list of alternative projects the set that provides maximum payoff to the company. It takes into account resources dependencies, budget constraints, technical interactions, market interactions, and programme considerations (Martino 1995).

Resource Dependency

The need to balance a portfolio stems from the fact that projects cannot always be considered in isolation. Sometimes projects may require sharing the same resources, such as equipment, facilities, or people. The decision maker must ensure that the requirements of the set of projects included in the selected portfolio do not exceed the capacity of any resources.

Budget Constraints

One of the dreams of R&D decision makers is to be able to fund all the projects that are expected to bring benefit to their companies. In reality, available budget plays as a constraint so that decision makers have to select the portfolio that satisfies the R&D budget even if the maximum benefit is reached.

Technical and Market Interactions

Interdependency between projects is another factor to be considered when selecting a balanced portfolio. The success or failure of one project could lead to the success or failure of another project(s). To solve this problem, interdependent projects can be considered as one project if other constraints are satisfied. Other interactions could be targeting the same market with similar products. Selection of portfolios should prevent, if necessary, any market interactions among projects included in the portfolio.

Programme Considerations

Company policies or political considerations may force the decision makers to include certain projects in the selected portfolio. For example, decision makers may adopt a policy that a certain number of projects should be taken from each research division in the company even if that leads to reduce the total monetary payoff from the portfolio.

When interviewing some people from the R&D of ARAMCO refining operations, one researcher pointed out that head managers occasionally insist of including certain projects in the final portfolio. This can be dealt with as 'golden' projects when balancing the portfolio, where the gut-feeling of head managers is strong about the benefit of selecting those projects!

Considering the previously presented factors, a discussion of the available R&D portfolio selection methods is presented in the following section.

3.3 R&D Portfolio Selection Methods

The portfolio selection methods described in literature have many different forms that lie between subjective judgment of R&D managers at one extreme and highly formalised techniques at the other.

Due to the large number of methods available in literature, portfolio selection methods are classified into different groups or families, with each family encompasses a number of methods that are similar. There are different classifications of project evaluation methods depending on the similarity factors taken into consideration. Some methods divide portfolio selection into two phases: project evaluation and portfolio selection and balancing, while, on the other hand, other methods give only the final balanced portfolio. Certain common features between the different portfolio selection methods are illustrated in Figure 3-1.

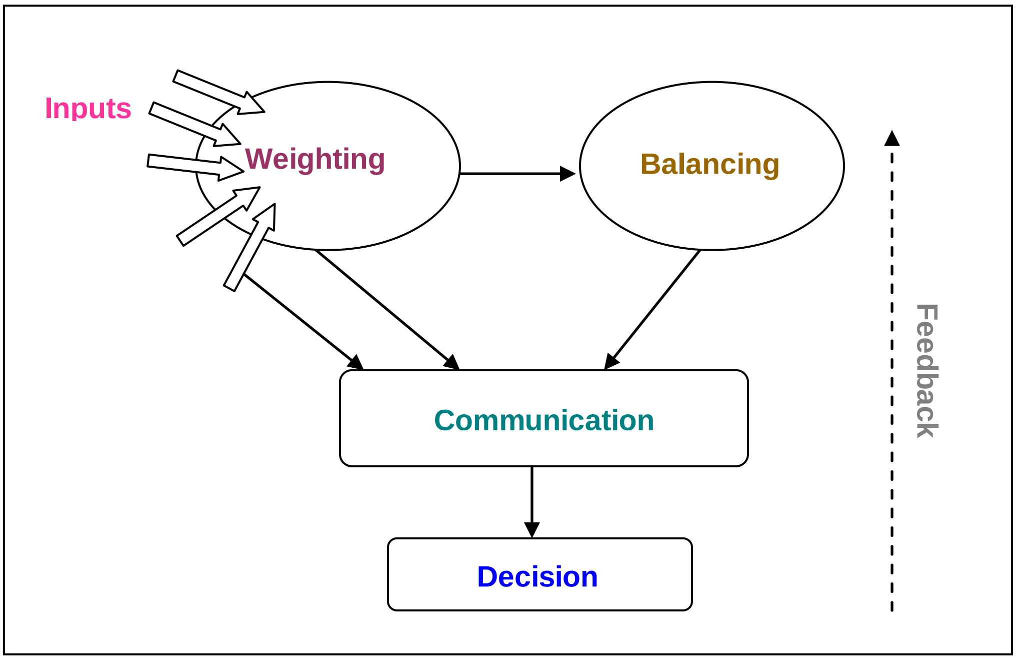

Figure 3-1: A Model of the Portfolio Evaluation Process
(Source: EIRMA 1995)

The *inputs* to the process reflect those criteria of R&D projects and the business environment which the company believes to be important. The output is a *decision* about whether to proceed with the portfolio or not. If modifications are needed to the portfolio, or even the individual projects, it can be done at the decision step. Typical inputs include:

- Technological issues.
- Aspects of the R&D.
- Financial issues.
- Likelihoods of success or failure.
- Timescale.
- Intangible opportunities seen by the company.

It is clear that the inputs can be relatively certain, some can be very subjective. These inputs will be gathered from different sources, such as marketing, finance and technical staff, which will make important contributions.

After selecting and obtaining the inputs, an important step next is *weighting* them to reflect the importance, or preference, of one input relevant to other inputs. For example, the importance of financial issues for the company against technological and opportunity issues. There are many ways of deriving weight for different criteria presented in Appendix E.

After obtaining the weights, it is important to ensure that the final portfolio is balanced. Management must *balance* the attractions and disadvantages of the portfolio and take into account constraints, such as the available budget and the overlap between different projects, because separate evaluation of individual projects is unlikely to ensure the most efficient use of limited R&D resources.

Another aspect of portfolio evaluation and selection is the *communication* between the interested parties in order to build a consensus about the portfolio. It should be an on-going discussion between the parties involved in the selection process to ensure maximum effectiveness and benefit from communication.

Feedback provides lessons learnt during each step of the selection process in order to fine-tune or amend the weights. The process can be extended to cover the steps after execution of projects for post-evaluation activities.

In a report titled 'Evaluation of R&D Projects', the European Industrial Research Management Association (EIRMA) (1995) divided portfolio evaluation and selection methods into 14 families according to three different approaches.

The *financial* approach involves methods as simple as taking the ratio of benefits and costs of projects. Financial methods became more sophisticated but with one drawback remained: the figures used are only estimates and not that precise. There are other factors which are not easily expressed in purely monetary values and the results of a project will often be seen to have depended on those factors.

The second approach is the *human judgement* approach which aims to overcome some of the deficiencies of financial methods by including judgements of people involved in project evaluation.

More recent methods follow the *learning* approach, where projects are compared with past experience considering changes in markets and in the economic environment. The last two approaches combine certain amount of quantitative and subjective information for project evaluation.

Other classifications of project evaluation tend to maintain the financial approach methods and subdivide the human judgement and learning methods into smaller categories. Such classifications are presented by Baker (1974), Baker and Freeland (1975), Liberatore and Titus (1983), Hall and Nauda (1990), Martino (1995), and Cooper et al. (2001).

A more comprehensive classification was introduced by Heidenberger and Stummer (1999), which divides project evaluation methods into six categories: benefit measurement, mathematical programming, decision analysis, simulation Modelling, heuristics, and cognitive modelling methods. A seventh category, ad hoc, is added to highlight two project selection methods that do not fit neatly into any of the six categories (Martino 1995). Figure 3-2 shows the different categories of R&D Portfolio selection methods.

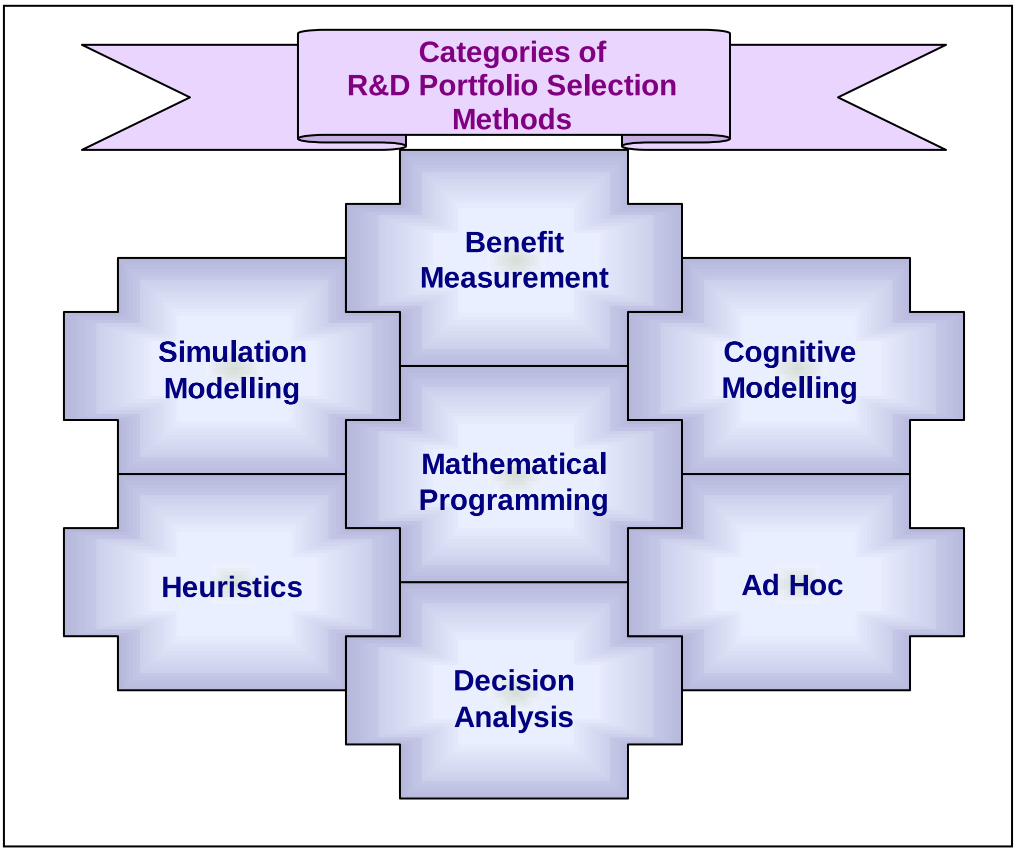

Figure 3-2: Categories of R&D Portfolio Selection Methods

These categories are discussed and the methods under some categories are updated and slightly modified in the following sections.

3.3.1 Benefit Measurement Methods

Benefit measurement methods attach a preferability figure to each project under evaluation. The project with greater benefit is considered more attractive than other projects. Methods under benefit measurement are subdivided into comparative models, scoring models, economic models and group decision techniques.

3.3.1.1 Comparative Models

The starting point of comparative models is for each project to be compared with a project or a set of alternative proposals. Once the comparisons are available, projects are then ranked using different methods. The major drawback of these models is that the benefit measures obtained have meaning only in relation to the projects under evaluation. If an alternative project is added or deleted, the whole process of comparisons must be done again which means that a considerable amount of time is needed.

One of the comparative models used is *Q-sort*. It is a psychometric method of rank order classifying of items according to the individual options of a decision group (Souder 1975). Each individual of the group sorts and resorts projects into several designated categories according to a single criterion (e.g. priority). Projects are then ranked in each category according to how the individual feel about them. The group's results are then statistically analysed for inter-individual similarities and overall group consensus. Projects are then taken from top to bottom until reaching the level of budget exhaustion.

Another method used is the Analytic Hierarchy Process (AHP). It is used to derive ratio scales on a variety of dimensions both tangible and intangible from the application of paired comparisons in multilevel hierarchic structures (Saaty 2000). It allows decision makers to structure a complex multi-criteria evaluation problem in the form of a hierarchy. Each level of the hierarchy consists of several criteria (or sub-criteria) with alternative projects at the bottom. After applying the steps of AHP, a list of prioritised projects is obtained and ranked. If the number of criteria, sub-criteria and alternative projects involved is big, the large number of pairwise comparisons may tire the decision makers and lead to biased results (Khorramshahgol et al. 1988).

There are many applications of AHP in the context of R&D project evaluation. Kuei et al. (1994) propose a model using AHP to rank and select advanced technologies. A greedy heuristic algorithm allocates resources to the different technologies. In the prioritisation of technologies at the Army Materials Technology Laboratory, Melachrinoudis and Rice (1991) introduce a model that combines five subjective criteria and one objective criterion. They determine the weights of the subjective criteria by using AHP, while the objective criterion is determined by a piecewise concave linear function. A software called ‘Expert Choice’ was used to solve the model. Khorramshahgol et al. (1988) used AHP to provide a systematic approach to set priorities and tradeoffs among the objectives of a Goal Programming (GP) model for project evaluation and selection.

The more recent applications use Analytic Network Process (ANP) as the general case of AHP. ANP allows decision makers to compare between criteria from any level or branch with each other so that all criteria could be treated as dependent on some or all of the other criteria. Meade and Presley (2002) present an application of an ANP-based model for selecting R&D projects at a small high-tech company. The model includes actors involved in the decision, stages of research, categories of merits, and individual metrics.

3.3.1.2 Scoring Models

Many scoring models involve a mathematical formula or algebraic expression that relates decision criteria, quantitative and subjective, believed to be important and produce a score for each project under consideration. The R&D people involved must determine the merit of each project with respect to each criterion. Each decision criterion is weighted to reflect the importance relative to the other criteria. Then each project's scores are substituted in the formula to give an overall benefit measure. Finally, projects are ranked in order of their scores.

Other scoring models develop a list of criteria to rate projects typically on 1-5 or 0-10 scales. Next, these rating scores are often multiplied by criteria's weightings and summed across all criteria to yield attractiveness scores for each project. Cooper et al. (2001) present several scoring models applied in different firms.

In contrast to comparative models, projects can be added or deleted without affecting the scores. Moore and Baker (1969) pointed out that scoring models can deal with subjective and quantitative input data estimates. One of the problems of dealing with mixed input data is the difficulty for decision makers to provide scores for each project against the different criteria (Jackson 1983). Another difficulty arises from the fact that decision criteria are, often, not independent (Cooper 1981). Henriksen and Traynor (1999) developed a scoring model that solved that problem be combining addition and multiplication of criteria in a function to obtain the final score. Projects are then ranked and selected from top to bottom until reaching the budget limit.

3.3.1.3 Economic Models

Economic models treat portfolio selection like a conventional investment decision (Cooper et al. 2001). Traditional approaches, such as payback period, return on investment, Net Present Value (NPV), and Internal Rate of Return (IRR) methods are used. These models treat R&D portfolio selection as a cost-return, pure financial problem. More about economic methods can be found in Appendix B.

3.3.1.4 Group Decision Techniques

These techniques systematically collect and combine the knowledge and judgement of experts from different fields. They are seen as a brainstorming or screening tool for obtaining data that are needed for more complex models (Khorramshahgol et al. 1988).

One of the well known group decision making techniques is the *Delphi* method. The purpose of the method is to elicit judgment, insights and expectations from a panel of experts, to organize the projects and have them evaluated by the whole group. Khorramshahgol et al. (1988) applied the Delphi method to identify the objectives and their corresponding aspiration levels prior to goal programming formulation for a portfolio selection problem.

The *impact* method for achieving organizational consensus is proposed by Souder (1975). It was used to choose criteria for portfolio selection at four different organisations. Each criterion is pair compared with another one and the group members discuss and interact with each other to specify the final criteria.

Souder (1978) used another technique called the *nominal interacting process*. It starts by asking the group to complete a Q-sort exercise in a nominal period. Q-sort results are then tabulated in a tally chart. The following steps are similar to the Delphi method.

3.3.2 Mathematical Programming

Mathematical programming models try to identify an *extreme* (i.e., minimum or maximum) point of an objective function(s), which furthermore satisfies a set of constraints. The objective function is optimised subject to constraints such as resources, research type, technology type, etc. R&D portfolio selection models using mathematical programming are divided into linear, non-linear, integer, goal, dynamic, and fuzzy mathematical programming.

As a fundamental tool of portfolio selection, linear programming (LP) aims to optimise an objective function representing the expected benefit from a portfolio of projects (e.g. revenue, attractiveness, etc.) subject to limits of available resources (e.g. budget, manpower, etc.). It assumes that both the expected benefit and resources consumption are linearly dependent on project size, and the objective function is linear.

Most models assume a number of alternative projects x_i with a payoff $p(x_i)$ exists for each project, where $i = 1, 2, \ldots, n$. Assuming that each project requires an amount of resources r_i , and a total of R resources is available, then the LP would find the portfolio of projects which maximises:

$$Z = \sum p(x_i)$$

subject to:

$$\sum r_i \leq R$$

The assumption of linearity is not always valid. Many real-life decision problems are *non-linear* by nature. In other cases, the nature of the decision variables is to capture go/ no go, select/ do not select or integer decision criteria. Those types of models are called *Integer Programming* (*IP*). A need for a model that can solve portfolio selection problems where the variables are of a mixed nature is essential.

Souder (1973) described a non-linear programming model that is converted to LP by using piecewise-linear function with integer programming variants. Martino (1995) presented an example of a Integer-Linear Programming (ILP) model for portfolio selection, where the objective is maximising the total revenue with constraints of R&D funds available, and operating hours in a fabrication shop and on a supercomputer using MS-EXCEL[TM] spreadsheets. Stummer and Heidenberger (2003) described a three-phases approach to aid decision makers in obtaining the most attractive R&D project portfolio. A ILP model is used to determine all efficient portfolios, taking into account various project interdependencies, time profiles, logical and strategic requirements, as well as resources and benefit constraints.

Arman et al. (2008) introduced a systematic process to aid decision makers in selecting the optimum portfolio of R&D projects in the manufacturing processes of large, high-technology companies using an ILP model. The optimum portfolio represents the most attractive projects as a combination that fulfils quantitative and qualitative objectives. The ILP model is based on the projects contribution towards company's business and market requirements utilising Strategic Technology Alignment Roadmapping (STAR) process, which is being developed at The University of Nottingham.

Another type of mathematical programming is *Goal Programming* (*GP*). This technique attempts to make the decision maker come as close as possible to his 'goals' with the preferences of the decision maker between the various goals are reflected by cardinal weights attached to the goals. In reality, GP is closer in its assumptions and methodologies than other multi-criteria decision making techniques but, at the same time, received many critics (Khorramshahgol et al. 1988).

Badri et al. (1999) formulated a mixed 0-1 GP model which is validated by applying it to a real-world information systems project selection data for health service institutions. The model included criteria such as decision maker preferences, benefits, costs, priorities, risks and resources availability.

Dynamic Programming (*DP*) is a mathematical programming technique that can be used to solve the problem of portfolio selection, where the decision criteria are of a mixed nature. It obtains solutions by working backward from the end of a problem toward the beginning, thus breaking up a large problem into a series of smaller, more tractable problems.

Hess's model (1962) is one of the earliest DP models sued to solve the problem of R&D portfolio selection. The objective of the model is maximising the present value of all current and future expected cash flows. R&D projects are killed as soon as they are technically successful but not necessarily economically successful as well.

In many cases, the type of input data, goals and constraints for mathematical models may be framed in terms of very broad ranges. Fuzzy input data, such as 'high', 'medium', 'fair' and 'low', could be used in a *fuzzy mathematical programming* model. Weber, Werners and Zimmermann (1990) presented a fuzzy model used in a situation where the decision maker is satisfied if a certain aspiration level is exceeded but not necessarily a maximum of the objective function is reached. It is no longer required that all constraints are satisfied and the violation of restrictions to a certain degree is tolerated.

3.3.3 Decision Analysis

There are two approaches of decision analysis used to select R&D portfolios. The objective is to give decision makers more insight about the R&D portfolio selection rather than providing direct answers about the portfolio to be selected.

Decision Trees considers possible future events of a company's environment that are uncertain with respect to occurrence and extent (Heidenberger & Stummer 1999). In a typical decision tree, squares represent decisions to be made, while circles represent chance events. The branches stemming from a square correspond to the choices available to the decision maker, and the branches emanating from a circle represent the possible outcomes of a chance node. The consequence of a decision is specified at the ends of branches. Figure 3-3 shows an example of a decision tree.

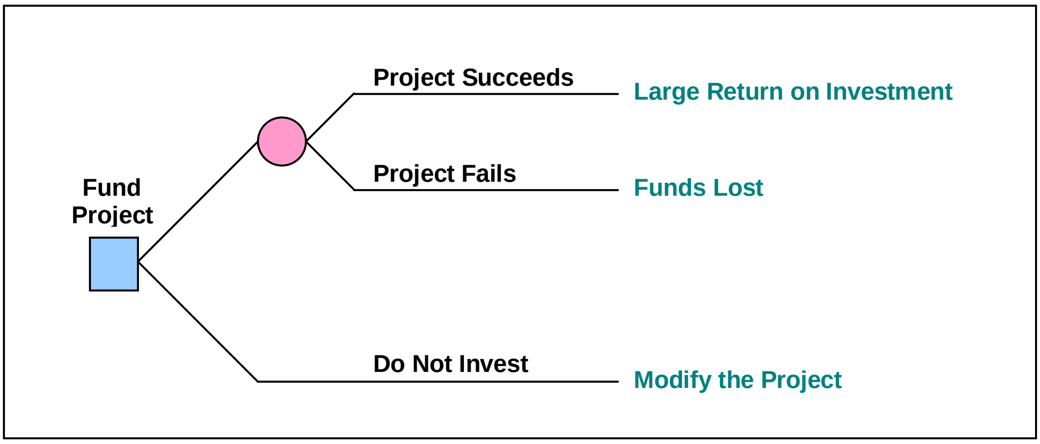

Figure 3-3: Basic Example of a Decision Tree

In R&D investment decisions, Heidenberger (1996) introduced a mixed ILP model resulted from applying the decision trees approach with each project is represented by a decision tree. The objective is to maximize the overall benefit subject to constraints of various qualifications and constraints on the node-dependent maximal number of go decisions if multiple go/no go decisions at nodes have to be made.

The other decision analysis approach used in R&D portfolio selection is the SMART technique (see section 2.4.4.5). EQUITY, computer software, was developed by London School of Economics to apply the steps of SMART. The final tradeoff between a group of portfolios is done using what is called the 'efficient frontier', based on a model developed by Nobel Laureate Harry Markowitz (1991), in order to select the investment portfolio.

Pereira and Veloso (2009) proposed an approach to allocate R&D program budget using Markowitz portfolio selection model. The approach starts by defining the program's objectives and covers the allocation of an R&D program budget, including R&D portfolio selection, according to specific criteria.

3.3.4 Simulation Modelling

Simulation is used to represent real-world systems when:

- projects in a portfolio have alternative outcomes to which probabilities can be attached,
- projects have alternative paths to the end goal depending on the chance outcome,
- projects have different payoffs for the different outcomes,
- experiments in the real-world are inappropriate, too expensive or time consuming, and/or

- when data required are not available or can not be acquired.

This is done in a sufficient large number of times to assure statistically valid results, which represents an estimate of the probability of different outcomes. In R&D portfolio selection context, Monte Carlo simulation uses random numbers generated from probability distributions to give insights about the spread of values of a benefit function about the mean (Martino 1995). Monte Carlo simulation is used as a more realistic estimate of expected rate of return and better understanding of the nature of competition (Souder & Mandakovic 1986; Martino 1995).

3.3.5 Heuristics

Decision makers who use heuristic models do not necessarily want to achieve optimal solutions but they will be satisfied if an acceptable solution is reached. R&D managers prefer this type of modeling because it provides a realistic approach considering lots of interactions between the various elements of different models (Heidenberger & Stummer 1999).

Coffin and Taylor (1996) used a filter beam search approach to include project scheduling as part of the selection criteria. If it is not possible to schedule the selected projects given the available resources, projects may be replaced with others that can be scheduled. A heuristic-based methodology was developed by Venkatraman and Venkatraman (1995) to enable the streamlining of R&D project schedules in organisations facing rapid product obsolescence.

3.3.6 Cognitive Modelling

The methods discussed in the previous sections tend to decompose global decision into components that can be analysed or judged separately. Combining the analyses and judgments leads to a global evaluation and selection of projects.

Cognitive modeling works in reverse of the above process. The analysis is done for global decisions to determine the components that went into them. The aim is to build on previous experience of decision makers in project selection to establish a model of the actual decision making process within an organisation (Hall & Nauda 1990). Cognitive modeling allows analysts and decision makers to calibrate a model on the limited set of cases and apply the results to the larger set.

Martino’s (1995) experience with *replication* cognitive modeling has shown that simple linear regression of a sample set of decisions “seems to do an adequate job of capturing the thinking of the person or group being modeled, so long as the data used as input to the model is itself consistent with the decision maker(s) mental model.”

Added to the advantages of replication models, *evaluation* cognitive models allow analysts to evaluate the factors that went into the decision of selecting the R&D portfolio and their relative strengths.

3.3.7 Ad Hoc

The two methods introduced in this section can not be easily fit in one of the previous six categories. *Profiles* and *interactive* portfolio selection methods are described as "largely pragmatic in nature" (Martino 1995).

The *profiles* method looks similar to scoring models. The decision maker identifies several criteria and projects are given scores against each criterion. Each criterion has a preset cutoff, and if a score falls below it, a project may be rejected. Projects that dominate others on all, or most, criteria are then selected. If funds are still remaining, projects with the 'best' profiles are selected from those remaining, where 'best' is largely subjective.

Figure 3-4 shows an example of one profile (Cost £1000), where the cutoff line represents projects will be rejected if they exceed £70,000. The viewer can easily see the effect of a specific cutoff line, and the effects of adjusting the cutoff line up or down.

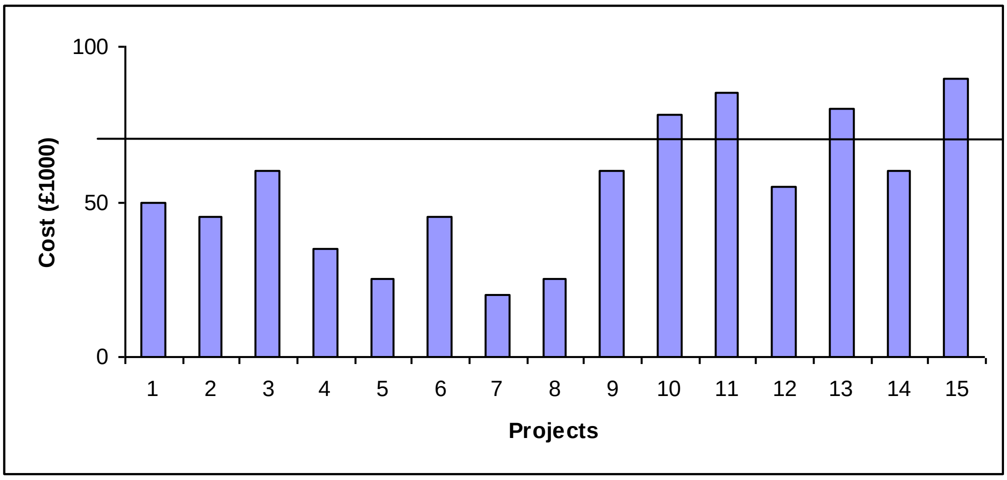

Figure 3-4: Example of a Profile for Portfolio Selection

The R&D director interacts with subordinate managers to determine what the selection factors should be in *interactive selection* method. The steps of this method go as follows:

1. Managers submit proposed projects that conform, as close as possible, to guidelines given earlier by their director.
2. The director selects only one of the proposals and explains the reasons or criteria of his/her selection.
3. Managers then revise their project proposals to conform more closely to, what in effect become, modified guidelines.
4. The process of revising project proposals and selecting one project from the revised and improved list continues until the director's budget is exhausted, or some other resource constraint become binding.

The R&D director's criteria become better defined as successive projects are selected and reasons are given for the selection. The 'back-and-forth' process gives manager an incentive to make their projects more attractive to fit the desires of the director.

3.4 Drawbacks of R&D Portfolio Selection Methods

The previous sections discussed the available R&D portfolio selection methods and their major characteristics classified into seven categories with examples of research done on them. Despite the availability of computer software supporting many methods, those methods have some drawbacks.

Comparative models are used quiet often but when adding or deleting an alternative project, the whole process of comparisons needs to be done again consuming a lot of time. AHP and ANP carry the same theoretical critics highlighted in Appendix A.

In spite of their popularity, scoring models need a considerable amount of time and information concerning how decision makers judge each criterion or objective and its relative importance. In a comparison between scoring and holistic ranking models, error from a single data item is more disastrous in scoring models (Lockett & Stratford 1987).

Group decision techniques, as well as comparative and scoring models, does not guarantee the satisfaction of different decision constraints. There is no clear way to maximise the benefit from selecting the R&D portfolio.

Economic models are based on monetary considerations and are closely related to the traditional techniques used for capital budgeting. Since the selection of R&D portfolios depends on financial and non-financial considerations, social, environmental and political costs and benefits can, in principal, be added to the calculations but they must be expressed in monetary terms. That is often not a trivial task (Jackson 1983).

Hess (1993) observes that the data required from mathematical programming models are difficult for R&D managers to provide. A considerable amount of gap between what mathematical programming has to offer and what is actually used for R&D portfolio selection (Heidenberger & Stummer 1999). R&D people in ARAMCO feels that mathematical programming is like a black box where decision makers do not always understand what is done inside it.

Decision trees method has limited applicability for R&D portfolio selection since it is based on a series of events and chances. Relying on the efficient frontier to tradeoff between portfolios on two axes is seen as a drawback when the STA research group in the University of Nottingham introduced it to some R&D managers.

Heuristics are seen complex sometimes. It is not easy to find all feasible solutions using models that consume a lot of time. Those models are described in a new literature and could help to compromise between solution quality and computational time.

Cognitive modelling needs input from experts and it is not suitable if the R&D activities are new or expertise is unavailable in the organisation. It is seen as a tactical decision tool than a strategic one (Rosenhead & Mingers 2001).

Profiles and interactive selection methods are not formal methods. They are time consuming, and can be used when none of the previous methods seem to be appropriate.

Martino (1995) compared between 15 portfolio selection methods according to 24 factors of suitability of selection methods. No single method satisfied all the factors, with decision analysis, mathematical programming, simulation modelling, and interactive selection satisfied between 16 to 17 factors. Those methods are used as tools for the decision making methodology presented in chapter 5.

In reality, R&D portfolio selection methods are not used widely. The methods presented in the previous sections lack one or more of the following issues (see for example Baker & Freeland 1975, Martino 1995, Cooper et al. 2001; Stummer & Heidenberger 2003):

- Treatment of multiple, often interrelated, criteria.
- Treatment of risk and uncertainty.
- Treatment of project interrelationship with respect to both value contribution and resource utilisation.
- Recognition and incorporation of the experience and knowledge of the R&D decision maker(s).
- Recognition and treatment of non-monetary aspects.
- Perceptions held by the R&D decision maker(s) that the models are unnecessarily difficult to understand and use.
- Treatment of the time variant property of data and criteria, and the associated problem of consistency in the research program and the research staff.
- The portfolio reflects the enterprise's business strategy.

3.5 Gaps in Literature

Literature review in this chapter showed the availability of R&D portfolio selection methods. The number of methods used reflects the importance of this issue. Although methods are available, drawbacks of theoretical and practical nature still exist (section 3.4). Due to the large number of methods; decision makers can not easily know which method to apply. Traditional economic methods should be part of the solution but not 'the' solution.

The methods presented previously tend to solve the final step of portfolio selection without clear insurance of alignment between organisational goals and objectives, and the final R&D portfolio selected for funding. Some methods are useful for screening R&D projects (e.g. profiles, scoring), other are more suitable for evaluating projects (e.g. benefit measurement methods, EQUITY, cognitive modelling), and some starts from obtaining input data until reaching the final balance R&D portfolio (e.g. mathematical programming, simulation, heuristics, ad hoc). Therefore, a framework or methodology that starts from identifying needs and ends by balancing the portfolio is required.

The major gaps that have been found using the literature review of R&D portfolio selection could be illustrated as follows:

- **Gap 1:** Literature provides a variety of R&D project evaluation and portfolio selection methods that could be used in various stages of the decision making methodology, but it does not fully explain *which method* should be used in which case (EIRMA 1995).

- **Gap 2:** The literature does not provide a clear methodology for selecting R&D portfolio starting from project creation to portfolio balancing and evaluation.
- **Gap 3:** The literature does not offer a consistent way of integrating R&D project evaluation and portfolio balancing.
- **Gap 4:** There is a lack of a procedure that ensures that the selected portfolio fits with company's strategy.
- **Gap 5:** The literature does not show a clear way of matching the decision making style of organisations with the appropriate R&D portfolio selection method.

Literature review (chapter 2 and 3) and gaps identified in this section represent the theoretical base for the development of the decision making methodology for R&D portfolio selection proposed by the researcher. Chapter 5 will introduce the proposed decision making methodology comprehensively, while a case study of R&D portfolio selection in oil refining operations of Saudi ARAMCO is presented in chapter 6.

4 Research Design and Methodology

4.1 Introduction

This chapter of the thesis describes the research methods applied, with explanation of the reasons why they were chosen and how they were utilised.

Research designs are plans and procedures for research that span the decisions from broad assumptions to detailed methods of data collection and analysis (Creswell 2009). They include the strategies and methods to be used in carrying out the research. Robson (2002) suggested that the selection of research design depends very much on the type of question the researcher is trying to answer.

Kumar (2005) summarised the different types of research described in literature in relation to three viewpoints which includes application, objectives and inquiry mode. Figure 4-1 illustrates Kumar's research typology from the three perspectives.

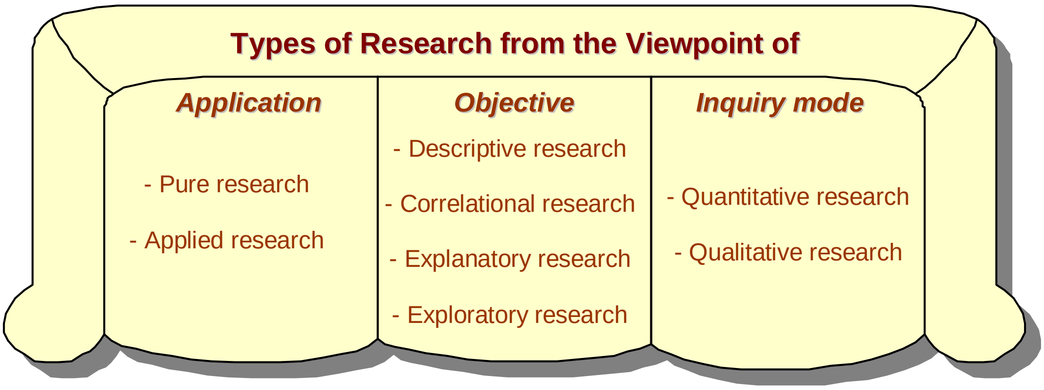

Figure 4-1: Classification of Research (Kumar 2005)

From the viewpoint of application, *pure* research involves developing and testing theories and hypotheses but may not necessarily have practical application at the current or future time. An example of pure research could be developing an instrument to measure the depression level in people. *Applied* research, on the other hand, requires research techniques, procedures and methods to be applied so that information gathered can be used, for example, for the enhancement of understanding of a phenomenon.

Four groups of research are distinctive from the objective viewpoint. A research that attempts to describe systematically a situation or phenomenon, such as describing the administrative structure of an organisation, is classified as *descriptive* research. The aim of *correlational* research is to study the existence of a relationship between two or more aspects of a situation. Studying the existence of a relationship between stressful living and incidence of heart attacks is considered of that group of research. *Explanatory* research attempts to explain why and how there is a relationship between two or more aspects of a situation. This type of research attempts to explain, for example, why stressful living results in heart attacks. In *exploratory* research, a study is conducted to explore an area where little is known or to develop, refine and/or test measurement tools and procedures.

The third viewpoint of research classification is the inquiry mode, which concerns the process adopted to find answers to research questions. The structured approach to inquiry is usually classified as *quantitative* research and unstructured as *qualitative* research. The study is classified as a *quantitative* if the purpose is to quantify the variation in a situation, phenomenon or problem. In this type, information is gathered using predominantly quantitative variables and then analysed to establish the magnitude of the variation. On the other hand, *qualitative* research aims to describe a situation, phenomenon or problem. Information is gathered through the use of variables measured on nominal or ordinal scales and the purpose of analysis is to establish the variation without quantifying it. For example, a study of how many people have a particular disease is considered a quantitative research, while the description of the disease spread in a community is considered as a qualitative research.

The three classifications by Kumar (2005) are not mutually exclusive. A research project classified from the perspective of *approach* can also be classified from the viewpoints of *objectives* and *inquiry mode* employed. The classification gives a general description of research types from different viewpoints but does not identify the appropriate research methods to be used.

4.2 Research Methods

According to Creswell (2009), research methods involve the forms of data gathering, analysis and interpretation that a researcher proposes for his/her study. The general principle for applying a research method is the appropriateness of that method to answer the research question (Robson 2002 and Yin 2009). Figure 4-2 shows the different research methods based on the form of research question.

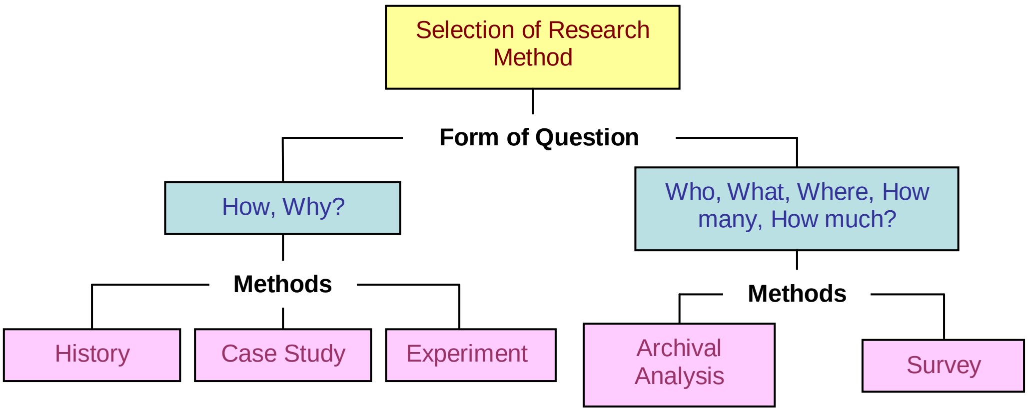

Figure 4-2: Research method based on the form of research question (Yin 2009)

Since the research question of this thesis asks a "how?" question, this leads to the use of History, case study, or/and experiment according to Yin's (2009) classification. Case study comes between two extreme approaches. When a researcher has no access to or control over actual behavioural events, history is the preferred method. On the other extreme, experiment is used when the researcher can manipulate behaviour directly, precisely, and systematically. Between those two extremes, case study is preferred in examining contemporary events, but when the relevant behaviour can not be manipulated. The sources for case study method is the same as history adding two more sources of evidence: direct observation of the events being studied and interviews of the people involved in the events (Robson 2002).

To start planning the implementation or investigation of their research, researchers need to select the suitable research method. This task is part of the research design mentioned previously, where decisions are spanned from broad assumptions to detailed methods of data collection and analysis (Creswell 2009).

Reviewing the literature of R&D portfolio selection showed that a wide range of portfolio selection methods could be used in the different stages of project evaluation and portfolio selection. However, there is no exact explanation of which method should be used in the different cases of R&D portfolio selection problem. This leads researchers to select the research design and methods that suits their individual cases.

According to Kumar's (2005) typology, an applied, explanatory, exploratory, and mixed quantitative and qualitative research type is preferred for the research in hand, with the method of case study is applied to develop and test a decision making methodology for R&D portfolio selection in the Saudi oil refining industry (i.e. chapter 6).

Yin (2009) defines a case study as:

"an empirical inquiry that investigates a contemporary phenomenon in depth and within its real-life context, especially when the boundaries between phenomenon and context are not clearly evident."

The characteristics of the case study inquiry:

- Copes with the technically distinctive situation where many more variables of interest than data points.
- Relies on multiple sources of evidence.
- Benefits from the prior development of theoretical propositions.

Although their benefit as a research method, case studies have been viewed as a less desirable form of inquiry than other methods. This is due to several critics. The greatest concern is the lack of rigor of case study research (e.g. not following systematic procedures, allowing biased views). Yin (2009) argues that this make case studies flexible to adapt to real-world events. Allowing biased views to influence the direction of the research findings and conclusion is a common issue in other approaches, such as experiments. Another criticism is that they take too long, which is not necessary because of the availability of alternative ways of writing case studies where the traditional lengthy ones can be avoided. One important concern about case studies is that they provide little basis for scientific generalisation. The case study method's goal is to generalise theories (analytic generalisation) and not to enumerate frequencies (statistical generalisation). Generalisation of a case study to cover other cases depends on the assumptions used by researchers (Kumar 2005; Creswell 2009).

Figure 4-3 illustrates the overall research design related to each chapter.

4.2.1 Research Methods Applied in This Thesis

The review of chapter 2 and chapter 3 identified the key problems and gaps in existing R&D portfolio selection methods (section 3.5), and chapter 5 presents the proposed solution methodology with a case study of Saudi ARAMCO's R&D oil refining operations. Table 4-1 shows the research components and techniques used in this thesis.

Table 4-1: Research Components and Techniques Used

Research Components	Techniques and Approaches Used	Relevant Chapters
Research Questions	• Literature Review • Leading Practice	Chapter 1
Conceptual Methodology	• Literature Review • Leading Practice • Model Generation • ILP	Chapter 5
Sampling and Data Collection	• Informal Interviews • Posted Questions • Using Documents and Records • Simulation • ILP	Chapter 6

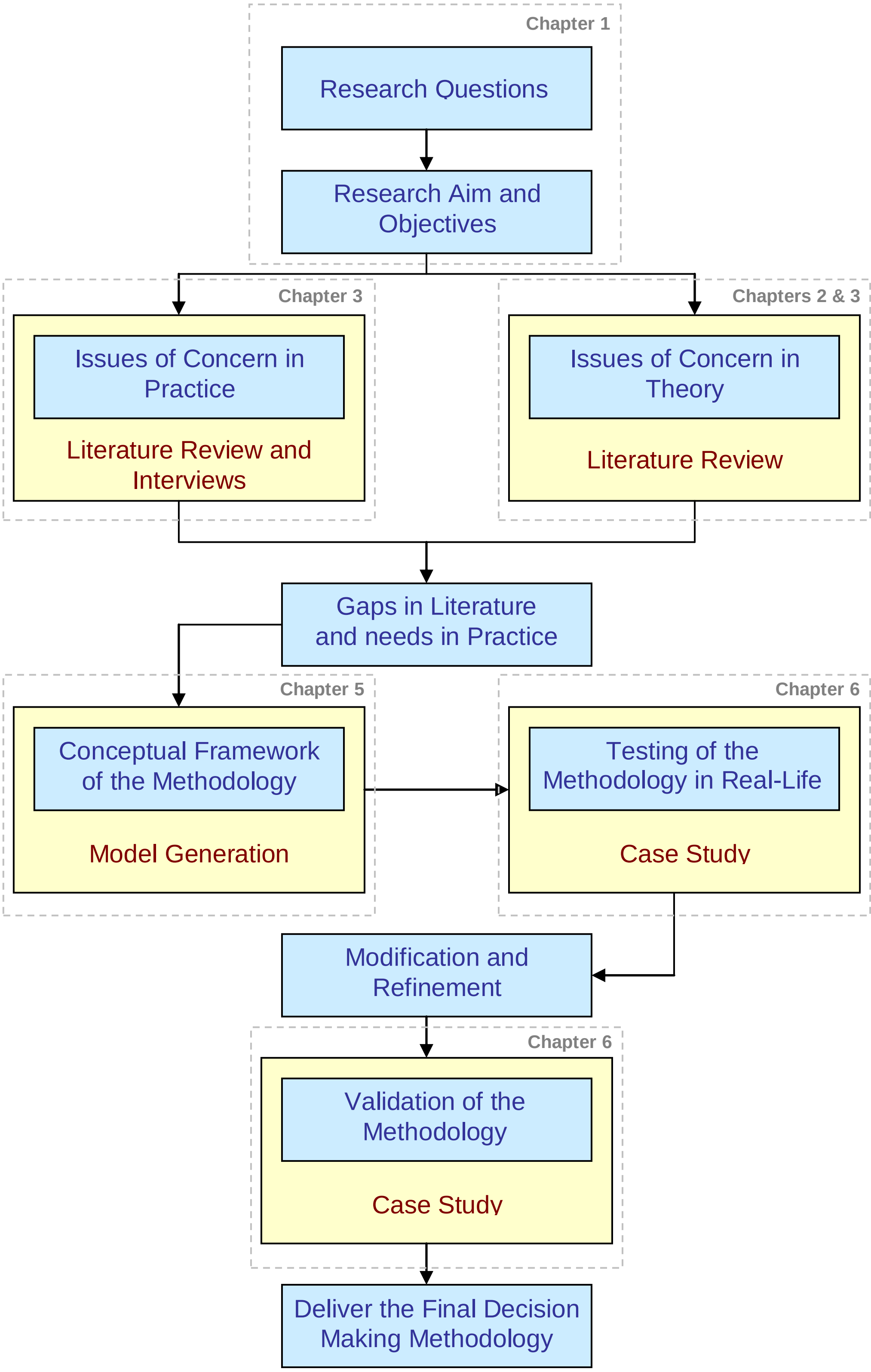

Figure 4-3: Overall Research Design

5 The Proposed Decision making Methodology for R&D Portfolio Selection

5.1 Introduction

When decision problems involve a number of criteria, or attributes, unaided decision makers tend to avoid making tradeoffs between these attributes. One of the problems that involve dealing with multiple attributes is the selection of R&D projects that form a company's R&D portfolio.

This chapter addresses a great part of the gaps identified in the literature review and discusses the needs that arose out of a case study carried out by the researcher about R&D portfolio selection in Saudi Aramco's oil refining operations. A description of a decision making methodology for R&D portfolio selection is presented in this chapter, while the case study is provided at chapter 6.

In Chapter 2 and 3, the literature review of Decision making in general and the R&D portfolio selection methods resulted in the generation and development of the decision making methodology. The discussion of multi-criteria decision making methods (section 2.4.4) and the existing methods of R&D portfolio selection (section 3.3) helped in identifying the gaps (section 3.5) and developing the methodology.

The decision making methodology for R&D portfolio selection discussed in this chapter went through different stages of refinement until reached the final form. Theoretical and practical developments were reasons for such modifications. Informal feedback from people in the Saudi Ministry of Petroleum and Mineral Resources, Ministry of Economy and Planning, and Aramco helped in fine-tuning the final methodology.

The methodology is based on modifications on the SMART method (section 2.4.4.5), and using TOPSIS (section 2.4.4.3) with the aid of a simple ILP model in different stages of the methodology. The methodology covers the steps needed before generating any R&D project through to the step of making the final decision of selecting the R&D portfolio to be funded.

The aim of this methodology is to enable decision makers to gain an increased understanding of the case of selecting R&D projects, taking into consideration not only the financial attributes (i.e. cost and return) of projects but also other non-financial (subjective) issues (e.g. technology, opportunity and risk) that add value to the enterprise. It also considers the high involvement of decision makers of some governmental organisations in the selection process by using the previously stated methods and techniques.

The next section provides a detailed description of the different stages and steps of the methodology.

5.2 R&D Portfolio Selection Methodology

The methodology which will be used to analyse the selection of R&D projects, that will form the R&D portfolio, is based on the Simple Multi-Attribute Rating Technique (SMART). The technique has been widely applied because of the simplicity of both the responses required of the decision makers and the ways in which the responses are analysed.

The main steps of the SMART technique are eight steps (Goodwin & Wright 2004). In this research, new steps were added and some steps were modified in order to make the methodology specific for portfolio selection. The main stages and steps of the methodology are illustrated in Figure 5-1.

The *preparatory* stage identifies the decision makers and the objectives of the current R&D portfolio selection period that are derived from the strategic goals of the company. It also identifies the initial thresholds and different attributes which projects will be evaluated against.

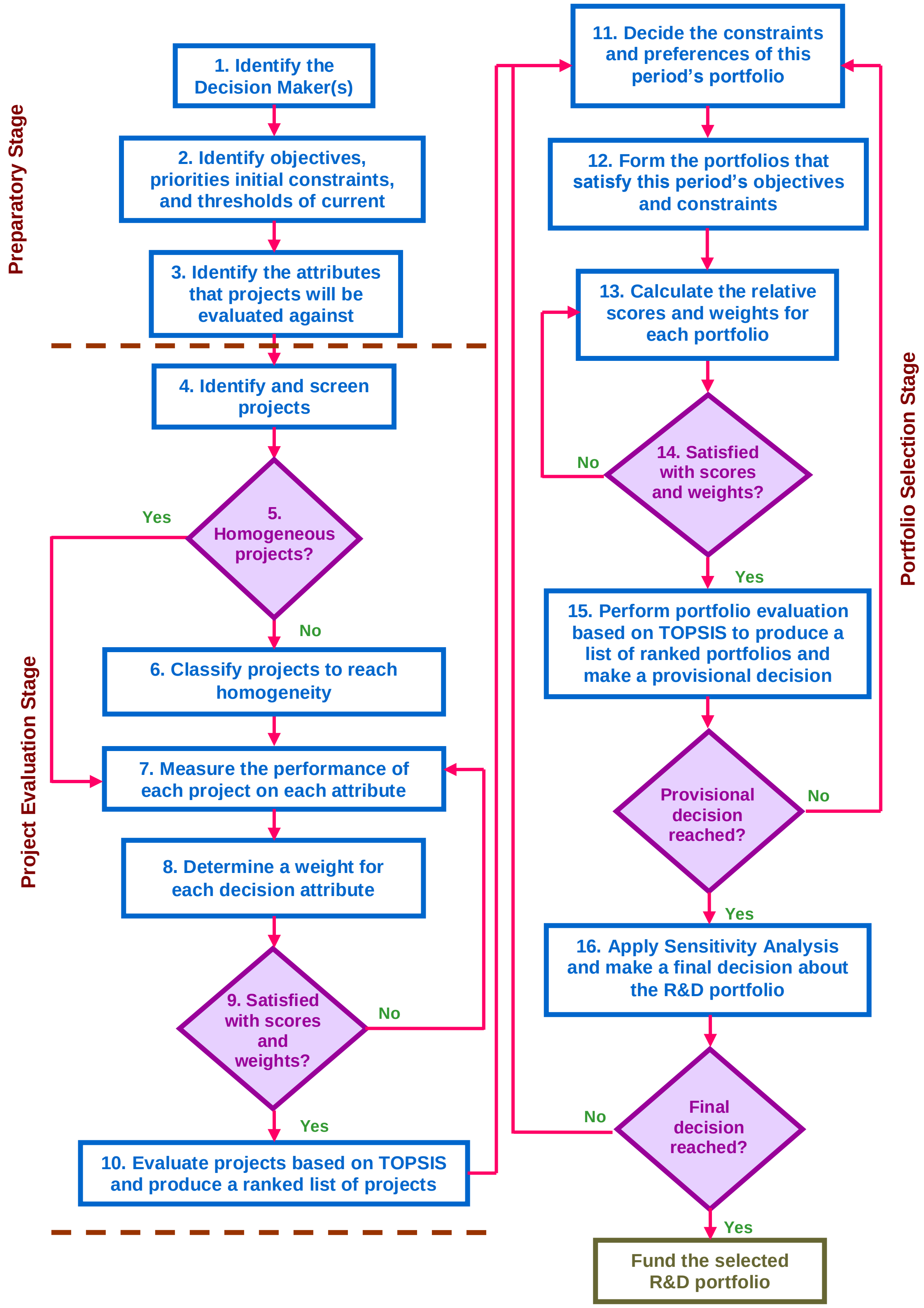

Figure 5-1: Flowchart of Decision Making Methodology for R&D Portfolio Selection

The second stage concentrates on the *evaluation* of individual projects by first screening them to identify projects that are worthy of detailed evaluation. The next steps of this stage are measuring the performance of each project on each attribute and assigning weights to each one of the attributes. If the decision makers are satisfied with the scores they gave to projects and the weights they assigned to attributes, projects are then evaluated using TOPSIS to produce a ranked list of projects.

In the *portfolio selection* stage, the decision makers agree about the final constraints and form portfolios that satisfy this period's objectives and constraints using Integer Linear Programming (ILP). Portfolios are then evaluated using TOPSIS to produce a ranked list of portfolios which will give a provisional decision. The final step is to apply sensitivity analysis to reach a final decision about the R&D portfolio.

The decision making methodology uses methods and techniques that are know for their simplicity and applicability. A detailed description of the methodology is presented below.

5.2.1 Preparatory Stage

The aim of the steps of this stage is to make sure that the decision maker(s) is well prepared to give the guidance to project managers about the overall shape of the R&D projects to be generated. This is to prevent unwanted projects from being generated and save the time of project managers to concentrate on projects aligned with the needs of the organisation. It also saves the time of the decision maker(s) for project evaluation. The steps of the preparation stage are as follows:

Step 1: Identify the Decision Maker(s)

Before getting through the process of generation, evaluation and selection of R&D projects, it is important to know who will be involved in taking such decisions. Is it just an individual decision maker or a group of decision makers? In most organisations, the task of R&D portfolio selection is made by a group of decision makers. Often, the R&D director has the responsibility to select the members of the group and decide the goals and tasks of the group. Whether he will be the group leader or not, the R&D director should select group members according to their familiarity and experience in the areas of R&D, marketing and finance. Heads of R&D divisions should be involved to explain or defend issues related to their divisions' projects.

Group decision making and judgment were issues of concern from a long time ago. Despite its power in improving the quality of the final decision, group decision making has its pitfalls (Lock 1987).

Step 2: Identify Objectives, Priorities and Initial Constraints of Current Selection Period.

The next step after identifying the decision making group is to outline the needs and objectives of the current R&D portfolio selection period. If the frequency of the process of selecting R&D projects is once a year, then the objectives of this year may, or may not, differ from last year's. Objectives could be, for example, reaching a portfolio with a balanced number of projects from each R&D area or department. Setting the objectives must reflect the potential goals and strategy of the organisation.

Objectives should include specific important things that are desired to be seen in individual projects. At the same time, the organisation could have general R&D priorities that are required to be reflected in the final selected portfolio. It may wish to concentrate in this period more on specific types of technologies or researches. If the organisation have many priorities and is struggling to choose which to be fulfilled, a ranked list of priorities could help using any of the ranking techniques presented in Appendix E.

Constraints represent conditions and restrictions that individual projects or portfolios need to satisfy, either fully or partially. The extent of satisfying those constraints depends on the ability of the decision making group of experts to achieve a portfolio that satisfy all of them. At this stage, they are treated as initial constraints to enable decision makers add to or avoid some of them when reaching the portfolio selection stage.

Thresholds, on the other hand, are certain conditions where decision makers do not want projects to go above or below. They are of a max/min nature and should not be exceeded. For example, a project will not go through full evaluation if the return/cost ratio is less than 2. Thresholds are useful in the screening step of the project evaluation stage.

Objectives, priorities, constraints or thresholds could be decided by the group of experts during the preparatory stage or earlier by higher level managers. The important thing is assuring that the group of decision makers fully understand them before starting the evaluation process because it will be their responsibility to give the final guidance to project creators about what is 'good' for the organisation.

Step 3: Identify the Attributes that Projects will be Evaluated Against.

The next step is to identify the attributes which the decision maker considers to be relevant to the portfolio selection problem. As mentioned in section 2.4.4, an attribute measures the performance of an objective that states the desired level of goal achievement. The main idea of using attributes is to measure the performance of courses of action in relation to the objectives of the decision maker (Belton and Stewart 2002). This means that we need to arrive at a set of project's attributes which can be assessed on a numeric scale.

Decision attributes could be very general and they may therefore need to be broken down into more specific attributes (i.e. decision elements) before measurement can take place. A hierarchy (or a value tree) can be used to identify the different levels of decision attributes (Saaty 2000).

The top-down approach is one way to construct the hierarchy by addressing the attributes which represent the general concerns of decision makers. Initially, let us assume that the decision makers identify two main attributes, which they decides to call 'cost' and 'attractiveness'.

The next step is to decompose them to a level where they can be assessed. Assume that they decide that attractiveness can be subdivided into 'return', 'opportunity' and 'risk'. Opportunity and risk can be each divided into ‘technical-related’ and ‘market-related’ attributes. The decision makers can compare projects if they decompose the technical-related-opportunity attributes into 'strategic alignment', 'technical impact' and ‘employment'. Similarly, market-related-opportunity attributes can be decomposed to ‘competition’ and ‘market size’. On the other hand, technical-related-risk attributes can be divided into ‘probability of technical success’, ‘time’, ‘budget’, and ‘competence’, while market-related-risk attributes is ‘probability of market success’. The lower-level attributed will be called the ‘decision elements’ of the problem.

Another way to construct the hierarchy is by identifying all the ‘decision elements’ that the decision makers feel that they can help them to evaluate projects (i.e. Bottom-up approach). They may start with the lower-level attributes and then divide them into groups where each group represents a common feature between the attributes, and so on. The hierarchy for the above example is shown in Figure 5-2.

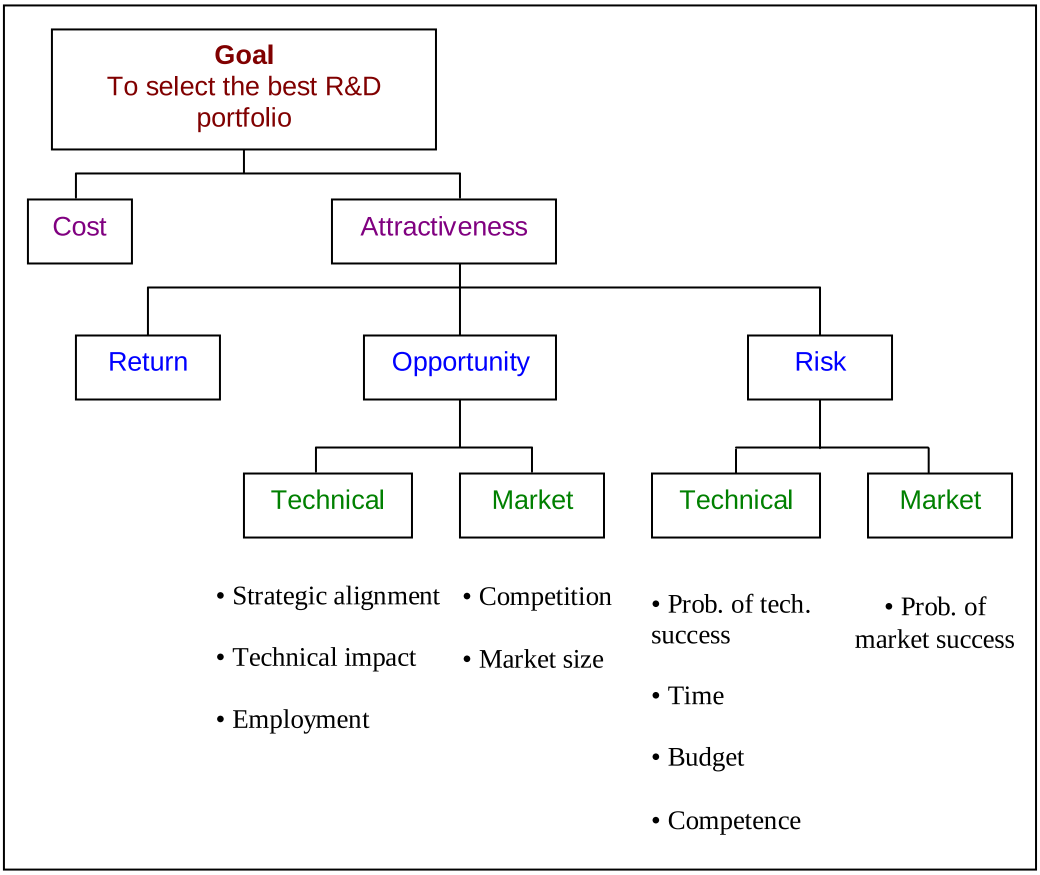

Figure 5-2: Example of a Hierarchy of Attributes

Keeney and Raiffa (1993) have suggested five criteria which can be used to judge the hierarchy:

(i) *Completeness*. If the hierarchy is complete, all the attributes which are of concern to the decision makers will have been included.

(ii) *Operationality*. If all the decision elements in the hierarchy are specific enough for the decision maker to evaluate and compare them for the different alternatives, this criterion is met.

(iii) *Decomposability*. This criterion requires that the performance of an alternative on one attribute can be judged independently of its performance on other attributes.

(iv) *Absence of redundancy*. If two attributes duplicate each other because they actually represent the same thing then one of these attributes is clearly redundant and may lead to double-counting.

(v) *Minimum size*. Attributes should not be decomposed beyond the level where they can be evaluated. If the hierarchy is too large, any meaningful analysis may be impossible.

It is not always easy to satisfy all the five criteria. For example, a hierarchy can not be operational unless its size is large.

By the end of this step, the decision making group are able to produce a statement with guidelines for project creators to generate projects that satisfy the organisation's needs. The group should be careful when writing the statement to ensure creating a variety of projects and encourage creativity when generating them.

5.2.2 Project Evaluation Stage

The starting point of this stage is to receive R&D project proposals in order to evaluate them to make sure that they are beneficial for the organisation. After giving guidance and time to project creators, projects are generated and ready to be examined. The following steps represent the evaluation stage:

Step 4: Identify and Screen Projects.

This step can be described as a 'check' point. Projects are gathered and screened to make sure that they are worthy to go through detailed evaluation. They are examined against predefined thresholds (see step 2) to ensure meeting the minimum requirements for further evaluation. By not satisfying the thresholds, such projects could be put on hold for modification or 'killed'. Project creators must be careful when generating projects since thresholds are provided with the general guidelines statement. The remaining projects can proceed to the following steps.

Step 5: Check the Homogeneity of Projects.

The importance of checking projects' homogeneity is to treat projects equally when evaluating them. For example, small projects may need evaluation against some, but not all, decision attributes. Part of the decision attributes may not become suitable anymore to evaluate some projects. An example could be the difficulty of estimating financial return of some pure research projects. If the decision makers can not see any reason for not evaluating projects in the same way, projects will pass directly to step 7. If projects are not homogeneous, decision makers need to go to step 6.

Step 6: Classify Projects to Reach Homogeneity.

Projects are not always homogeneous. Decision makers, sometimes, need to classify them into homogeneous groups of projects. There are different criteria for classifying projects. Type of R&D, for example, could make it difficult to deal with pure research projects in the same way of dealing with applied research projects. Project size, project duration, and technology type are other examples of criteria for project classification.

Identifying too many classifications could complicate the evaluation stage. The researcher suggests constructing a ‘projects matrix’ to help decision makers visualise different classifications. The projects matrix could be of two dimensions or of three dimensions of classifications (i.e. decision cube). From experience with a research done by the STA group on a couple of companies, more than three classifications make the evaluation of project more difficult and confusing. Figure 5-3 illustrates an example of a projects matrix.

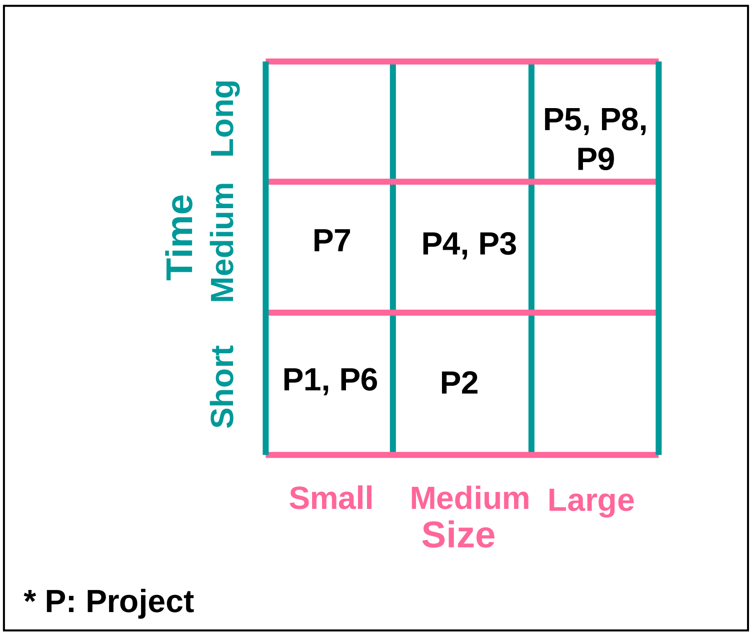

Figure 5-3: Example of a Projects Matrix

The benefit of a projects matrix can be seen as a visualisation tool for identifying further portfolio constraints (step 11), and helps in steps 7 & 8 of the project evaluation stage.

Step 7: Measure the Performance of Each Project on Each Attribute.

The decision makers are now aware that all the projects arrived to this stage are worth to be examined. The next step is to find out how well the different projects perform on each of the attributes in the hierarchy.

In measuring those attributes, it would be easier if the decision making group can identify variables to represent the attributes. For example, the cost and return of a project can be represented by its monetary value (e.g. £, $, etc.). Similarly, the number of people employed in a project provides a suitable approximation for the attribute 'employment'. However, for other attributes such as 'strategic alignment' and 'competition' it will be more difficult to find a variable which can be quantified. Because of this, there are three alternative approaches which can be used to measure the performance of the projects on each attribute: direct rating, the use of value functions and performance scales.

Direct rating

For simplification, assume that the attribute ‘attractiveness’ is composed of only two main attributes with six lower-level sub-attributes: Opportunity-related (strategic alignment, employment, market size), and Risk-related (budget, competence and effect on oil prices). Now, consider those attributes which can not be represented by easily quantifiable variables, starting with the attribute 'strategic alignment'. Assuming that we have seven projects to be evaluated and some of them will be selected to form the investment portfolio, the decision makers are first asked to rank the projects in terms of their strategic alignment from the most preferred to the least preferred. The rankings may be as follows:

Rank	Projects	Cost (£)
1	Project A	30,000
2	Project E	15,000
3	Project F	5,000
4	Project D	12,000
5	Project G	30,000
6	Project B	15,000
7	Project C	10,000

Project A, the best project for strategic alignment, can now be given a value for strategic alignment of 100 and Project C, the project with the least strategic alignment, can be given a value of 0. The use of 0 and 100 makes the judgments much easier and it also simplifies the calculations.

The decision makers are now asked to rate the other projects in such a way that the space between the values they give to the projects represents their strength of preference for one project over another in terms of strategic alignment. Figure 5-4 shows imaginary values that can be allocated by the decision makers. This shows that the improvement in strategic alignment between Project C and Project G is perceived by the decision maker to be twice as preferable as the improvement in strategic alignment between Project C and Project B. Similarly, the improvement in strategic alignment between Project C and Project A is seen to be ten times more preferable than the improvement between Project C and Project B.

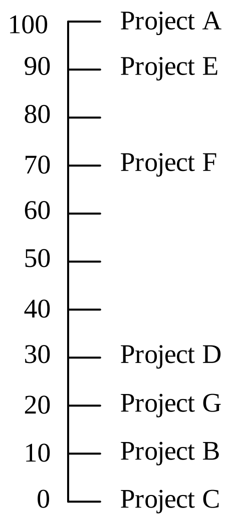

Figure 5-4: Value Scale for 'Strategic Alignment' of Projects

The decision makers can not say that the strategic alignment of Project G is twice as preferable as that of Project B. This is because the allocation of a zero to represent the strategic alignment of Project C was arbitrary, and we therefore have what is known as an 'interval scale', which allows only intervals between points to be compared.

The initial set of values for strategic alignment should be checked to see if they consistently represent the preferences of the decision makers. This can be achieved by asking the group, for example, if they are happy that the improvement in strategic alignment between Project E and Project A is roughly as preferable as the improvement in strategic alignment between Project G and Project D. Similarly, are they happy that the improvement in strategic alignment between Project C and Project D is less preferable than that between Project D and Project E? The answers to these questions may lead to a revision of the values. If the decision makers find it very difficult to make these sorts of judgments, they may need to return to the hierarchy and see if they can break the strategic alignment down into more measurable attributes.

This procedure for obtaining values can be repeated not only for the other less easily quantified attributes but also for attributes which can be easily represented by quantified variables

Value functions

Consider the attractiveness attributes which can be represented by easily quantified variables. First, we need to measure the decision makers' relative strength of preference for projects of different employment numbers. The number of people that can be employed for each project is shown below.

	Employment (people)
Project A	1000
Project B	550
Project C	400
Project D	800
Project E	1500
Project F	400
Project G	700

Now it may be that an increase in number of people from 500 to 1000 is very attractive to the decision makers. The improvements to be gained from an increase from 1000 to 1500 might be marginal and make this increase less attractive. Because of this, number of people employed is translated into values. This can be achieved as follows.

The decision makers may judge that the larger the number of people employed in a project, the more attractive it is. The project with the largest number of people to be employed is Project E with 1500 people to be employed, so 1500 people can be given a value of 100. In mathematical notation, it can be said that:

$$v(1500) = 100$$

where v(1500) means 'the value of 1500 people'. Similarly, the projects with the smallest employment (Project C and Project F) both employs 400 people and can have a value of 0 to this number, i.e. $v(400) = 0$.

The remaining now is to find the value of the employment for projects which fall between the most-preferred and least-preferred numbers. Decision makers can directly rate the employment of the projects under consideration by deriving a value function. This will help in estimating the values of any project's employment between the most and least preferred. One of the most widely applied methods is bisection.

This method requires the owner to identify a project whose value is halfway between the least-preferred number (400) and the most preferred number (1500). Initially, the decision makers may suggest that the midpoint number would be 700 people, so v(700) = 50.

Having identified the midpoint value, the decision makers are now asked to identify the 'quarter points'. The first of these will be the project that has a value halfway between the least-preferred number (400 people) and the midpoint number (700 people). They may decide that this is 500 people, so v(500) = 25. Similarly, they are asked to identify a number that has a value halfway between the midpoint number (700 people) and the best number (1500 people). They may judge this to be 1000 people, which implies that v(1000) = 75. The decision making group now has the values for five employment numbers and this enables the group to plot the value function for project employment, which is shown in Figure 5-5. This value function can be used to estimate the values for the actual number of people to be employed by the projects under consideration. For example, Project B has a number of employments of 550 people and the curve suggests that the value of this area is about 30.

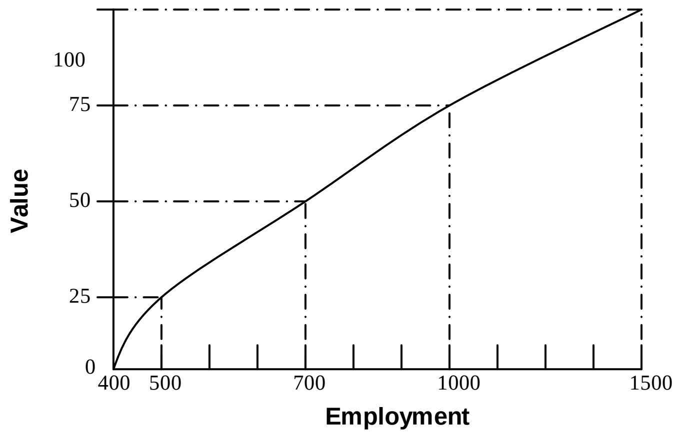

Figure 5-5: Constructing a Value Function for Projects' 'Employment'

Performance Scales

As mentioned before, decision makers deal with two kinds of data: attributes which can be represented by easily quantified variables and attributes that lack quantified variables. Performance scales method overcomes this problem by constructing scales for each attributes, where the points on the scale indicates how strong (or weak) the performance of a project on that attribute. The decision makers are free to choose the highest point (e.g. 100, 10 or 5), the lowest point (e.g. 0 or 1) and the number of divisions but they need to provide the reason and meaning behind their choice. An easy way is to select the highest point and call it 'strong', the middle point and call it 'moderate' and the 'weak' point is the lowest point in the scale.

The decision maker is then asked to score each individual project on the scales of each attribute and this will indicate the performance of that project on the attributes. The strength of this method is not only dealing with both subjective and objective data but also the flexibility where each project can be assessed without the need to see the data related to other projects. At any point of the analysis, the decision making group can change the scores of a project without the need to alter all the scores of other projects.

Step 8: Determine a Weight for Each Decision Attribute.

In order to evaluate R&D projects, the decision making group need to combine the values for the different attributes in order to gain a view of the overall attractiveness which each project has to offer. Achieving this can be done through attaching weights to each one of the attributes that reflect their importance to the decision maker. There are many ways of deriving attribute weights (see Appendix E).

The decision making group needs to select the weighting methods that suits them taking into consideration the conformity between the weighting method used and the performance measurement method applied.

Step 9: Check the Satisfaction of the Decision Making Group with the Scores and Weights.

This step is necessary to make sure that the group will not change the scores and weights at any further step. After evaluating projects, some members of the group could ask for changing the weights or scores of their divisions' projects because the results of their evaluation are poor. The methodology tries to stop such behaviour by ensuring the satisfaction of the group with scores and weights before going to further steps. If the group is not satisfied, they can go through steps 7 and 8 again until reaching agreement about the scores and weights.

Step 10: Evaluate Projects Based on TOPSIS and Produce a Ranked List of Projects.

In this step, the decision making group is asked to apply the 7 steps of TOPSIS discussed in section 2.4.4.3. Before the application of TOPSIS, the group needs to identify what will be the positive and negative 'ideal' projects of each attribute. According to TOPSIS, the positive ideal is the extreme weighted score of projects, while negative ideal is the reverse extreme weighted score of projects in each attribute. The decision making group can suggest another definition of ideal projects by deciding that the highest possible score (e.g. 100) multiplied by the attribute weight is the positive ideal, while the lowest possible score (e.g. 0) multiplied by the attribute weight is the negative ideal.

After applying TOPSIS, the projects are then ranked according to the C_i^+ ratio. This will help decision makers to select all projects or choose from them to form the alternative portfolios in Step 12 of the portfolio selection stage.

5.2.3 Portfolio Selection Stage

After projects are evaluated and ranked, the decision makers can not easily take the highest ranked projects until the budget is exhausted to form the R&D portfolio without fulfilling other constraints and preferences. As seen in the project evaluation stage, alternative portfolios are formed, evaluated and the final portfolio is selected by the end of this stage. The steps of the portfolio selection stage are described as follows:

Step 11: Decide the Constraints and Preferences of this Period's Portfolio.

Initial constraints and priorities were identified in step 2 at the first stage of the methodology. At Step 11, decision makers are given the opportunity to modify or add more constraints for the selection of the final portfolio. For example, the director of R&D could insist on including a specific project in the final R&D portfolio. This is treated as a 'golden' project and added to the list of constraints of portfolio selection. Examples of constraints that decision makers could think of are shown in Table 5-1, where x represents a binary value of 1 when project is selected and 0 otherwise.

Constraints can be also generated from the factors of portfolio balancing discussed in section 3.2.1.

Table 5-1: Examples of Constraints and their Representation in ILP

Logic of Constraint	Constraint Representation in ILP
Not more than 3 projects to be selected from one classification	$x_1 + x_2 + x_3 + x_4 + x_5 \leq 3$
Project 1 is a golden project	$x_1 = 1$
Projects 1 and 2 should not appear together in the portfolio	$x_1 + x_2 \leq 1$
Projects 1 and 2 should appear together in the portfolio	$x_1 - x_2 = 0$

Step 12: Form the Portfolios that Satisfy this Period's Objectives and Constraints.

This step deals with the issue of generating alternative portfolios to be evaluated. From the first glance, this step appears to be easy. In reality, it is not. The number of combinations between projects could be very high especially if the constraints are few. In order to do this, the researcher developed a integer linear programming (ILP) model that can generate portfolios by maximising the number of projects in the portfolio, subject to different constraints and preferences. The objective function is shown below:

$$Max(\sum_{i=1}^{k}(x_i)), \quad i = 1, 2, \ldots, k$$

Where *x* is a binary variable of 1 if project *i* is selected, or 0 if the project is not selected in the portfolio, and *k* is the total number of projects.

ILP enables decision makers to express their preferences and constraints in the model. For example, a maximum budget constraint can be written as follows:

$$\sum_{i=1}^{k}(b_i * x_i) \leq B, \quad i=1, \ldots, k$$

Where *b* represents project budget and *B* is the total budget for this period's R&D portfolio.

It is known that ILP gives only one solution, so how can we generate many portfolios using this model? The answer is to replace the first solution of projects as a constraint in the model and solving the model again. This will give us the second 'best' portfolio according to the model. The word 'best' means the portfolio that maximise the number of projects subject to given constraints. For example, assume that projects 1, 2 and 4 appeared in the first portfolio, adding this as a constraint for finding the second portfolio is represented as follows:

$$x_1 + x_2 + x_4 \leq 2$$

The idea is to prevent projects 1, 2 and 4 from appearing in the next portfolio. The second solution of the model will enter the model as a constraint, and so on for the next solutions until all possible portfolios are generated.

If the model do not give a solution, then the decision making group needs to relax some constraints and resolve the model again.

Step 13: Calculate the Relative Scores and Weights for Each Portfolio.

After generating alternative portfolios, the group could specify new weights for the portfolio because the importance of an attribute for projects is different from the importance of the same attribute for portfolios. This could happen if the projects are not all homogeneous and individual groups of projects were treated differently than others. Goodwin and Wright (2004) present a method of dealing with this type of change in Chapter 13 of their book.

The decision makers calculate scores by combining the weighted scores of projects in the portfolio for each attribute and multiply it by the relative weight of the same attribute in the portfolio.

Step 14: Check the Satisfaction of Decision Makers with Scores and Weights.

Again, this is a check point where decision makers emphasise on the attributes' weights and scores of portfolios. If they are not satisfied, they can return back to the previous step and recalculate weights and scores of alternative portfolios again. If satisfaction is reached, decision makers can proceed to the next step.

Step 15: Perform Portfolio Evaluation Based on TOPSIS to Produce a List of Ranked Portfolios and Make a Provisional Decision.

This step assesses how 'good' a portfolio is compared to other portfolios. By applying TOPSIS on portfolios in the same way done previously on alternative projects, the portfolios can be ranked according to their ratio of C_i^+.

Most probably, the decision maker will select the portfolio that is ranked at the top of the list as a provisional decision. More investigations on the portfolio can be done in the next step if the group agreed about the provisional portfolio. If not agreed, the group should return back to Steps 11 to 14 again and make modifications on the constraints, alternative portfolios, scores, or/and weights.

Step 16: Apply Sensitivity Analysis and Make a Final Decision About the R&D Portfolio.

Sensitivity analysis is a useful tool in structuring and solving of decision models using decision analysis techniques. It answers the question, “What makes a difference in this decision?” (Clemen & Reily 2001). It is used to examine how robust the choice of an alternative is to changes in the figures used in the analysis (Goodwin & Wright 2004). Analysing the factors used in the R&D portfolio selection methodology, changing weights could change the choice of the R&D portfolio. Scores are very difficult to change due to the large number of changes which is time consuming.

Spider graphs are good sensitivity analysis visualisation tool where continuous changing of one variable results in visualising the effect on the final score. Decision makers can use this tool to see how sensitive their provisional portfolio is to changes of attribute weights. If small changes affect the provisional portfolio, decision makers need to discuss whether to choose another portfolio or stick with the one in hand.

Decision makers can use other visualisation tools to ensure the attractiveness of the portfolio. Using Pie Charts representing the different technologies addressed by the portfolio is one example of visualising the characteristics of the selected portfolio.

By the end of this step, decision makers are able to decide whether to carry on and fund the selected R&D portfolio or return back to Steps 11 to 16 again. If the decision makers are satisfied with the selected portfolio, the final decision is reached.

An important point needs to be emphasised about projects that did not appear in the final portfolio: it is essential that decision makers look again and examine individual rejected projects to make sure that good projects, or projects that need some modifications, are not killed. Rejecting a project could be due to budget availability, portfolio balance issues, or simply because this period’s projects are too good. Those rejected projects could be modified and may enter next R&D selection period.

In the next chapter, a case study of selecting R&D portfolio in the Saudi oil refining industry is presented. Details of constructing the decision hierarchy are provided and a numerical example using simulation is discussed. The methodology benefited from informal feedbacks from decision makers in the

Saudi Ministry of Petroleum and Mineral Resources, Ministry of Economy and Planning, and Aramco.

6 Industrial Case Study

6.1 Introduction

This chapter presents the application of the multi-attribute decision making methodology for selecting new R&D portfolios in the form of a case study of R&D activities in Saudi Aramco oil refining operations. The aim of this case study is to verify and connect findings with certain gaps identified in the literature review and the research questions.

Numerical data was produced using simulation instead of real data. This is due to security and confidentiality issues from Aramco despite a gentlemen agreement of providing real data with senior decision makers in the Saudi Ministry of Petroleum and Mineral Resources, and the Saudi Ministry of Economy and Planning (see section 1.2.3). Nevertheless, using simulation gave the researcher insights about the operationality of the methodology.

This chapter describes the process of application of the methodology and the outcomes resulting from using Monte Carlo simulation based on the view of the researcher and informal feedback from R&D people at Aramco. The researcher used MS-EXCEL™ spreadsheets to organise data and apply the calculation methods more easily.

The ranges of cost data and other general information about R&D refining projects used by the researcher are from R&D refining projects of the National Energy Technology Laboratory, US (2007). The projects are considered by R&D people as similar to Aramco's R&D refining projects

Based on the literature review and the needs of the Saudi oil refining industry, the decision making methodology for selecting R&D portfolios was developed and modified. The methodology is based on the decision making concepts described in the literature review (see chapter 2) and by adapting some of the famous methods to fill research gaps and fulfill the demands and needs of R&D organisations.

6.2 Oil Refining at Saudi Aramco

Over the past decade, Saudi Aramco has grown from mainly an oil and gas producing company to an integrated company with substantial shipping and refining assets. Saudi Aramco today is the world's largest oil producer and tenth in refining capacity. It is committed to ensuring that Saudi Arabia will be self-sufficient in meeting domestic demand for refined products well into the next century.

Oil refining is an essential operation to provide markets with important products such as gasoline, kerosene, diesel and asphalt. Aramco operates five domestic refineries and two domestic joint-venture refineries. More than half of the company's refining capacity is at international equity and joint-venture refineries.

The main issues in refining are the need to meet increasingly stringent environmental requirements while operating efficiently and profitably. Refining upgrades have been undertaken with Saudi Aramco's joint venture partners in the United States and Korea, and are planned in the Philippines and in the Kingdom of Saudi Arabia.

The responsibility of Aramco towards the country is very high not only because of economic profitability but also because of other internal and external factors that influence the Saudi oil industry (see Figure 6-1).

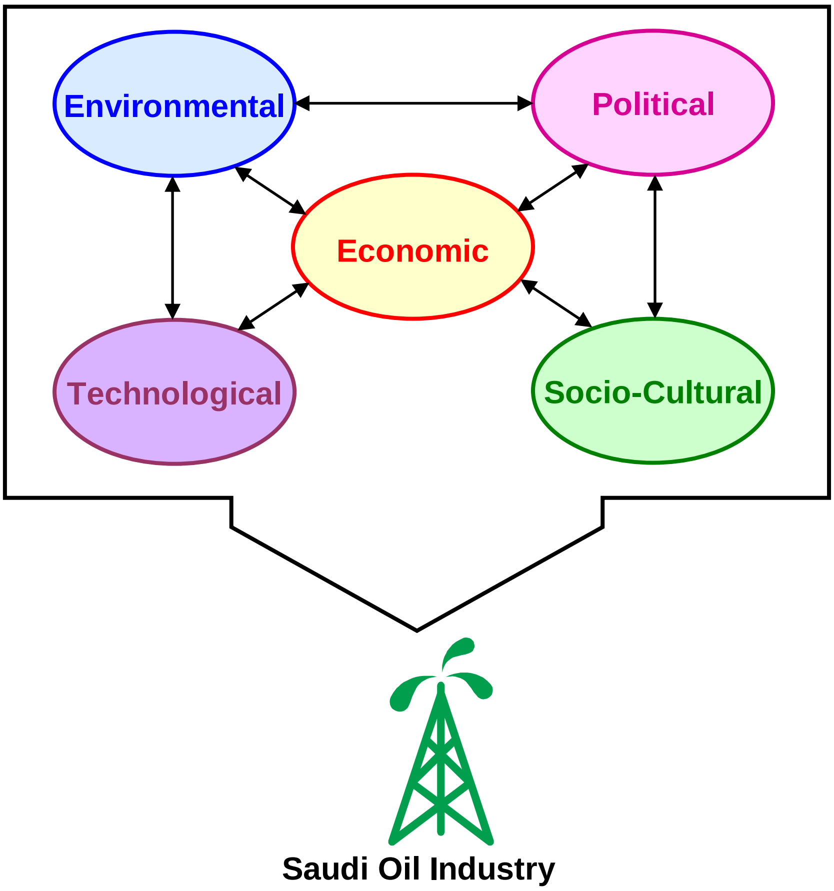

Figure 6-1: Factors Influencing the Saudi Oil Refining Industry

Economic Issues

Crude oil production is very important for Saudi Arabia since about %75 of the state income is from crude oil (ANON. 2003). It is estimated that Saudi will stay depending on oil as the first source of income for the next years. Aramco's officials say that their experts are looking at production strategies for the year 2054. The main responsibility of Aramco is to ensure efficient use of this natural resource by investing wisely to increase profitability. Aramco is a major supplier of crude oil to the US, the European market and other Asian economies.

One of Aramco's economic responsibilities is providing the fuel and feedstock needed for future economic development and diversification. Refined products are main inputs for many industries (e.g. petrochemical industry) and it needs to satisfy the demand of those industries. The increasing domestic demand for fuel is an important factor that has influence on the Saudi oil industry. At the same time, the wages it pays, the contracts it lets, and the goods it purchases are also important drivers for the kingdom's domestic economy. During 2003, Saudi Aramco executed contract actions worth some $3.5 billion, with a majority going to Saudi-owned or Saudi joint-venture companies. Aramco also issued purchase orders of $1.6 billion for materials, equipment and supplies: 87 per cent of that total was placed directly with Saudi manufacturers and vendors.

Globalisation in the new millennium makes it easier for companies to operate outside the mother land. Saudi Aramco attracts foreign investments from different parts of the world, including companies from the US, Japan, UK, China, India and other international companies.

Political Issues

Through establishing relations with international companies, Aramco is considered as a key player for strengthening the bounds between Saudi and other countries. For example, signing oil projects with companies from China and India is one way to make political relations with the two new economic giants more strong. Political agreements between OPEC countries is another important factor to ensure oil production stability.

Technological Issues

Aramco is a leader in the field of advanced technology. The computing facility in the Exploration and Petroleum Engineering Centre (EXPEC) is ranked among the world's top computer centres of any kind. It stores roughly four times as much as what NASA handles. The Saudi company is one of the world's largest users of SAP technology, and utilises the latest business integration systems to manage its ongoing operations.

The new R&D centre located in the east coast has a major responsibility to develop technologies and solutions for today's exploration, refining, environmental and other challenges. The R&D centre, staffed by more than 400 employees, has 17 registered patents in addition to more than 90 patent applications. The areas of R&D activities of Aramco are illustrated in Figure 6-2.

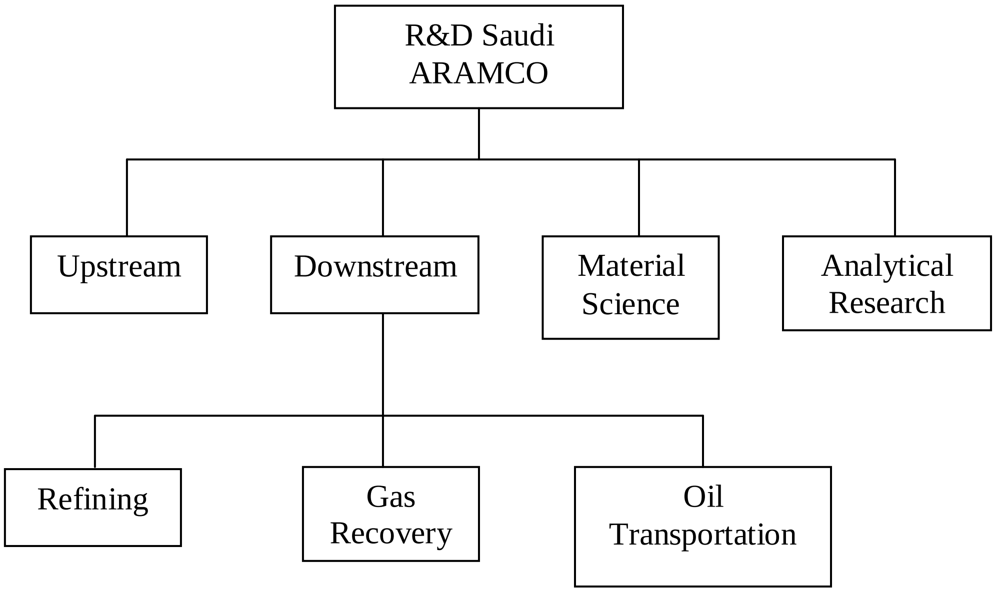

Figure 6-2: R&D Activities in Aramco

Environmental Issues

Saudi is among the countries that are concerned with today's environmental challenges, such as reducing carbon emission and desulphurising fuel. The residuals of oil consumption have continuous negative effects on the environment since there is no proven replacement for oil as a major source of energy.

Socio-Cultural Issues

Aramco has long been a leader in the area of Saudisation (i.e. employing Saudi nationals). While having citizens of more than 50 different nations on its employment rolls, about 85 per cent of its workforce is made up of Saudi nationals, and hold roughly 97 percent of the top 200 jobs in the company. According to the Saudi Eighth Development Plan published by the Saudi Ministry of Economy and Planning (2004), Aramco is one of the national companies that the country depends on to absorb new Saudi entrants to the domestic market.

The issues discussed above have some interdependencies between each other. Political agreements, such as Kyoto Protocol, force oil companies to seek reasonable solutions for environmental challenges. To face environmental concerns, R&D has an important role to develop new technologies that can efficiently solve or at least minimize the effects of oil consumption on the environment. Reducing unemployment in the country has an economic, political and socio-cultural impact. But most importantly, all the influencing factors have direct or indirect effect on the country's economy.

All those issues and other factors were considered during the identification of decision attributes for evaluating projects and portfolios of the R&D selection methodology in Aramco's oil refining operations.

6.3 Application of the R&D Portfolio Selection Methodology for Saudi Oil Refining

The multi-attribute decision making methodology for selecting new R&D projects developed by the researcher requires testing to ensure its validity and operationality. Few research work available in literature about selection of R&D projects in the oil industry. Heinemann, Hoefner and Donlon (1998) proposed a method for quantifying the value of upstream oil technologies using a value-to-cost analysis for selecting upstream R&D portfolio at Mobil. Suslick and Furtado (2001) introduce a framework for portfolio selection of oil exploration projects. The framework is based on the Multi-Attribute Utility Theory (MAUT) considering three objectives: technological, environmental and financial gain.

There is no available literature about selecting R&D refining portfolios and the proposed methods lack some issues discussed in section 3.4. Although the general attributes can be shared for project evaluation between upstream and refining projects, but the decision elements under the general headings are different as will be seen when identifying the decision attributes for oil refining projects.

The methodology for selecting R&D portfolios in Saudi oil refining operations is applied in the same way described in chapter 5.

6.3.1 Preparatory Stage

Step 1: Identify the Decision Maker(s)

The decision making group consists of the head of R&D in Aramco’s centre of research and development and the heads of research divisions of oil refining. At the beginning, the group needs a facilitator who understands the methods used and tools applied by the methodology. Another person is needed to help in using computer spreadsheets, which will be described later in the methodology.

Step 2: Identify Objectives, Priorities and Initial Constraints of Current Selection Period.

The objectives and priorities of this year’s portfolio selection activity were received as searching and developing technologies that are related to the following areas:

- Clean fuels.
- Hydrogen (H_2) production.
- Production of petrochemicals feedstock and chemicals from refined product.
- Upgrading low-value refined products.

R&D for oil refining has its own budget which is seen as a constraint for selecting the portfolio. Another constraint is that each one of the above areas should be represented with projects in the selected portfolio. Thresholds such as projects that can harm the environment should not go through full evaluation. A final constraint assumed to stop projects with expected return to cost ratio less than 2.

Step 3: Identify the Attributes that Projects will be Evaluated Against.

Using literature about general project evaluation attributes, documents, such as the Eighth Development Plan, and Aramco’s requirements, the researcher used the bottom-up approach for constructing the decision hierarchy for evaluating oil refining R&D projects shown in Figure 6-3.

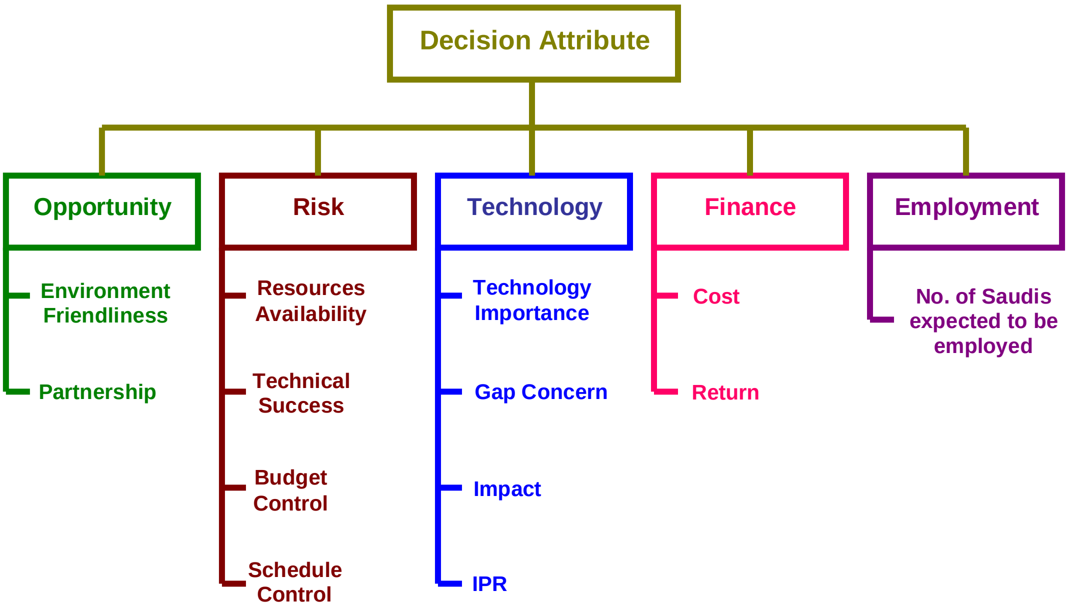

Figure 6-3: Decision Attributes for Evaluating R&D Project in the Saudi Oil Refining Industry

The definition of each decision attribute is provided below. The methods for quantifying each attribute are presented in Step 7 of the methodology.

Finance (F)

This attribute represents the expected monetary gain (or loss) form carrying out a specific project. It uses estimated values of cost and return. The details about Cost (C), Return (RE) and economic methods for financial estimation are provided in Appendix B. Though, Aramco has its own way of estimating the finance attribute using special designed computer software.

Technology (T)

Technology is an important strategic asset for Aramco. One of the common definitions used for technology is "the application of knowledge to useful objectives" (Boer 1999). Therefore, technology emerges when the related knowledge is developed into visible application. Technology could be physical items (e.g. machines or equipment) or also be methods, techniques or computer software that are required to solve different problems or achieve certain objectives.

The aim of the technology attribute is to assess the impact of a project's technology on the needs and objectives of Aramco in oil refining, on the improvement in competitive position of Aramco and the level of knowledge available to implement it. To achieve this aim, the following decision elements are used:

- *Technology Importance (TI)*: The importance of the technology that this project is targeting. Importance could emerge from the priority of the technology used or developed by the project, or from the importance of the refined product targeted by the technology.

- *Gap Concern (G):* the importance of acting on the gap between Aramco and major oil refining competitors in relation to this technology. That is the importance of the technological gap that this project aims to bridge.

- *Impact (I)*: The scope of impact of this technology on different research areas or different refining products. A project can be seen more attractive if the technology applied has positive influence on more than one product or R&D area of interest.

- *Intellectual Property Rights (IPR)*: Sometimes it is difficult to acquire the rights of a technology due to property rights of other companies that developed it in the first place. Aramco's strategy is to try to develop its own technologies in order to patent them and be able to exploit them commercially.

Employment (E)

The Employment attribute assesses the expected number of Saudis to be employed from implementing a project. It aims to emphasise on the concept of Saudisation in Aramco and creating job opportunities for Saudis to work in the organisation. Reducing the number of expatriate employees is one of the main objectives of the Saudi Eighth Development Plan.

Opportunity (O)

This attribute represents all the subjective benefits that can be gained from implementing a project. The decision attributes under opportunity can not be easily quantified in monetary values, so decision makers deal with them based on experience and judgement. The decision elements that represent opportunity for Aramco are:

- *Environment Friendliness (EF)*: One of the conditions that Aramco require about selecting project is to be environmental friendly. Whether the outputs are harming the environment or not is screening factor not a decision attribute. The degree of friendliness of the project is what is assessed by this decision element.

- *Partnership (P)*: This decision element assesses the opportunity of establishing partnerships with other companies to carry out the project under evaluation. This is to encourage projects that strengthen relationships with companies outside Saudi Arabia like China and India.

Risk (R)

Risk is defined in the context of the methodology as the probability that the project will deliver its goal and objectives successfully. If the probability of success is low, the risk is considered high and vice versa. Risk elements are:

- *Resources Availability (RA)*: The availability of people, equipment, material... etc. to carry out a project. For example, do we have the required people to implement this project? The company may need to recruit more people or share expertise with other R&D divisions.

- *Technical Success (TS)*: the probability that a project will succeed to achieve its technical goals. If the project goal and objectives are not well defined, probability of technical success is considered low.

- *Budget Control (B)*: the probability that a project will successfully finish within its specified budget. It is the degree of accuracy when estimating the costs of a project.

- *Schedule Control (S)*: the probability that a project will successfully finish within its specified time duration. Some projects could be very complex that they may take longer than expected.

Risk in the context of the methodology is not related to project management risk that is assessed after project execution. Project creators need to write a description for each of the decision elements under the attribute "risk" to help decision makers understand the overall probability of success of projects.

By the end of Step 3, the group generates a general guideline statement that include the objectives, priorities and preferences of this year's portfolio selection period, highlighting the constraints, conditions, and decision attributes that projects will be evaluated against. Project creators take this statement and try to fulfil these requirements when generating projects. The following statement is an example of guidelines for creating R&D project for oil refining:

"*It is desirable that a project should address one of our four main R&D areas: clean fuels, Hydrogen (*H_2*) production, production of petrochemicals feedstock and chemicals from refined product, and upgrading low-value refined products. It is important that the technology addressed in a project complies with environmental standards and preferred to minimise negative effects on the environment. We are looking forward for opportunities to* *establish R&D partnerships with companies in China and India, and maintain good relations with other international companies.*

The company needs projects that apply our important technologies. Aramco has a very high level of concern in relation to competitiveness in these technologies to maintain and improve our position as leaders in some of them and bridge the gap between us and other competitors in other technologies where we are lagging. The more the probability of benefiting from the technologies in the different R&D divisions and generating patents, the more attractive projects are seen.

As a company policy, any project with less than our normal return to investment ratio of less than two is very unlikely to attract funding in this selection period. However this will not apply to R&D projects addressing pure research relating to new products which the company is always keen to encourage. The investment required to carry out projects for this year is again limited to £10m. Projects' financial estimations have to be calculated according to the company's financial procedures and follow its financial guidelines.

A brief description of estimated project risk is required for each project according to the different elements of risk attached with this statement and your R&D head of division will discuss them with you in details. As usual the company is looking for a balanced R&D project portfolio with a good mix of *projects that address our product requirements and advance the state of art of our technologies*".

Project creator can be given up to one month to prepare projects that are aligned, as close as possible, with the guidelines described above.

6.3.2 Project Evaluation Stage

After creating projects, the decision making group tries to evaluate projects to measure the strength and attractiveness of each project. To make sure that all projects are worthy to go through detailed evaluation, decision makers need to be careful when applying Step 4.

Step 4: Identify and Screen Projects.

This is the gate where projects will be stopped from further evaluation if they do not comply with the conditions of return to cost more than 2 and environmental regulations. Usually, a number between 20 and 30 projects are allowed to go through detailed evaluation in Aramco's oil refining R&D. This research takes the maximum extreme of 30 projects to go through the full evaluation process.

Step 5: Check the Homogeneity of Projects.

As discussed in section 5.2.2, projects are not always similar and they should not, therefore, be evaluated in the same way. Although most of the time refining projects at Aramco are treated equally, this research explores two scenarios:

Scenario 1: Projects are homogeneous.

Scenario 2: Classify project to reach homogeneity

The research shows the differences between the two scenarios when evaluating projects using TOPSIS.

Step 6: Classify Projects to Reach Homogeneity.

To reach homogeneity, projects were classified according to different refining R&D areas. The projects matrix for this classification is shown in Figure 6-4.

		Projects
R&D Area	Clean Fuels	P1 to P8
	Upgrading Low Value Refined Products	P9 to P16
	Petrochemicals Feedstock and Chemicals from Refined Products	P17 to P23
	H2 Production	P24 to P30

Figure 6-4: Projects Matrix

Step 7: Measure the Performance of Each Project on Each Attribute.

Projects are now ready to be fully evaluated against the different attributes identified in Step 3. Due to the mix nature of quantitative and subjective attributes of projects, the researcher prefers to use the *direct rating* technique used by SMART. The strong involvement of the decision makers is another factor for choosing the technique where all projects are compared against the best and worst projects according to each attribute (see Step 7 of section 5.2.2).

Each attribute consists of one or more decision elements where the direct scoring of decision attributes is not straightforward. The score of one decision attribute is a function of weights and scores of decision elements. The weighted scores for the different attributes are obtained from the following functions:

$$E = (w_E * E \text{ score})$$

$$F = [(w_C * C \text{ score}) + (w_{RE} * RE \text{ score})]$$

$$O = [(w_{EF} * EF \text{ score}) + (w_P * P \text{ score})]$$

$$T = [(w_G * G \text{ score}) + (w_{TI} * TI \text{ score}) + (w_I * I \text{ score}) + (w_{IPR} * IPR \text{ score})]$$

$$R = [(w_{RA} * RA \text{ score}) + (w_{TS} * TS \text{ score}) + (w_B * B \text{ score}) + (w_S * S \text{ score})]$$

Where w is the weight of each decision element. Therefore, the full measurement of performance of projects on each attribute is fully calculated after Step 8. Projects scores for the two scenarios are presented in Appendix C.

Step 8: Determine a Weight for Each Decision Attribute.

At this step, decision makers will assign weights that reflect the importance of each attribute. Choosing the attribute weighting technique depends on how comfort are the decision makers with the technique and the synergy between the weighting technique and scoring technique they used in Step 7. Swing weights (described in Appendix E) fulfill both conditions.

There are five decision attributes that the decision makers identified before: Finance, Technology, Employment, Opportunity and Risk. The decision makers are asked to imagine a hypothetical project with all these attributes at their least-preferred levels, that is, a project which has the least financial gain, the worst technology, the least number of Saudis to employ, the least opportunity, and the highest level of risk. Then they are asked: if just one of these attributes could be moved to its best level, which would they choose? The decision maker may select ‘Finance’. After this change has been made, they are asked: which attribute they would next choose to move to its best level, and so on until all the attributes have been ranked. The decision makers’ rankings are:

(1) Finance

(2) Technology

(3) Employment

(4) Opportunity

(5) Risk

The decision makers can now give ‘Finance’ a weight of 100. Since decision makers have already obtained the scores of projects in Step 7, the other weights are assessed as follows: the decision makers are asked to compare a swing from the least project in Technology to the most one in Technology, with a swing from the project with smallest financial gain to the largest one. He may decide that the swing in 'Technology' is 40% as important as the swing in 'Finance', so Technology is given a weight of 40. Similarly, a swing from the worst 'Employment' to the best is considered to be 40% as important as a swing from the smallest to the largest financial gain, so 'Employment' is assigned a weight of 40. The same is done with 'Opportunity' and 'Risk' the weights assigned are 90 and 10 respectively. Figure 6-5 illustrates the results.

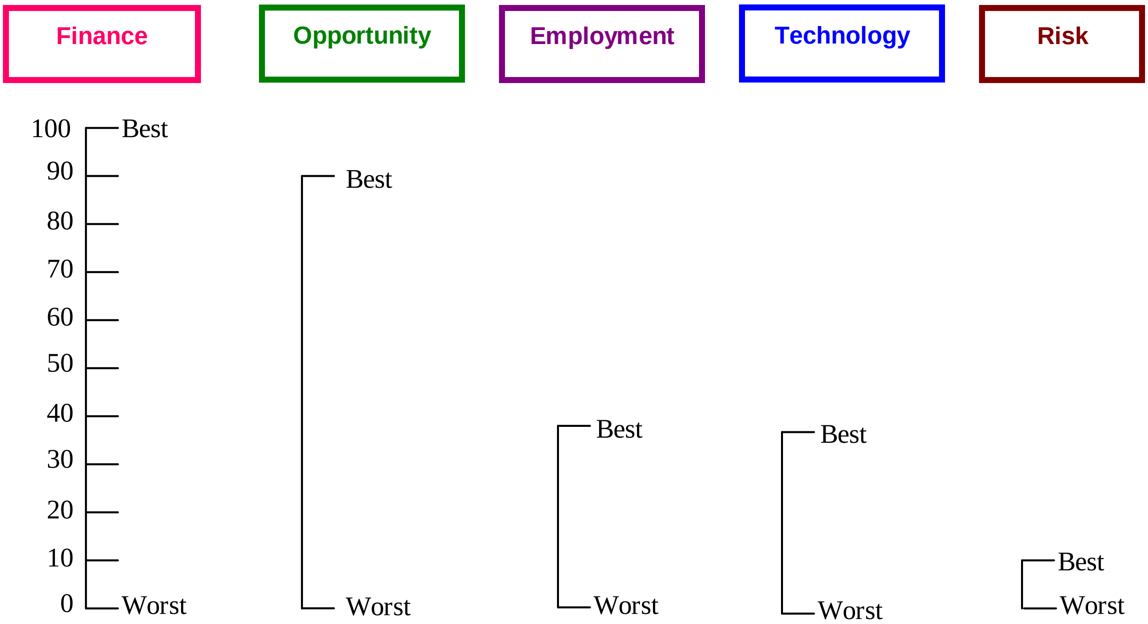

Figure 6-5: Swing Weights for the R&D Oil Refining Project Attributes

As shown below, the five weights obtained sum to 280, and it is better to 'normalise' them so that they add up to 100 to make it easier for decision makers. Normalisation is achieved by simply dividing each weight by the sum of the weights (280) and multiplying by 100.

Attribute	*Original weights*	*Normalised Weights*
Finance	100	36
Technology	40	14
Employment	40	14
Opportunity	90	32
Risk	10	4
	280	100

The same process can be made on the decision elements by comparing all of them with the best and worst decision element. After obtaining decision elements' weights, full scoring of projects can be done (see Step 7).

Steps 7 and 8 require using numerical data so that further analysis can be applied for full evaluation of projects. As discussed before, due to security of information, the researcher used Monte Carlo simulation to generate numerical data.

Monte Carlo simulations are described as static rather than dynamic simulation. It is defined as: "*a scheme employing random numbers, that is, U(0,1) random variates, which is used for solving certain stochastic or deterministic problems where the passage of time plays no substantive role*" (Law & Kelton 2000). Other definitions view Monte Carlo simulation as *any* simulation involving the use of random numbers. It is called Monte Carlo simulation because the random number used for each trial is analogous to a spin of the roulette wheel at a casino.

In this research, Monte Carlo simulation was used to mimic the steps of eliciting projects' scores and attributes' weights done by the decision makers to evaluate R&D projects and select the portfolio. Using MS-EXCEL™ spreadsheets, random numbers where obtained using Excel's Random Number Generator representing scores and weights. The probability distribution used was uniform since the probability of having a score or weight between 0 and 100 is the same. That is, decision makers could give any attribute a weight between 0 and 100, and projects could have scores between 0 and 100. Appendix C shows the spreadsheets where random numbers were used.

Step 9: Check the Satisfaction of the Decision Making Group with the Scores and Weights.

As mentioned in section 5.2.2, this step prevents decision makers from changing the weights and scores after Step 10. If they have any skeptics about a score or weight, they should resolve it at this step. If no changes are required, the group could start Step 10.

Step 10: Evaluate Projects Based on TOPSIS and Produce a Ranked List of Projects.

After obtaining the scores and weights by using the Excel function of Random Number Generator, the next step was designing spreadsheets to evaluate projects using the TOPSIS technique. TOPSIS identifies positive and negative ideal weighted scores and calculates how far a project is from the negative ideal and how near it is from the positive ideal. The technique then ranks projects according to the position of projects from the ideal weighted scores.

There is a TOPSIS spreadsheet for each homogeneity scenario. The difference between them is that the evaluation in scenario 2 is done for each R&D area while scenario 1 spreadsheet deals with projects as if they are all from the same classification. A radar diagram of the top five projects is shown in Figure 6-6.

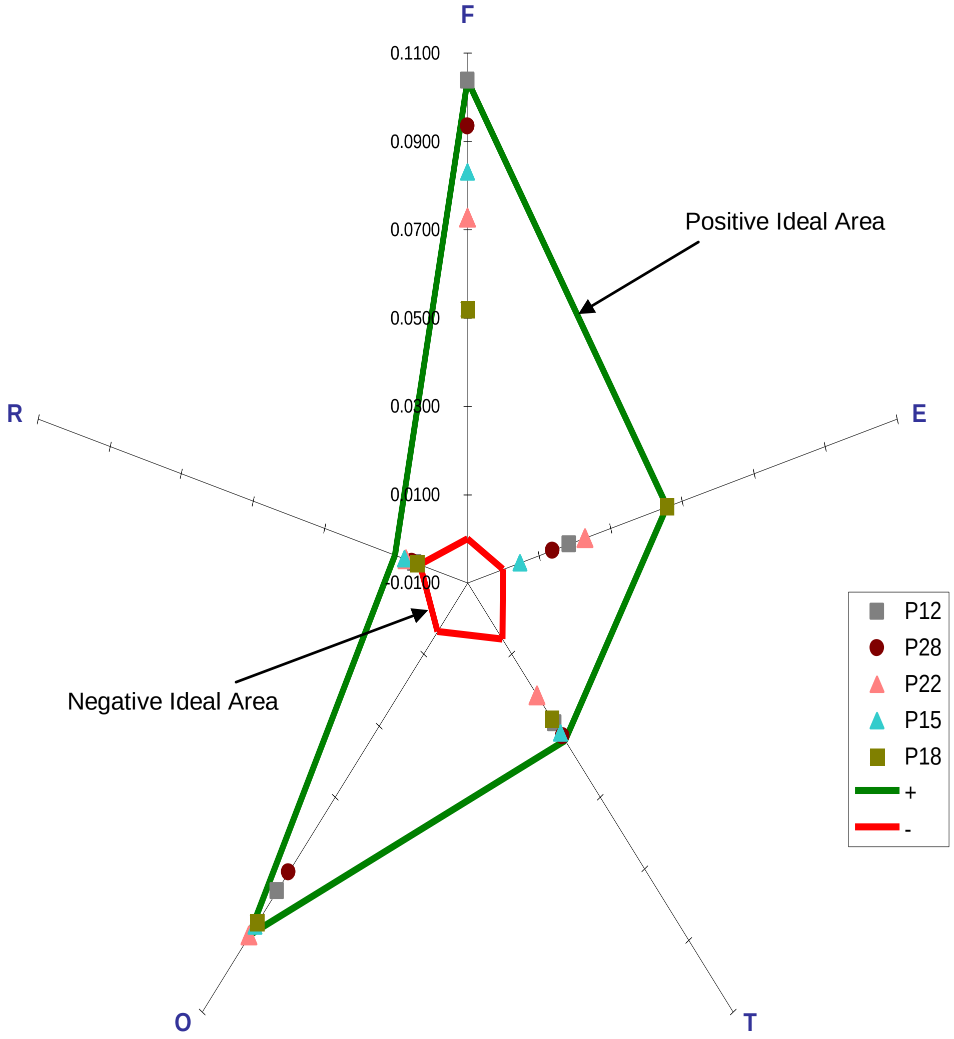

Figure 6-6: Radar Diagram of the Top Five Evaluated Projects

The spreadsheet compares the ranking of TOPSIS with SMART ranking. Chapter 6 presents this comparison as part of the research discussion.

6.3.3 Portfolio Selection Stage

Projects evaluation shows how good each project is. Taking the top projects without balancing the portfolio could be misleading for decision makers and the need to consider the constraints and their preferences. The following steps show how this is done for the case study.

Step 11: Decide the Constraints and Preferences of this Period's Portfolio.

The initial constraints and preferences defined in Step 2 represent the bases for balancing portfolios. The researcher did not recognise a need for additional constraints.

Another constraint generator is the projects matrix. Decision makers can assign percentages of budget for each classification. The percentages multiplied by the total budget are constraints for generating portfolios. Figure 6-7 shows an example of a constrained projects matrix.

		Projects	Budget
R&D Area	Clean Fuels	P1 to P8	40%
	Upgrading Low Value Refined Products	P9 to P16	20%
	Petrochemicals Feedstock and Chemicals from Refined Products	P17 to P23	20%
	H2 Production	P24 to P30	20%
			100%

Figure 6-7: Example of a Constrained Projects Matrix

The constraint for the 'clean fuels' classification of the above example can be written as follows:

$$x_1*b_1 + x_2*b_2 + x_3*b_3 + x_4*b_4 + x_5*b_5 + x_6*b_6 + x_7*b_7 + x_8*b_8 \leq 0.4*B$$

where x is a binary variable of 0 or 1, b represents a projects budget or cost, and B is the total budget.

Step 12: Form the Portfolios that Satisfy this Period's Objectives and Constraints.

To select the R&D portfolio, decision makers should evaluate alternative portfolios that satisfy this year's objectives and constraints. The researcher developed a ILP model that aims to generate alternative portfolios that comply with different constraint. The objective function is:

$$Max(\sum_{i=1}^{30}(x_i), \quad i = 1, 2, \ldots, 30$$

Where *x* is a value of either 0 or 1. Satisfying the objective function is subject to:

- Budget constraint: the total investment of the selected portfolio should not exceed this year's budget for oil refining R&D projects (i.e. £10m)

$$\sum_{i=1}^{30}(b_i * x_i) \leq 10, \quad i=1, \ldots, 30$$

- Classifications constraints: at least one project from each R&D area should be included in the selected portfolio

$$x_1 + x_2 + x_3 + x_4 + x_5 + x_6 + x_7 + x_8 \geq 1$$

$$x_9 + x_{10} + x_{11} + x_{12} + x_{13} + x_{14} + x_{15} + x_{16} \geq 1$$

$$x_{17} + x_{18} + x_{19} + x_{20} + x_{21} + x_{22} + x_{23} \geq 1$$

$$x_{24} + x_{25} + x_{26} + x_{27} + x_{28} + x_{29} + x_{30} \geq 1$$

The researcher used Premium Solver which is a tool that operates under Excel. It is a powerful tool to find optimum solutions for functions that have restrictions. To be able to use Premium Solver, the model needs to be written in a special way (see Appendix D). The first solution of the model was a portfolio of 6 projects: 8, 12, 18, 22, 26 and 28, with an investment of exactly £10m. This portfolio will enter the model as a constraint to generate another portfolio. The constraint is written as follows:

$$X_8 + x_{12} + x_{18} + x_{22} + x_{26} + x_{28} \leq 5$$

This resulted with another portfolio of 6 projects: 8, 15, 18, 22, 26 and 28, with an investment of £9.9. This portfolio will enter again as a constraint in the model with the previous portfolio to generate another alternative portfolio, and so on until reaching a state of no solution. The number of portfolio generated was more than 50 portfolios and the researcher selected the first 40 portfolios to go through the next step.

Step 13: Calculate the Relative Scores and Weights for Each Portfolio.

For each portfolio of the 40 portfolios generated, decision makers calculate the relative scores of portfolios and assign attributes' weights. As discussed in Step 13 of section 5.2.3, decision makers tend to keep the same weights of project evaluation for portfolio selection. The scores were calculated by adding project scores of each attribute.

Table 6-1 shows the scores of individual projects and the calculation of their portfolio scores for the first selected portfolio of scenario 1.

Table 6-1: Example of Attribute Weights and Total Portfolio Scores

		Attributes				
		F	E	T	O	R
	Weights	**0.36**	**0.14**	**.014**	**0.32**	**0.04**
Projects	**P8**	60	40	57.50	83	38.89
	P12	100	40	59.17	86	39.26
	P18	50	100	56.67	96	34.07
	P22	70	50	43.33	100	59.26
	P26	80	80	33.75	45	38.89
	P28	90	30	66.25	80	45.93
	Portfolio	**450**	**340**	**316.67**	**490**	**256.3**

The full TOPSIS evaluation of alternative portfolios is shown in Appendix C.

Step 14: Check the Satisfaction of Decision Makers with Scores and Weights.

Decision makers need to make sure that they reached consensus about the weights and scores. If there is any issue of concern about weights or scores, decision makers should resolve it before getting to the next step.

Step 15: Perform Portfolio Evaluation Based on TOPSIS to Produce a List of Ranked Portfolios and Make a Provisional Decision.

The TOPSIS technique ranks portfolios according to their distance from the positive and negative ideal weighted scores. The ranking showed that portfolio PT26 of projects 8, 12, 15, 18, 21 and 28 is the top ranked portfolio with total investment of £9.9m. Decision makers should consider this portfolio as a provisional decision. The next step applies more analysis and provides some visualisation tools to reach a final decision.

Step 16: Apply Sensitivity Analysis and Make a Final Decision About the R&D Portfolio.

Sensitivity analysis illustrates how changing the different portfolio weights could affect the ranking of alternative portfolios. Figure 6-8 shows how changing the swing weight of Finance affects the ranking of portfolios in a spider graph. It shows that once the weight of Finance is between 100 and 82, the top portfolio will remain as PT26. If the weight is between 82 and 70, the decision will change to PT27, while the top ranked portfolio will be PT8 if the weight I less than 70. Decision makers at this point could either stick with their provisional portfolio (i.e. PT26) or select PT8 if they are not confident that the Finance weight could go under 82. PT27 is considered sensitive to changes and selecting it could be ‘risky’. Decision makers could assess the sensitivity of other attributes’ weights in the same way it is done for Finance.

Other visualisation tools could be applied to ensure the balance of the provisional portfolio. Figure 6-9 and Figure 6-10 illustrate the distribution of projects and investment size in the final portfolio according to R&D areas by using pie charts.

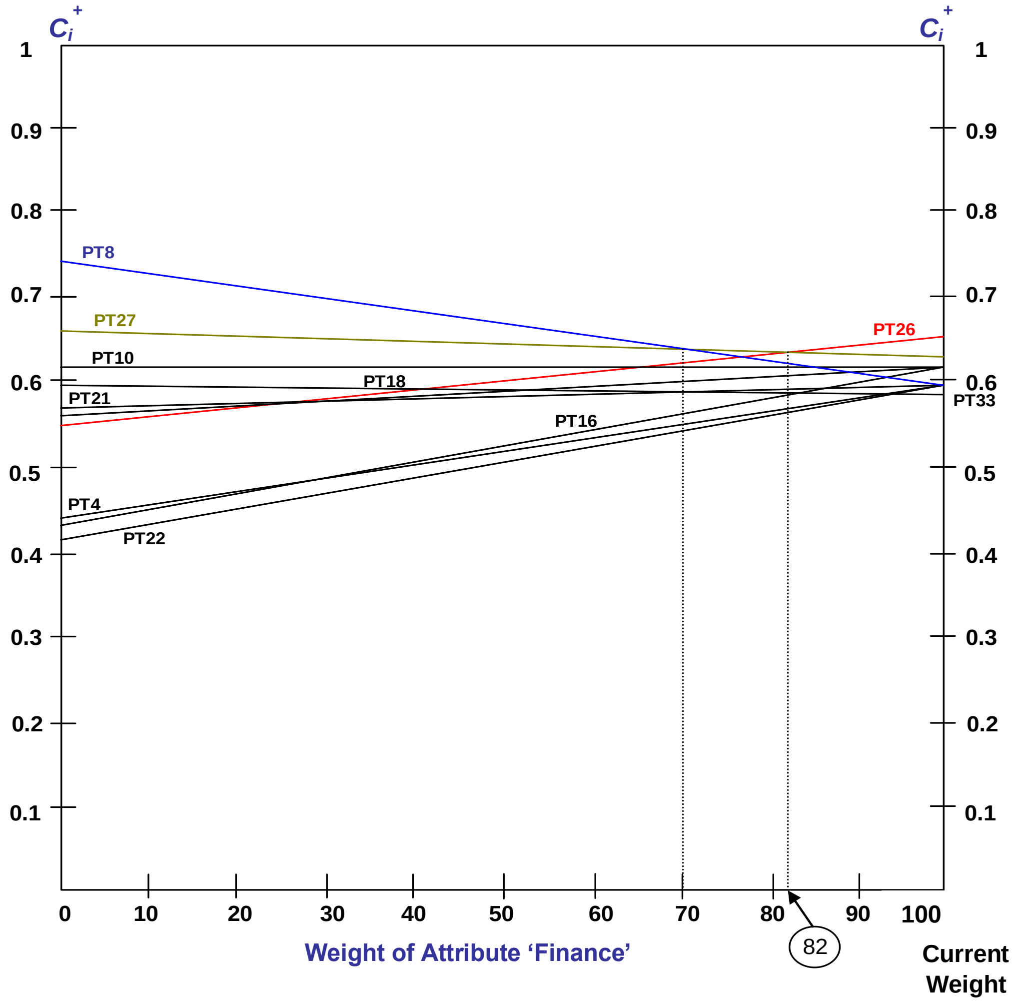

Figure 6-8: Spider Graph for Changing 'Finance' Weight

After assessing the sensitivity of weights and ensuring the balance of the portfolio, decision makers either stick with PT26 or returning back to Steps 11 to 16 again. From the viewpoint of the researcher, many decision makers treat Finance as the most important attribute and the likelihood of assigning a weight of less than 82 to Finance is low. PT26 looks balanced and there is no need to replace it with another portfolio. PT26 is the final decision that represents the selected R&D portfolio of refining projects for the current year.

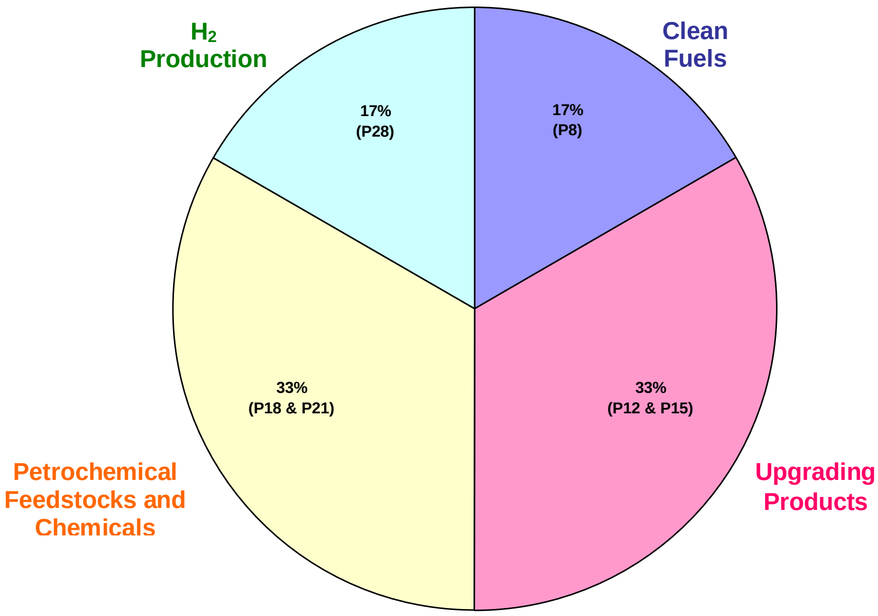

Figure 6-9: Distribution of Projects According to R&D Areas

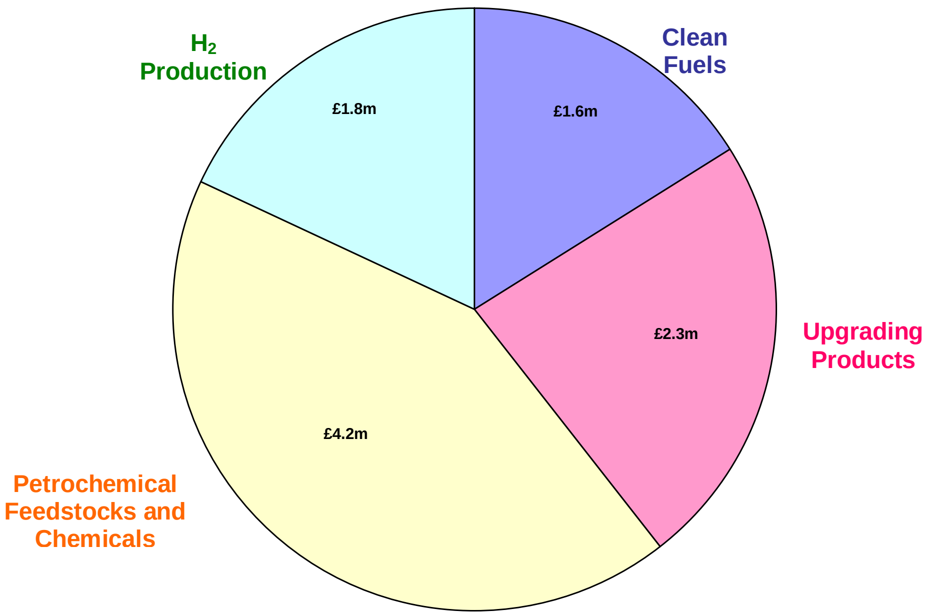

Figure 6-10: Distribution of the Total Investment According to R&D Areas

Despite that the case study represents the selection of R&D portfolio of oil refining projects in Aramco using a mix of real information, and simulated responses and data, but it gave insights to the researcher of how the methodology can flow from step to step and modifications needed to improve the methodology. Discussion of the case study and conclusions are presented in chapter 7.

7 Discussion and Conclusions

7.1 Introduction

Increased energy demand is a major factor for the energy industry to invest in innovative technologies by developing processes and products that deliver improved efficiency and environmental performance. With oil continues to satisfy a major part of the energy needs, it is important for oil companies to invest wisely in R&D projects.

Literature is full of significant contributions and many methods and techniques exist in practice in the area of R&D project selection. However, available methods lack a framework that starts from the creation of projects to balancing and selection of the portfolio. Moreover, there is a lack of studies in portfolio selection where the involvement of the decision maker is significantly high.

This thesis investigated methods and techniques used for the purpose of R&D project evaluation and portfolio selection. With the aim of application in a government-owned oil company, this has resulted in the development of a decision making methodology by mainly combining and modifying two techniques of decision making, SMART and TOPSIS, to support R&D portfolio selection. The methodology is divided into three stages with different steps in each stage.

The preparatory stage identifies the decision makers and the objectives of the current R&D portfolio selection period that are derived from the strategic goals of the company. It also identifies the initial thresholds and different attributes which projects will be evaluated against.

The second stage concentrates on the evaluation of individual projects by first screening them to identify projects that are worthy of detailed evaluation. The next steps of this stage are measuring the performance of each project on each attribute and assigning weights to each one of the attributes. If the decision makers are satisfied with the scores they gave to projects and the weights they assigned to attributes, projects are then evaluated using TOPSIS to produce a ranked list of projects.

In the portfolio selection stage, the decision makers agree about the final constraints and form portfolios that satisfy this period's objectives and constraints using Linear Integer Programming (LIP). Portfolios are then evaluated using TOPSIS to produce a ranked list of portfolios which will give a provisional decision. The final step is to apply sensitivity analysis to reach a final decision about the R&D portfolio.

A case study about selecting oil refining R&D portfolio at a Saudi, government-owned oil company (Aramco) is presented with Monte Carlo simulation of two different scenarios for application.

7.2 Discussion

There is a large amount of literature available about the problem of R&D portfolio selection (chapter 3) but managers struggled to apply them due to different reasons (section 1.2). The review of the literature in chapter 3 revealed that there is a lack of a clear methodology of R&D portfolio selection that assures managers that the final portfolio is aligned with their enterprises' goals and objectives.

Reviewing various decision making concepts and methods was essential in this research to produce a methodology that utilises important concepts to ensure its ability to serve managers in their problem of portfolio selection (chapter 2). The area of MCDM is rich with concepts and methods that require some modifications to suite the problem of R&D portfolio selection (section 2.4.4).

Literature review in section 1.1 revealed that there is a need for oil companies to invest in innovative technologies to satisfy the increasing demand for energy. Differences between NOCs and IOCs were identified, with differences between Saudi Aramco and other NOCs highlighted. It showed the high involvement of managers in making decisions whether .they are day-to-day or strategic decisions.

As a response to the above, the main research question in chapter 1 "*How can an effective decision making methodology be designed and implemented for R&D project evaluation and portfolio selection at government-owned oil* *enterprises?*" addresses the research aim to gain a thorough understanding of R&D portfolio selection, and to develop a methodology to support enterprise's technology investment decisions. Research questions and gaps in literature and practice showed the need for an easy-to-apply portfolio selection methodology that is driven by enterprise's objectives and preferences (chapter 5).

The case study presented in chapter 6 showed how to apply the multi-attribute decision making methodology for selecting R&D projects for Saudi Aramco's oil refining operations. The case study described in details the application of the different stages and steps of the methodology and provided numerical testing data using Monte Carlo simulation to represent the responses of decision makers. The researcher developed a ILP model and implement it as one way to generate combinations of projects that satisfy several objectives and constraints.

The identification of the five attributes of projects and portfolios (i.e. Finance, Technology, Employment, Opportunity and Risk), and the relative decision elements helped in evaluating and selecting R&D projects. The researcher proposed additional attributes and decision elements but some experts thought that including them is not applicable for the current time. Under the attribute 'Employment', for example, the researcher suggested including a decision element that assesses the education level needed for the jobs to be offered by a project, but the Eighth Development Plan shows that there is a need to employ Saudis from different education backgrounds and this decision element will not make any difference when assessing projects.

The methodology produced visualisation tools to aid and give insights to decision makers about the selected portfolio and its characteristics. Spider graphs, pie charts and radar diagram assists decision makers to examine how good the portfolio is to the company. The researcher compared between the results of the R&D portfolio selection methodology and portfolios ranking produced by the SMART technique and ILP to show decision makers the differences between the methods.

SMART combines the different projects' scores and attribute weights by calculating the overall 'attractiveness' of portfolios using the additive weighted scores for each project in a portfolio as shown below:

$$Attractiveness = \sum_{i=1}^{n}[(w_F * F_i) + (w_T * T_i) + (w_E * E_i) + (w_O * O_i) + (w_R * R_i)]$$

Where w_F, w_T, w_E, w_O, and w_R are the weights of the attributes, and *F, T, E, O* and *R* are the scores of each project in the portfolio.

On the other hand, the ILP model aims to find portfolios which maximise the overall attractiveness. The ranked results showed that using TOPSIS gave significantly different portfolio rankings than SMART and ILP as shown in Table 7-1. The reason for that difference is due to the applied concepts behind each method. SMART and ILP tries to maximise the overall attractiveness of portfolios, while TOPSIS ranks portfolios according to their overall attributes distance from the positive and negative ideal solution. The concept behind TOPSIS is to balance positives and negatives which is more cautious than maximising the overall positives only.

Table 7-1: Comparison between TOPSIS, SMART and ILP

	Rankings		
Portfolios	**TOPSIS**	**SMART**	**ILP**
PT1	13	31	31
PT2	30	40	40
PT3	40	23	23
PT4	9	8	8
PT5	39	38	38
PT6	37	36	36
PT7	22	26	26
PT8	6	22	22
PT9	16	24	24
PT10	3	19	19
PT11	36	20	20
PT12	28	18	18
PT13	38	39	39
PT14	34	37	37
PT15	12	4	4
PT16	4	2	2
PT17	18	5	5
PT18	5	3	3
PT19	32	25	25
PT20	21	21	21
PT21	7	**1**	**1**
PT22	8	7	7
PT23	17	6	6
PT24	19	9	9
PT25	26	11	11
PT26	**1**	10	10
PT27	2	15	15
PT28	11	13	13
PT29	20	17	17
PT30	15	12	12
PT31	29	16	16
PT32	33	27	27
PT33	10	28	28
PT34	27	30	30
PT35	35	29	29
PT36	14	35	35
PT37	25	33	33
PT38	31	34	34
PT39	24	32	32
PT40	23	14	14

The researcher conducted another comparison between TOPSIS and the efficient frontier which plots normalised weighted scores of alternative portfolios against two axes. Each axis represents an attribute. For example, selecting the portfolio according to F and T results in a trade off between the portfolios that appear in the top-right corner of the plot as shown in Figure 7-1. The decision maker can plot different combinations of attributes and select the portfolio that always occur on the preferred top-right region of the plot. Using the efficient frontier concept showed that portfolio 24 is the one that fulfil the previous condition, while it is ranked 19 in the TOPSIS ranking list of portfolios.

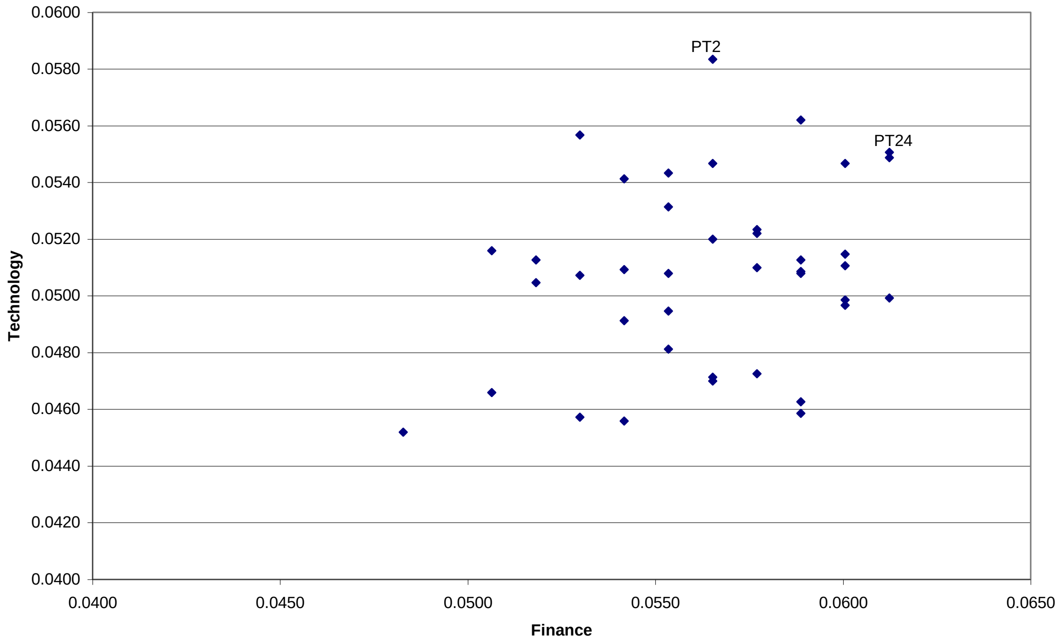

Figure 7-1: Portfolios Plot of Finance vs. Technology

The testing of two scenarios of projects' homogeneity showed how decision makers can evaluate projects in different ways. If projects are homogeneous (scenario 1), the whole lot of projects should be evaluated as one group. In the case of different projects' classifications (scenario 2), projects should be evaluated in each classification separately from other classifications. Ranking of projects will be within each classification in scenario 2, while in scenario 1; projects will be ranked over all alternative projects. Weights can remain unchanged for scenario 2 and the remaining evaluation are unchanged. Appendix C presents the spreadsheets used to evaluate projects based on the different scenarios.

The time to carryout the whole methodology could be an area of concern for decision makers in the last two stages of the methodology. The number of alternative projects and portfolios available could consume a lot of time for decision makers to explore and evaluate. This is acceptable when considering the high involvement of decision makers in the methodology. Time management is very important so that discussions about individual projects and evaluating them should not exceed the time duration planned for that step. According to similar applications with the STA group in the University of Nottingham, decision makers can take one working day to accomplish an individual stage of the methodology with the aid of computer software.

Feedback from decision makers in Aramco, the Saudi Ministry of Economy and Planning, and the Saudi Ministry of Petroleum and Minerals declare how this methodology is easy-to-use and that the different decision attributes describe important factors for R&D managers to consider when evaluating oil refining R&D projects.

7.3 Conclusions

Economic, political, environmental, technological and socio-cultural factors set difficult challenges for government-owned technology-oriented companies in the new millennium. There is a need for tools to help facing these challenges by wisely investing in innovative technologies to develop processes and products that deliver improved efficiency and environmental performance. R&D is becoming more and more important for those companies.

R&D portfolio selection methods are available in literature but lack some theoretical and practical issues. The methodology outlined in this thesis aims to help decision makers to select a balanced R&D portfolio of projects that is aligned with their enterprise's needs and objectives stated in the guidance statement submitted to project creators. The different stages of the methodology provided decision makers with the tools required to create, evaluate and select R&D projects in a step-by-step, east-to-use procedure. Dividing the methodology into three stages enables more concentration on the different tasks of R&D portfolio selection.

Selection of R&D portfolios is not a simple problem. This research showed the amount of information and effort needed to tackle this 'stone wall'.

Nevertheless, the methodology simplified this problem by breaking it into different stages and steps so decision makers can end up with a solution that is connected with their enterprise's strategy.

Applying the methodology using a real-life case study gave more ideas about identifying attributes for project and portfolio evaluation. Decision attributes and elements had to satisfy not only the objectives of Aramco as a company, but also the needs and requirements of the Saudi government. Literature provides different kinds of attributes but deciding which attributes that represent a particular problem is not easy. For example, the context of oil refining is different than oil exploration and, therefore, decision attributes for assessing R&D projects for both operations are different. The multi-attribute decision making methodology for selecting R&D portfolio went through different stages of attributes modification and process improvement to be in this final shape.

The methodology was intended to consider the decision making style of government-owned oil companies and the degree of involvement of decision makers in the task of selecting R&D portfolios. The tools and techniques used are suitable for Aramco where decision makers are highly involved operationally. The three stages and their relative steps ensure that decisions are made by decision makers not on behalf of them.

7.4 Contribution to Theory and Practice

This research makes several contributions to the field of R&D portfolio selection. In summary, the principal contribution comes under two headings:

- Contribution to theory; by developing a comprehensive R&D portfolio selection methodology that addresses the research aim, objectives and a great part of the gaps identified in the literature.
- Contribution to practice; by developing a workable, easy-to-use decision making methodology that addresses the needs of R&D portfolio selection in the oil refining industry. Feedback from people in the field suggests that it is an easy to follow and useable tool.

The contribution components are summarised in the following points:

1. **Contribution to the understanding of decision making concepts and approaches (chapter 2):** Literature review about decision making and its different approaches has been carried away to understand decision making processes and methods used. A great part was dedicated to MCDM as a useful approach to develop the R&D portfolio selection methodology.
2. **Contribution to the understanding of R&D portfolio selection methods and techniques (chapter 3):** An extensive literature review has been included to show the different R&D portfolio selection methods available and understand their advantages and drawbacks.
3. **Identification of gaps in literature (chapters 1, 2 & 3):** Reviewing the literature, specifically on R&D portfolio selection

methods, revealed gaps that need to be addressed through a formal research driven by the research objectives. Gaps identified are explained in chapter 3.

4. **Identification of needs in practice (chapters 5 & 6):** Conducting real-life case study to test the theoretical methodology developed previously have contributed to perceiving the industrial requirements.
5. **A new decision making methodology for selecting R&D portfolio (chapter 5):** A new methodology has been developed that combines different tools and techniques to answer and resolve issues discussed in chapter 1. The elements of the methodology have been tested in a industrial case study.
6. **Identification of decision attributes to evaluate and select Saudi oil refining R&D projects (chapter 6):** Multiple project attributes have been identified to satisfy the needs of Saudi Aramco as a government-owned company. Those attributes are illustrated in section 6.3.1.
7. **A tool to generate alternative portfolios (chapter 5 & 6):** A ILP model has been developed to generate portfolios that fulfil the preferences and constraints of R&D portfolios.

7.5 Future Research

This thesis has discussed some of the decision making methods that many companies are trying to adopt in order to select R&D portfolios that help them to face the accelerating changes and challenges of today's technological environment. The methodology described in this research provides outputs and insights for decision makers to select projects. However, it is important to integrate the methodology in a strategic technology plan that aligns projects selected with technological needs of enterprises.

The future research could be reviewed in some challenging issues appeared during the study. These issues are summarised below:

- **Broader validation of the R&D portfolio selection methodology:** Full application with decision makers' responses would improve the operationality of the methodology and show how groups reach consensus about different decisions. Further implementation in different sectors would give profound insights on strengths and weaknesses of the methodology which was developed based on an individual oil sector (oil refining).
- **Computer software development:** The methodology uses different tools and techniques which consumes valuable amount of time in analysing the data. Developing computer software would make the flow of the methodology faster.
- **Further investigation about the interaction of the R&D selection methodology and other management tools:** Embedding the methodology in the overall strategy of the company is an interesting

issue. Many management operations and process interacts and may influence the portfolio selection methodology.

- **Extension of application to cover projects' post-execution phase:** The methodology ends when the R&D portfolio is selected. Extending the methodology to cover the next phases would be useful as a full portfolio management package.
- **Matching R&D portfolio selection with decision makers' style:** The different styles of managers in making decisions create a problem when applying portfolio selection methods. Classification of the available methods according to the decision making style would be helpful for R&D mangers. Behavioural decision making describes the different styles of making decision and integrating it with portfolio selection sounds to be promising.

Appendix A Examples, Strengths and Weaknesses of Some Decision Making Methods

Example of Linear Programming (LP) (MacCarthy 2003)

A medical institute is making two types of pain relieving tablets 'A' and 'B' consisting only of Aspirin and Caffeine as follows:

Tablet	Aspirin Content (grams)	Caffeine Content (grams)
A	3	2
B	4	1

There is a stock of 120 grams of Aspirin that cost 4p per gram and 60 grams of Caffeine that cost 5p per gram. The institute can sell tablets A at 24p each and tablets B at 23p each. How many of each tablet should the institute make from the stocks in order to maximise profit ignoring all other costs?

First, consider what the decision variables might be as follows:

Quantity of tablets of type A produced – denote by x_1

Quantity of tablets of type B produced – denote by x_2

Second, consider the objective function, which is to maximise profit. Assume that the profit = sales revenue – costs.

Sales revenue = $24\ x_1 + 23\ x_2$

Costs = $[(3 \times 4) + (2 \times 5)]\ x_1 + [(4 \times 4) + (1 \times 5)]\ x_2$

$= 22\ x_1 + 21\ x_2$

Profit (z) = $2\ x_1 + 2\ x_2$

Third, decide on the constraints that limit the values of the variables for the problem as follows:

For the stock of Aspirin: $3\ x_1 + 4\ x_2 \leq 120$

For the stock of Caffeine: $2\ x_1 + x_2 \leq 60$

For non-negative quantities of tablets: $x_1, x_2 \geq 0$

This stage completes the formulation of the LP problem. The general form of representing the formulas is as follows:

Objective: Maximise Profit $z = 2\ x_1 + 2\ x_2$

Subject to: $3\ x_1 + 4\ x_2 \leq 120$

$2\ x_1 + x_2 \leq 60$

$x_1, x_2 \geq 0$

The graphical solution for this problem is shown in Figure A-1:

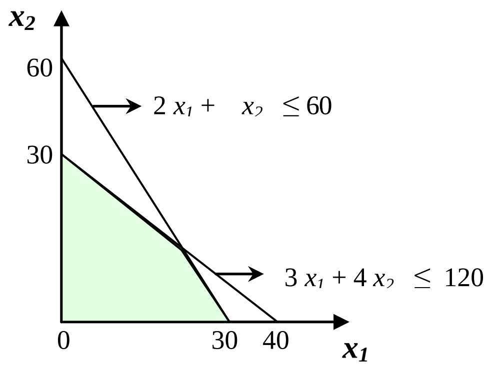

Figure A-1: Graphical Solution for LP Example

The green area represents the region where the optimum solution is expected to be. The values of x_1 and x_2 which maximise the profit are x_1 = 24, and x_2 = 12. The maximum profit = 2(24) + 2(12) = 72p.

Example of Goal Programming (GP) (Winston 1994)

The Leon Burnit Advertising Agency is trying to determine a TV advertising schedule for Priceler Auto Company. Priceler has three goals:

Goal 1: Its ads should be seen by at least 40 million high-income men (HIM)

Goal 2: Its ads should be seen by at least 60 million low-income people (LIP)

Goal 3: Its ads should be seen by at least 35 million high-income women (HIW)

Leon Burnit can purchase two types of ads: ads shown during football games and ads shown during soap operas: at most $600,000 can be spent on ads. The advertising costs and potential audiences of a one-minute ad of each type are as follows:

	HIM	LIP	HIW	Cost
Football ad	7 million	10 million	5 million	$100,000
Soap opera ad	3 million	5 million	4 million	$60,000

Leon Burnit must determine how many football ads and soap opera ads to purchase for Priceler.

- To solve this problem, assume the following:

  x_1 = number of minutes of ads shown during football games

  x_2 = number of minutes of ads shown during soap operas

- Then construct the formulas as done in the LP method:

Objective: Maximise $z = x_1 + x_2$

Subject to:

$7x_1 + 3x_2 \geq 40$ (HIM constraint)

$10x_1 + 5x_2 \geq 60$ (LIP constraint)

$5x_1 + 4x_2 \geq 35$ (HIW constraint)

$100x_1 + 60x_2 \leq 600$ (Budget constraint)

$x_1, x_2 \geq 0$

- Draw the graphical representation of the problem as shown in Figure A-2.

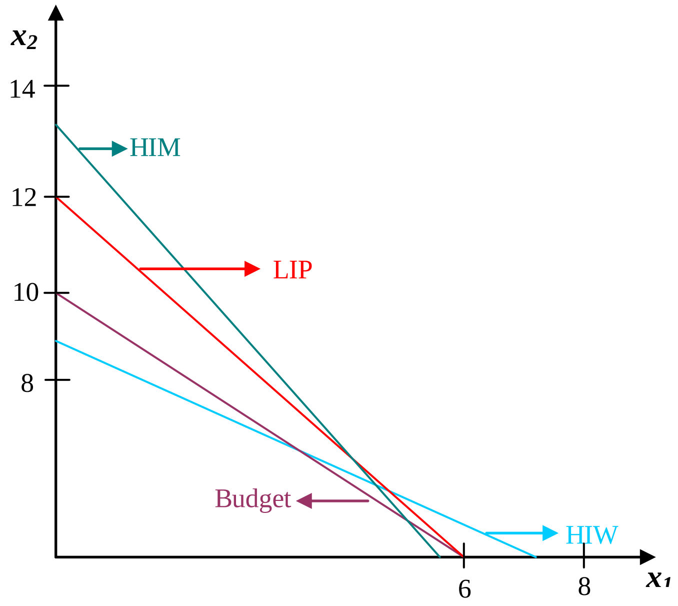

Figure A-2: LP Graphical Solution for GP Example

- From the graph, there is no point that satisfies the budget constraint meets all three of Priceler's goals. Since it is impossible to meet all of Priceler's goals, Leon Burnit might ask Priceler to identify, for each goal, a cost (per-unit short of meeting each goal) that is incurred for failing to meet the goal. Suppose Priceler determines that:
  - Each million exposures by which Priceler falls short of the HIM goal costs Priceler a $200,000 penalty because of lost sales.
  - Each million exposures by which Priceler falls short of the LIP goal costs Priceler a $100,000 penalty because of lost sales.
  - Each million exposures by which Priceler falls short of the HIW goal costs Priceler a $50,000 penalty because of lost sales.

- Burnit now can formulate an LP that minimises the cost incurred in deviating from Priceler's three goals. To do so, define the following deviational variables:

s^{+}_{i} = amount (in millions) by which numerically the *ith* goal is exceeded.

s^{-}_{i} = amount (in millions) by which numerically the *ith* goal is under-satisfied.

- The objective function will be: minimise $z = 200\, s^{-}_{1} + 100\, s^{-}_{2} + 50\, s^{-}_{3}$.

  The objective function coefficient for the variable associated with goal *i* is called the *weight* for goal *i*. The most important goal has the largest weight, and so on.

- The final formulation for the problem will be as follows:

  Objective: Minimise $z = 200\, s^{-}_{1} + 100\, s^{-}_{2} + 50\, s^{-}_{3}$

  Subject to: $7\, x_1 + 3\, x_2 + s^{-}_{1} - s^{+}_{1} = 40$ (HIM constraint)

  $10\, x_1 + 5\, x_2 + s^{-}_{2} - s^{+}_{2} = 60$ (LIP constraint)

  $5\, x_1 + 4\, x_2 + s^{-}_{3} - s^{+}_{3} = 35$ (HIW constraint)

  $100\, x_1 + 60\, x_2 = 600$ (Budget constraint)

  $x_1 , x_2 , s^{-}_{1} , s^{+}_{1}\ s^{-}_{2} , s^{+}_{2}\ \ s^{-}_{3} , s^{+}_{3} \geq 0$

- The optimal solution to this LP is $z = 250$, $x_1 = 6$, $x_2 = 0$, $s^{-}_{1} = 0$, $s^{+}_{1} = 2$, $s^{-}_{2} = 0$, $s^{+}_{2} = 0$, $s^{-}_{3} = 5$, and $s^{+}_{3} = 0$.

Example of the Analytic Hierarchy Process (AHP)

To illustrate how the AHP works, take the example of a job seeker (Winston 1994) who needs to choose between job offers. The job seeker (call her Jane) might choose between the offers by determining how well each offer meets the following four objectives:

Objective 1: High starting salary (SAL)

Objective 2: Quality of life in city where job is located (QL)

Objective 3: Interest in work (IW)

Objective 4: Job location near family and relatives (NF)

The difficulty of choosing between offers is the importance of the multiple objectives to the decision maker (Jane). For example, one job offer may give the nearest location to family and relatives, but the same job offer may score poorly in the other three objectives. Another offer may provide a higher starting salary and higher quality of life in city where job is located, but it is so far from family and relatives.

Suppose Jane has three job offers and must determine the offer to accept (see Figure A-3).

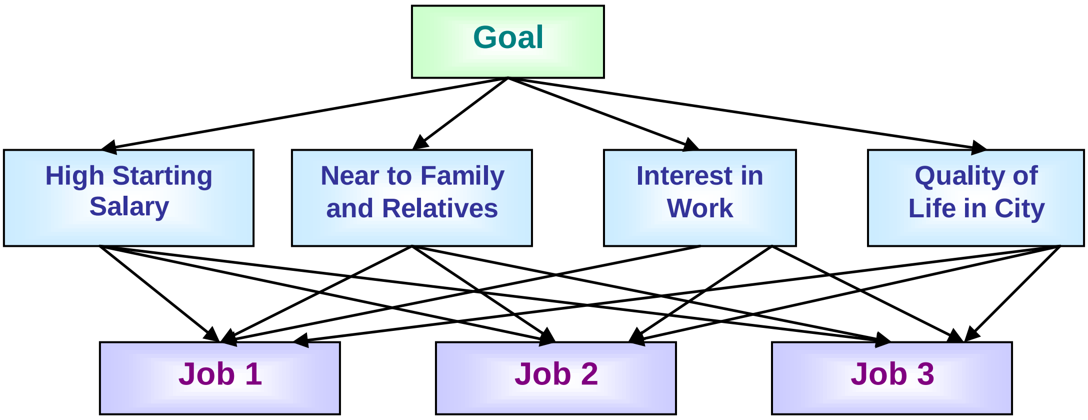

Figure A-3: The Hierarchy for Job Selection

For the *i*th objective (i.e. i = 1, 2, 3, 4), the AHP generates a weight w_i for each objective using the following method:

- Start by writing down an n X n matrix A (known as the pairwise comparison matrix). The entry row I and column j of A (call it a_{ij}) indicates how much important objective i is than objective j. 'importance' is to be measured on an integer-valued 1 – 9 scale (the fundamental scale), where a_{ii} = 1. If, for example, a_{13} = 3, objective 1 is weakly more important than objective 3 and a_{31} = 1/3.

- Suppose that Jane identified the following pairwise comparison matrix for her four objectives:

$$A = \begin{array}{c} \\ SAL \\ QL \\ IW \\ NF \end{array} \begin{array}{c} \begin{array}{cccc} SAL & QL & IW & NF \end{array} \\ \begin{pmatrix} 1 & 5 & 2 & 4 \\ 1/5 & 1 & 1/2 & 1/2 \\ 1/2 & 2 & 1 & 2 \\ 1/4 & 2 & 1/2 & 1 \end{pmatrix} \end{array}$$

- Unfortunately, some of Jane's pairwise comparisons are inconsistent. Jane feels SAL is twice as important as IW (a_{13} = 2). Since a_{32} = 2, Jane also believes that IW is twice as important as QL. Consistency of preferences would imply that Jane should feel that SAL is 2*2 = 4 times as important as QL. Since a_{12} = 5, Jane believes that SAL is 5 times as important as QL which shows that Jane's comparisons have a slight inconsistency. Slight inconsistencies are common and do not cause serious difficulties.

- For each of *A*'s columns, divide each entry in column *i* of *A* by the sum of the entries in column *i*. This will yield to a new matrix in which the sum of the entries in each column is 1 and we call it normalised *A*:

$$\text{Norm. } A = \begin{pmatrix} .5128 & .5000 & .5000 & .5333 \\ .1026 & .1000 & .1250 & .0667 \\ .2564 & .2000 & .2500 & .2667 \\ .1282 & .2000 & .1250 & .1333 \end{pmatrix}$$

- Estimate w_i as the average of the entries in row *i* of Norm. *A* as follows:

$$w_1 = \frac{.5128 + .5000 + .5000 + .5333}{4} = 0.5115$$

$$w_2 = \frac{.1026 + .1000 + .1250 + .0667}{4} = 0.0986$$

$$w_3 = \frac{.2564 + .2000 + .2500 + .2667}{4} = 0.2433$$

$$w_4 = \frac{.1282 + .2000 + .1250 + .1333}{4} = 0.1466$$

Now, a four-step procedure is used to check for the consistency of the decision maker's comparisons:

1. Compute *Aw* as follows:

$$\text{Norm. } Aw = \begin{pmatrix} .5128 & .5000 & .5000 & .5333 \\ .1026 & .1000 & .1250 & .0667 \\ .2564 & .2000 & .2500 & .2667 \\ .1282 & .2000 & .1250 & .1333 \end{pmatrix} \begin{pmatrix} .5115 \\ .0986 \\ .2433 \\ .1466 \end{pmatrix} = \begin{pmatrix} 2.0775 \\ 0.3959 \\ 0.9894 \\ 0.5933 \end{pmatrix}$$

2. Compute:

$$1/n \sum_{i=1}^{i=n} \frac{i\text{th entry in } Aw}{i\text{th entry in } w}$$

$$= (1/4)\left\{\frac{2.0775}{.5115} + \frac{.3959}{.0986} + \frac{.9894}{.2433} + \frac{.5933}{.1466}\right\}$$

$$= 4.05$$

3. Compute the consistency index *CI* as follows:

$$CI = \frac{\text{(Result from step 2) - n}}{\text{n - 1}} \quad = \frac{4.05 - 4}{3} = 0.017$$

4. Compare *CI* to the random index (*RI*) in Table A-1. It has been shown that if (*CI*/*RI*) < 0.10, the degree of consistency is satisfactory, but if (*CI*/*RI*) > 0.10, serious inconsistency may exist and the AHP may not yield to meaningful results. For the example, (*CI*/*RI*) = (0.017 / 0.9) = 0.019 < 0.10.

Table A-1: Values of the Random Index (RI) (Source: Winston 1994)

n	RI
2	0
3	0.58
4	0.9
5	1.12
6	1.24
7	1.32
8	1.41
9	1.45
10	1.51

To obtain the scores of an alternative for an objective, all the previous sets of steps will be made but for job offers instead of objectives. So for SAL, suppose we obtain the following pairwise comparison matrix:

$$
\begin{array}{c|ccc}
 & \text{Job 1} & \text{Job 2} & \text{Job 3} \\
\hline
\text{Job 1} & 1 & 2 & 4 \\
\text{Job 2} & 1/2 & 1 & 2 \\
\text{Job 3} & 1/4 & 1/2 & 1
\end{array}
$$

As it was done before, obtain the Norm. *A*:

$$
\begin{array}{c|ccc}
 & \text{Job 1} & \text{Job 2} & \text{Job 3} \\
\hline
\text{Job 1} & .571 & .571 & .571 \\
\text{Job 2} & .286 & .286 & .286 \\
\text{Job 3} & .143 & .143 & .143
\end{array}
$$

And the weights for each offer will be as follows:

Job 1 salary score = 0.571

Job 2 salary score = 0.286

Job 3 salary score = 0.143

The scores show that the best offer in respect of salary is Job 1. Next is to continue for the rest objectives and select the best of offers in the overall scores.

Example of AHP Using Benefit/Cost Ratio (Saaty 2001)

This is an example of purchasing word processing equipment with two hierarchies of costs and benefits (Figures A-4 and A-5) showing the criteria, features, and decision alternatives.

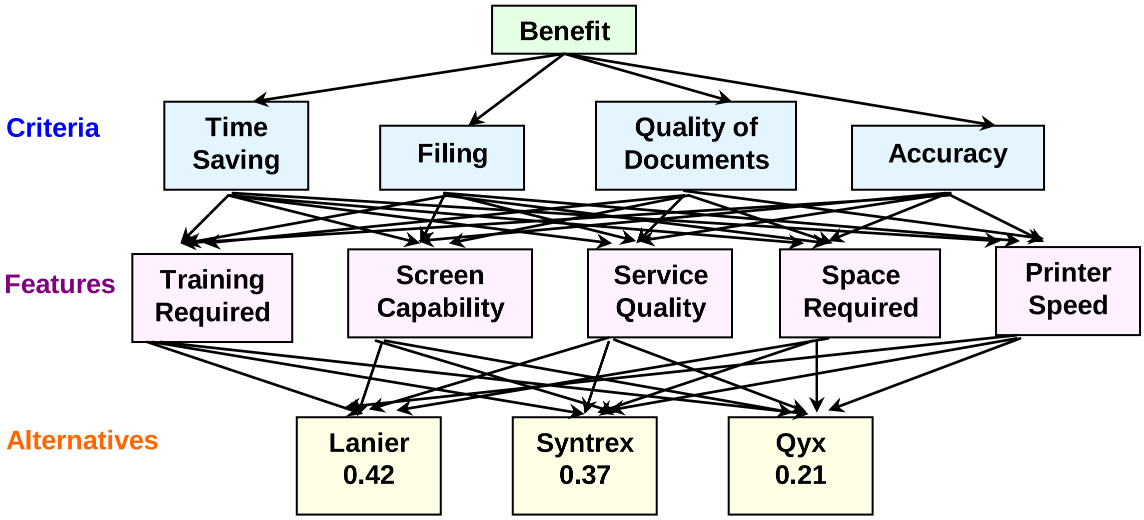

Figure A-4: Benefits Hierarchy

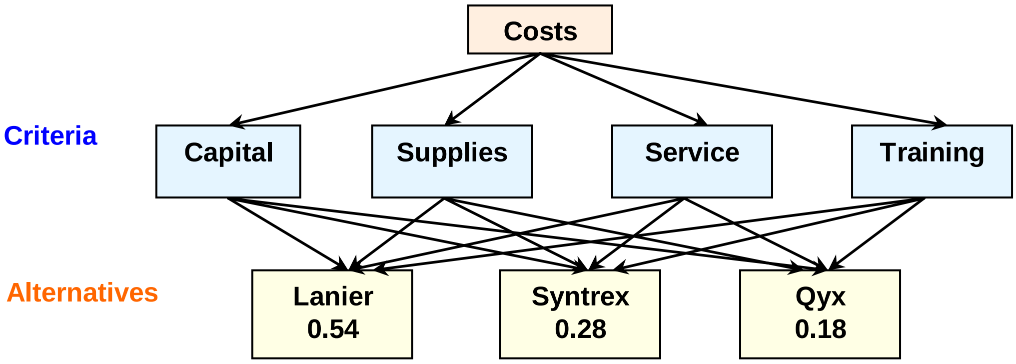

Figure A-5: Costs Hierarchy

After the pairwise comparison (as illustrated in the previous example), the benefits/costs ratios are calculated as follows:

	Lanier	Syntrex	Qyx
Benefits/Costs	0.42/0.54 = **0.78**	0.37/0.28 = **1.32**	0.21/0.18 = **1.17**

From the above table, the preferred alternative with the highest ratio is *Syntrex*.

Example of the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) (Yoon and Hwang 1995)

The example is about a sociology department facing the case of selecting a student to receive a fellowship award from among applicants to its graduate program. GRE, GPA, college rating, recommendation rating, and faculty interview rating are the selection attributes and their scores are derived from different scales. Table 3 shows the evaluation of six applicants based on these attributes. The department assigned the following importance weights for the five attributes as: 0.3, 0.2, 0.2, 0.15 and 0.15 respectively.

Table A-2: Profiles of Graduate Fellowship Applicants

Applicants	***GRE (X_1)***	***GPA (X_2)***	***College Rating (X_3)***	***Recommendation Rating (X_4)***	***Interview Rating (X_5)***
A	690	3.1	9	7	4
B	590	3.9	7	6	10
C	600	3.6	8	8	7
D	620	3.8	7	10	6
E	700	2.8	10	4	6
F	650	4.0	6	9	8

Step 1: Normalised Ratings. Normalisation is required since each attribute is measured on a different scale. The normalised ratings are shown below:

	X_1	X_2	X_3	X_4	X_5
A	0.4381	0.3555	0.4623	0.3763	0.2306
B	0.3746	0.4472	0.3596	0.3226	0.5764
C	0.3809	0.4128	0.4109	0.4301	0.4035
D	0.3936	0.4357	0.3596	0.5376	0.3458
E	0.4444	0.3211	0.5137	0.2150	0.3458
F	0.4127	0.4587	0.3082	0.4838	0.4611

Where r_{11} was obtained from:

$$0.4381 = 690 / \sqrt{(690^2 + 590^2 + \ldots + 650^2)}$$

Step 2: Weighted Normalisation. Multiplying weights with each column of the normalised rating matrix produces the following:

	X_1	X_2	X_3	X_4	X_5
A	0.1314	0.0711	0.0925	0.0564	0.0346^-
B	0.1124^-	0.0894	0.0719	0.0484	0.0865^+
C	0.1143	0.0826	0.0822	0.0645	0.0605
D	0.1181	0.0871	0.0719	0.0806^+	0.0519
E	0.1333^+	0.0642^-	0.1027^+	0.0323^-	0.0519
F	0.1238	0.0917^+	0.0616^-	0.0726	1.0692

Where v_{11} was obtained from:

$$0.1314 = 0.3 * 0.4381$$

Step 3: Positive-Ideal Solutions. Since all the chosen attributes are of benefit (the higher, the more performance), the positive-ideal solution consists of the largest value of each column, which are denoted by the symbol "$^+$" in Step 2. That is, A^+ = (0.1333, 0.0917, 0.1027, 0.0806, 0.0865).

Step 4: Negative-Ideal Solutions. The group of smallest values of each column in Step 2 (denoted by the symbol "$^-$") makes the negative-ideal solution. That is, A^- = (0.1124, 0.0642, 0.0616, 0.0323, 0.0346).

Step 5: Separation Measures. The separation measures from A^+ for alternative A is computed as follows:

$$S_A^+ = \sqrt{\sum (v_{Aj} - v_j^+)^2}$$

$$= \sqrt{(0.1314 - 0.1333)^2 + \ldots + (0.0346 - 0.0865)^2} = 0.0617$$

Separation measures from A^+ of all alternatives are:

$$(S_A^+, S_B^+, S_C^+, S_D^+, S_E^+, S_A^+) = (0.0617, 0.0493, 0.0424, 0.0490, 0.0655, 0.0463)$$

The separation measures from A^- for alternative A is computed as follows:

$$S_A^- = \sqrt{\sum (v_{Aj} - v_j^-)^2}$$

$$= \sqrt{(0.1314 - 0.1124)^2 + \ldots + (0.0346 - 0.0346)^2} = 0.0441$$

Separation measures from A^- of all alternatives are:

$(S_A^-, S_B^-, S_C^-, S_D^-, S_E^-, S_F^-) = (0.0441, 0.0608, 0.0498, 0.0575, 0.0493, 0.0609)$

Step 6: Similarities to Positive-ideal Solution. The Value of C_A^+ is calculated as follows:

$$C_A^+ = S_A^- / (S_A^- + S_A^+)$$

$$= 0.0441 / (0.0617 + 0.0441) = 0.4167$$

All similarities to the positive solution are:

$(C_A^+, C_B^+, C_C^+, C_D^+, C_E^+, C_F^+) = (0.4167, 0.5519, 0.5396, 0.5399, 0.4291, 0.5681)$

Step 7: Preference Rank. Based on the descending order of C_i^+, the preference order is given as: F, B, D, C, E, A, which selects applicant F as the awardee of the fellowship. Table A-3 shows the contrasting of three preference orders based on the positive-ideal (S^+), negative-ideal (S^-) and TOPSIS (C^+).

Table A-3: Three Sets of Preference Rankings for the TOPSIS example

Applicants	S^+		S^-		C^+	
	Value	***Rank***	***Value***	***Rank***	***Value***	***Rank***
A	0.0617	5	0.0441	6	0.4167	6
B	0.0493	4	0.0608	2	0.5519	2
C	0.0424	1	0.0498	4	0.5396	4
D	0.0490	3	0.0575	3	0.5399	3
E	0.0655	6	0.0493	5	0.4291	5
F	0.0463	2	0.0609	1	0.5681	1

Example of Elimination Et Choix Traduisant La Réalité (ELECTRE) (Yoon and Hwang 1995)

In 1988, a significant budget reduction at the University of Wyoming left the Athletic Department nearly $700,000 short on operating funds compared to previous biennium. The alternatives capable of realising the proposed budget cuts included dropping an entire sport from the university's intercollegiate athletic family. After much deliberation only three feasible alternatives were presented: The elimination of (A_1) the men's and women's ski programs, (A_2) the baseball program, and (A_3) the women's golf team. The Athletic Department decided on the following attributes to evaluate the alternatives: (X_1) the number of people directly affected, (X_2) money saved by the Athletic Department, and (X_3) miscellaneous. The decision matrix for this problem is presented below:

$$\begin{array}{c} \\ A_1 \\ A_2 \\ A_3 \end{array} \begin{array}{c} \begin{array}{ccc} X_1 & X_2 & X_3 \end{array} \\ \left(\begin{array}{ccc} 30 & \$174,140 & 3 \\ 29 & \$74,683 & 4 \\ 12 & \$22,496 & 5 \end{array} \right) \end{array}$$

Step 1: Normalisation. Attributes X_2 and X_3 are of benefit criterion (the more, the better) but attribute X_1 is of cost. Therefore, the values of X_1 (30, 29, 12) are inverted (1/30, 1/29, 1/12) in order to transform this attribute to a benefit one. Normalisation is necessary to make the values comparable since each attribute has different measurement scales. The normalised matrix is shown below:

$$\begin{array}{c} \\ A_1 \\ A_2 \\ A_3 \end{array} \begin{array}{c} \begin{array}{ccc} X_1 & X_2 & X_3 \end{array} \\ \left(\begin{array}{ccc} 0.3466 & 0.9126 & 0.4243 \\ 0.3587 & 0.3914 & 0.5657 \\ 0.8667 & 0.1179 & 0.7071 \end{array} \right) \end{array}$$

Where r_{21} was obtained from:

$$0.3587 = (1/29) / \sqrt{(1/30)^2 + (1/29)^2 + (1/12)^2}$$

Step 2: Weighted Normalisation. A_1, A_2 and A_3 were given the following weights: 0.2, 0.7, and 0.1. Those weights are multiplied with each column of the normalized matrix. The weighted normalized matrix is shown below:

$$
\begin{array}{c} \\ A_1 \\ A_2 \\ A_3 \end{array}
\begin{array}{c} \begin{array}{ccc} X_1 & X_2 & X_3 \end{array} \\
\begin{pmatrix} 0.0693 & 0.6388 & 0.0424 \\ 0.0717 & 0.2740 & 0.0566 \\ 0.1733 & 0.0825 & 0.0707 \end{pmatrix} \end{array}
$$

Where v_{11} was obtained from:

$$0.0693 = 0.2 * 0.3466$$

Step 3: Concordance and Discordance Sets. The concordance and discordance sets for the Athletic Department problem are obtained as:

$C(1, 2) = \{2\}$ $D(1, 2) = \{1, 3\}$

$C(1, 3) = \{2\}$ $D(1, 3) = \{1, 3\}$

$C(2, 1) = \{1, 3\}$ $D(2, 1) = \{2\}$

$C(2, 3) = \{2\}$ $D(2, 3) = \{1, 3\}$

$C(3, 1) = \{1, 3\}$ $D(3, 1) = \{2\}$

$C(3, 2) = \{1,3\}$ $D(3, 2) = \{2\}$

Step 4: Concordance and Discordance Indexes. The complete set of concordance and discordance indexes is as follows:

$C_{12} = 0.7$	$D_{12} = 0.0435$
$C_{13} = 0.7$	$D_{13} = 0.1921$
$C_{21} = 0.3$	$D_{21} = 0.9565$
$C_{23} = 0.7$	$D_{23} = 0.3766$
$C_{31} = 0.3$	$D_{31} = 0.8079$
$C_{32} = 0.3$	$D_{32} = 0.6234$

Where C_{21} is obtained as follows: Since $C(2, 1) = \{1, 3\}$, $C_{21} = w_1 + w_3 = 0.2 + 0.1 = 0.3$. D_{21} is computed as follows: Since $D(2, 1) = \{2\}$, $D_{21} = |0.2740 - 0.6388| / (|0.0717 - 0.0693| + |0.2740 - 0.6388| + |0.0566 + 0.0424|) = 0.9565$.

Step 5: Outranking Relationships. For the given problem, $C = (0.7 + 0.7 + \ldots + 0.3)/6 = 0.5$ and $D = (0.0435 + 0.1921 + \ldots + 0.6234)/6 = 0.5$.

Table A-4 shows the determination of outranking relationships. Three outranking relationships are obtained: ($A_1 \rightarrow A_2$), ($A_1 \rightarrow A_3$), and ($A_2 \rightarrow A_3$). Only alternative A_1 remains in the kernel, which is a set of preferred alternatives defined by ELECTRE. The kernel **K** should satisfy two conditions: (1) each alternative in **K** is not outranked by any other alternative in **K**, and (2) every alternative not in **K** is outranked by at least one alternative in **K**. This makes A_1 the optimal choice.

Table A-4: Determination of Outranking Relationships

C_{ij}	Is ($C_{ij} \leq C$)?	D_{ij}	Is ($D_{ij} < D$)?	Is ($A_i \rightarrow A_j$)?
C_{12}	Yes	D_{12}	Yes	Yes
C_{13}	Yes	D_{13}	Yes	Yes
C_{21}	No	D_{21}	No	No
C_{23}	Yes	D_{23}	Yes	Yes
C_{31}	No	D_{13}	No	No
C_{32}	No	D_{32}	No	No

Strengths and Weaknesses of AHP, TOPSIS, ELECTRE and SMART

Tables A-5 to A-7 represent literature review over the strengths and weaknesses of the MCDM methods of AHP, TOPSIS, ELECTRE and SMART. Each point of strength for the methods is referenced, while the weaknesses and the defense against them are highlighted and referenced as well.

Table A-5: Strengths of AHP, TOPSIS, ELECTRE and SMART

Method	Strength	Source
AHP	1. The ease with which judgements can be elicited and the clarity that the formal structuring of the problem provides.	Watson and Buede (1987)
	2. Over-specifying inputs through explicit pairwise comparisons.	Watson and Buede (1987)
	3. A number of special issues in refereed journals have been devoted to AHP and the use of pairwise comparisons in decision making.	Triantaphyllou (2000)
	4. Widely accepted and applied in different areas (e.g. economic, social, political, etc.)	Saaty and Vargas (1994)
	5. The use of a consistency index enables one to determine those judgments that need reassessment.	Harker and Vargas (1987), Belton (1986)
TOPSIS	1. To choose the positive and negative ideal solutions as reference points is accepted by decision makers.	Lai, Liu and Hwang (1994)
	2. The aim of the decision made is not only to make as much profit as possible, but also to avoid as much risk as possible.	Lai, Liu and Hwang (1994), Yoon and Hwang (1995)
ELECTRE	1. Widely used and applied for many practical problems, particularly in French-speaking societies.	Watson and Buede (1987), Yoon and Hwang (1995), Triantaphyllou (2000)
	2. The method is indeed successful when considering user satisfaction.	Watson and Buede (1987)
SMART	1. It is robust.	Watson and Buede (1987)
	2. It benefited from the work and applications of psychologists, engineers, management scientists and mathematicians.	Edwards and Newman (1982), Belton and Stewart (2002)
	3. Weights elicitation can be done using a variety of methods which lead to identical results in at least 80% of the time.	Edwards and Barron (1994), Srivastava, Connolly and Beach (1995), Barron and Barrett (1996), Roberts and Goodwin (2002)
	4. Full involvement of the decision maker to gain an increased understanding of the decision problem.	Edwards and Newman (1982), Watson and Buede (1987), Goodwin and Wright (2004)
	5. SMART has been widely applied because of the simplicity of both the responses required of the decision maker and the manner in which the responses are analysed.	Watson and Buede (1987), Goodwin and Wright (2004)

Table A-6: Weaknesses and Defense of AHP and TOPSIS

Method	Weakness	Source	Defense	Source
AHP	1. The problem of making difficult judgments is taken away from the decision maker and replaced by standard assignments.	Watson and Buede (1987)		
	2. The failure to distinguish clearly between options and attributes reduces rather than increases the clarity with which a problem is perceived.	Watson and Buede (1987)		
	3. The identity of the recommended option can depend on whether or not the analysis includes an option which is clearly not a good one (ranking inconsistency).	Belton and Gear (1983), Watson and Buede (1987), Dyer (1990), Triantaphyllou (2000)	Identical alternatives should not be considered in the decision process. Alternatives that score within 10 percent of another alternative are better to be eliminated!	Saaty (1990), Harker and Vargas (1990), Saaty (1987)
	4. Large number of judgments required of the decision maker $(m(n^2-n)/2 + n(m^2-m)/2$, where n is the number of alternatives and m is the number of attributes).	Belton and Stewart (2002), Dyer (1990)	The maximum number of attributes that a decision maker can handle is between 10 to 15 attributes.	Saaty and Vargas (1994)
TOPSIS	1. Other alternative distance measures could be used instead of the Euclidean distance, in which case it is possible for one to get different answers for the same problem.	Triantaphyllou (2000)		

Table A-7: Weaknesses and Defense of ELECTRE and SMART

Method	Weakness	Source	Defense	Source
ELECTRE	1. It is not possible to investigate the sensitivity and robustness of the method in any automated or interactive way.	Belton and Stewart (2002)		
	2. The absence of clear operational and psychological meanings for the threshold levels C^* and D^* while their impact upon the ultimate result may be significant.	Belton and Stewart (2002), Yoon and Hwang (1995), Watson and Buede (1987)	The net outranking relationship is introduced to address this problem.	Yoon and Hwang (1995)
	3. Because the system is not necessarily complete, ELECTRE is sometimes unable to identify the most preferred alternative.	Triantaphyllou (2000)		
	4. Since the method does not provide a way of obtaining weights or scores, the numbers are accepted unchallenged as inputs to a complicated algorithm.	Watson and Buede (1987)		
	5. It compares alternatives but does not produce a single index of performance.	Rogers and Bruen (2000)		
SMART	1. It does not provide the decision maker with a list of ranked alternatives.		The main role of decision analysis is to enable the decision maker to gain an increased understanding of his decision problem	Edwards and Newman (1982)
	2. The cost of its simplicity is that the method may not capture all the detail and complexities of the real problem.	Goodwin and Wright (2004)	In practice, the approach has been found to be extremely robust	Watson and Buede (1987)

Appendix B Economic and Financial Methods

Financial evaluation methods are always concerned with the cash flows of the organisation. A cash flow is the movement of money in (e.g. cash in-flows: payment for products by customers) or out (e.g. cash out-flows: payment for goods or services) of the organisation. Any new project will cause a change in the organisation's cash flows. In evaluating a R&D project, the decision makers must consider these expected changes in the organisation's cash flows and decide whether or not they add value to the organisation. Successful R&D projects will increase the shareholder's wealth through increased cash in-flows. Next sections will discuss some financial and economic evaluation measurements (techniques) with expressing the suitability of each technique.

1. Net Present Value (NPV)

NPV is the best financial evaluation technique that links the goal of the organisation to the calculated output. The calculated NPV is the actual pound amount by which the organisation's current wealth will increase if the project is undertaken. Its calculation accounts for the time value of money (cash now is worth more than money promised in the future) at the required rate of return, and uses this as a data input, rather than as a decision output.

1.1 Example

Suppose a project, with a discount rate of 10%, was expected to yield the following:

Year	**0**	**1**	**2**	**3**
Investment	£100,000			
Costs		£15,000	£15,000	£15,000
Return		£50,000	£50,000	£50,000

The NPV = -100000 + (50000-15000)(1.1) + (50000-15000)$(1.1)^2$ + (50000-15000)$(1.1)^3$

= £27,435

The weaknesses and problems of the other financial evaluation techniques, as discussed in the following sections, demonstrate the superiority of the NPV technique.

2. Internal Rate of Return (IRR)

The IRR is the financial equivalent to an algebraic problem. The problem is: given a value for 'Y', what is the solution for 'x' in the following equation?

$$Y = C/(1+x) + C/(1+x)^2 + \ldots\ldots\ldots, \text{ where: C is a constant}$$

This geometric progression has the same structure as a set of discounted cash flows, where the numerator of the equation is the set of cash flows, and the 'x' value is an interest rate. In the IRR equation, however, it is difficult to define IRR in its own terms, because it effectively means something like: "the rate of return at which all funds, if borrowed at the IRR, could be repaid from the project, without the organisation having to make any cash contribution" (Dayananda *et* al. 2002). The IRR does not measure the contribution of the project to the organisation's value.

2.1 Example

For the NPV example, the funds will be prepaid from the project itself when the NPV = 0. The IRR that will do so is calculated s follows:

$$NPV = 0 = -100000 + (50000-15000)(1+i) + (50000-15000)(1+i)^2 + (50000-15000)(1+i)^3$$

$$i = 2.48\%$$

Since this rate is below the required rate of return 10%, the project will be rejected.

The IRR is useful for easily comparing the rate of return from the project being considered with various alternative returns. But there may be one or more solutions for the IRR. For example, a series of flows of -£190, £455, -£270, there can be up to two positive solutions for the IRR. These are: 8.49% and 31%. If the required rate of return is 15%, then one IRR is below and the other is above the required rate, the decision maker can come to no sensible decision as to whether to accept or reject the project.

There may be no solution for the IRR. For example, given the set of cash flows, -£210, £455, -£270, there is no IRR solution, even though at an assumed required rate of 15% per annum, there is a valid NPV solution of -£18.63.

3. Pay Back Period (PBP)

PBP is a measure of the time taken to recoup the initial outlay. For the NPV example, the PBP = 2.85 years. There are several problems with this measure:

a) The cash flows are not discounted. As the time value of money is not taken into account, the future cash flows cannot be related to the initial outlay.
b) The data outcome is not a decision variable. It does not relate to the organisation's goal of wealth maximisation.
c) There is no objective measure of what constitutes an acceptable PBP. Management may set an ad hoc target, but this value is not objectively related to the organisation's goal.
d) Cash flows accounting after the PBP are ignored. In the case where large outflows may occur on the termination of the project, a project may be wrongly accepted on the basis of a short PBP.

PBP is a very unsophisticated and misleading technique, and it is not recommended as a measure for accepting or rejecting projects (Humphreys 2005). It may be useful as a support measure to the NPV technique, as an aid and comfort to some decision makers when considering very risky R&D projects.

4. Accounting Rate of Return (ARR)

ARR is the ratio of average accounting return to investment value. For example, suppose a project has an initial outlay of £200, and subsequent annual cash flows of £80, £110, £70, and £120. The average annual accounting return would be (80+110+70+120)/4 = £95, and the ARR would equal 95/200 = 47.5%. Drawbacks of ARR can be summarised as follows:

- It does not account for the time value of money.
- It uses accounting data that is not directly related to the wealth of the organisation.
- It has no objective decision criterion.

While most of the evaluation of R&D projects in the past was concerned with direct or tangible costs and profits, other viewpoints must be considered nowadays (Riggs 2004). Projects are evaluated for different characteristics or attributes by people with different backgrounds. Giving the same proposal to several groups of evaluators from different backgrounds will end with completely different evaluation outcomes. Different attributes of the project would be given different levels of importance (or weights) according to the evaluation group's beliefs and experience.

Most of the evaluation techniques are based on the principles of Cost/Benefit Analysis (CBA). Brown and Jackson (1990) defined CBA as "*a practical way* *of assessing the desirability of projects, where it is important to take a long view (in the sense of looking at repercussions in the further as well as nearer future) and a wide view (in the sense of allowing for side effects of many kinds on many persons, industries, regions. Etc.), i.e. it implies the numeration and evaluation of all the relevant costs and benefits.*"

Shaner (1979) suggests four general approaches to be followed in selecting alternatives based on CBA with highlights on the term 'weights' for qualitative costs and returns. First, if costs and returns are to be quantified in monetary terms, a project is acceptable when returns exceed costs. Second, if returns exceed costs and are the same for all alternatives, the alternative with the least cost is the best choice. Third, if returns and costs vary with the alternative but cannot be measured in monetary terms, a cost-effectiveness approach – that deals with qualitative returns – should be taken. Finally, if some of the returns and costs can be measured in monetary terms, then 'weights' can be assigned to physical units to arrive at equivalent monetary values. These monetary values are not directly derived from the marketplace. Instead, they are deduced through the study of the actions of individuals and decision makers.

Some literature describes several difficulties in the use of weights but many of them are subjective and tend to put them aside for the simple reason that they imply more work for the people in charge of decisions. However, it is recognised by both authors and evaluators that there is no solid evidence that the use of weights is inadequate.

Appendix C MS-EXCEL^{TM} Spreadsheets

Scenario 1:

Random Numbers Generated for

Attribute Weights

And

Project Scores

Weights

F	E	T	O	R	G	TI	I	IPR	EF	P	RA	TS	B	S
95.3929	38.2733	37.1319	87.1517	9.7690	36.5307	84.4478	69.9118	34.4127	2.5941	89.8953	71.7612	87.0113	32.3069	52.5163

SCORES

Projects	F	E	G	TI	I	IPR	EF	P	RA	TS	B	S
1	53.2090	13.4678	36.5123	1.1628	20.0629	32.1818	17.2643	64.0614	18.1097	38.9569	41.9782	61.3788
2	54.7533	19.0619	4.9043	42.8602	97.1801	15.7537	7.1596	66.3045	65.7125	56.1998	7.8127	68.0624
3	19.7974	93.7773	98.2299	79.5038	80.4407	7.3489	95.4009	1.0346	58.5894	21.8635	48.4939	71.3340
4	72.0786	5.8351	91.1313	56.1510	6.5462	44.5112	36.5368	72.5394	35.6700	52.5285	46.2111	32.7403
5	58.2995	39.3353	9.5157	8.2705	86.5963	70.3726	85.2138	24.9519	63.6555	57.7349	16.0985	57.6128
6	36.9945	5.4384	25.9590	0.6470	76.3817	74.1508	82.8455	70.0583	5.6795	49.3912	44.2274	45.0301
7	21.8329	44.6211	69.1549	13.3030	88.3084	8.8656	56.7186	95.8708	92.0835	8.4902	13.0222	47.2854
8	59.0075	36.6497	29.9539	27.7291	82.1314	83.3277	13.8554	88.0276	4.1902	40.4798	27.4117	77.2088
9	58.8427	1.8159	81.8690	55.3758	22.1473	25.1167	60.7898	6.7110	6.4058	37.9284	12.4729	70.7083
10	83.4437	86.0073	44.6547	3.0366	74.8650	18.5858	59.3616	22.5471	65.8681	20.4291	9.7232	12.5340
11	47.3708	88.1558	25.5959	40.4950	44.3373	46.5102	70.9189	38.8653	28.5928	61.4551	93.0265	11.5085
12	97.1221	35.7433	14.0263	66.3961	88.6166	11.0843	44.9904	83.2118	15.1097	36.9701	28.8888	63.7989
13	1.2024	40.8856	46.4980	75.1549	44.2610	47.0687	32.2214	74.1020	9.2532	45.9029	16.9164	38.5022
14	56.1083	91.0794	70.9616	67.3208	49.0982	4.6144	45.2101	22.8278	29.9234	5.2248	85.9493	7.4252
15	76.8914	7.6785	93.3500	6.4852	93.8993	89.4070	64.9586	96.1760	59.8560	85.9584	81.6309	8.3865
16	61.7939	3.1343	14.9449	92.4467	9.7720	92.4436	38.0932	77.3553	78.4295	82.0856	70.1773	64.5375
17	60.9729	9.5798	54.7838	31.9895	54.2589	98.7945	62.1570	38.1573	3.0671	66.7470	91.1039	75.1274
18	40.6446	96.4751	29.1452	15.5675	98.2391	88.6196	59.6820	97.7599	14.4200	16.7180	96.1760	23.7068
19	2.7680	95.3551	38.0902	37.8216	36.6008	50.9781	11.7954	59.2395	44.2915	78.5730	23.6335	49.9588
20	66.7928	58.7848	38.9874	38.5754	42.9884	98.8800	37.8430	9.0121	98.0407	53.7339	98.7487	43.3973
21	92.7366	62.2852	39.2315	91.3968	16.5014	54.5610	75.7805	29.3191	19.8767	92.1934	46.3027	37.3577
22	67.5161	47.4593	23.3802	65.3005	29.6518	18.7536	97.4914	95.5718	86.1751	30.3781	36.1827	57.3809
23	81.8628	31.9468	13.5624	35.1451	34.9254	0.5676	83.0500	24.2714	97.3144	43.7880	3.3906	39.7656
24	32.4442	25.6478	15.4607	72.2709	69.5486	85.3053	33.1706	0.4120	26.2734	41.5601	55.7756	96.5300
25	6.5462	62.7155	77.0013	66.9698	4.9837	97.9888	55.3972	51.2192	52.0585	30.6253	50.8805	89.5840
26	70.0980	71.9901	35.5815	23.4535	14.4688	55.8184	3.7568	48.4115	0.0793	8.2461	89.7458	97.5188
27	38.2550	16.0222	61.5131	10.8676	88.6807	77.5719	94.0733	94.5860	87.3226	93.5453	83.6512	43.8032
28	82.8852	25.4311	47.0016	32.4564	82.1802	94.9858	79.9890	76.7449	12.3630	39.0210	87.4050	55.9587
29	30.5826	33.5215	28.5989	41.7707	26.7312	89.4101	25.8034	62.0258	59.3402	73.5130	68.4683	76.7968
30	26.5511	42.5489	77.3522	18.0639	30.0424	33.3140	31.2418	88.2168	16.8096	83.2759	63.0207	60.5457

ATTRIBUTES			FINANCE (F)	EMPLOYMENT (E)	TECHNOLOGY (T)					OPPORTUNITY (O)			RISK (R)				TOTAL
WEIGHTS			100	40	40					90			10				280
N. WEIGHTS			0.36	0.14	0.14					0.32			0.04				1.00
SUB-ATTRIBUTES					G	TI	I	IPR	TOTAL	EF	IPR	TOTAL	RA	TS	B	S	TOTAL
WEIGHTS					40	90	70	40	240	10	90	100	80	90	40	60	270
N. WEIGHTS					0.17	0.38	0.29	0.17	1.00	0.10	0.90	1.00	0.30	0.33	0.15	0.22	1.00
Clean Fuels	P1	SCORES	60	20	40	0	30	40	22.08	20	70	65.00	20	40	50	70	42.22
		W. SCORES	21.43	2.86			3.15				20.89				1.51		
	P2	SCORES	60	20	0	50	100	20	51.25	10	70	64.00	70	60	10	70	57.78
		W. SCORES	21.43	2.86			7.32				20.57				2.06		
	P3	SCORES	20	100	100	80	90	10	74.58	100	0	10.00	60	30	50	80	52.96
		W. SCORES	7.14	14.29			10.65				3.21				1.89		
	P4	SCORES	80	10	100	60	10	50	50.42	40	80	76.00	40	60	50	40	48.15
		W. SCORES	28.57	1.43			7.20				24.43				1.72		
	P5	SCORES	60	40	10	10	90	80	45.00	90	30	36.00	70	60	20	60	57.04
		W. SCORES	21.43	5.71			6.43				11.57				2.04		
	P6	SCORES	40	10	30	0	80	80	41.67	90	80	81.00	10	50	50	50	38.15
		W. SCORES	14.29	1.43			5.95				26.04				1.36		
	P7	SCORES	30	50	70	20	90	10	47.08	60	100	96.00	100	10	20	50	47.04
		W. SCORES	10.71	7.14			6.73				30.86				1.08		
	P8	SCORES	60	40	30	30	90	90	57.50	20	90	83.00	0	50	30	80	38.89
		W. SCORES	21.43	5.71			8.21				26.68				1.39		
Upgrading Low Value Refined Products	P9	SCORES	60	0	90	60	30	30	51.25	70	10	16.00	10	40	20	80	37.04
		W. SCORES	21.43	0.00			7.32				5.14				1.32		
	P10	SCORES	90	90	50	0	80	20	35.00	60	30	33.00	70	30	10	20	36.67
		W. SCORES	32.14	12.86			5.00				10.61				1.31		
	P11	SCORES	50	90	30	50	50	50	46.67	80	40	44.00	30	70	100	20	51.48
		W. SCORES	17.86	12.86			6.67				14.14				1.84		
	P12	SCORES	100	40	20	70	90	20	59.17	50	90	86.00	20	40	30	70	39.26
		W. SCORES	35.71	5.71			8.45				27.64				1.40		
	P13	SCORES	0	50	50	80	50	50	61.25	40	80	76.00	10	50	20	40	31.48
		W. SCORES	0.00	7.14			8.75				24.43				1.12		
	P14	SCORES	60	100	80	70	50	0	54.17	50	30	32.00	30	10	90	10	27.78
		W. SCORES	21.43	14.29			7.74				10.29				0.99		
	P15	SCORES	80	10	100	10	100	90	64.58	70	100	97.00	60	90	90	10	63.33
		W. SCORES	28.57	1.43			9.23				31.18				2.26		
	P16	SCORES	70	0	20	100	10	100	60.42	40	80	76.00	80	90	80	70	81.11
		W. SCORES	25.00	0.00			8.63				24.43				2.99		

		ATTRIBUTES	FINANCE (F)	EMPLOYMENT (E)	TECHNOLOGY (T)					OPPORTUNITY (O)			RISK (R)				TOTAL
		WEIGHTS	100	40	40					90			10				280
		N. WEIGHTS	0.36	0.14	0.14					0.32			0.04				1.00
		SUB-ATTRIBUTES			G	TI	I	IPR	TOTAL	EF	IPR	TOTAL	RA	TS	B	S	TOTAL
		WEIGHTS			40	90	70	40	240	10	90	100	80	90	40	60	270
		N. WEIGHTS			0.17	0.38	0.29	0.17	1.00	0.10	0.90	1.00	0.30	0.33	0.15	0.22	1.00
Petrochemicals Feedstock and Chemicals from Refined Products	P17	SCORES	70	10	60	40	60	100	59.17	70	40	43.00	0	70	100	80	55.93
		W. SCORES	25.00	1.43			8.45				13.82				2.00		
	P18	SCORES	50	100	30	20	100	90	56.67	60	100	96.00	20	20	100	30	34.07
		W. SCORES	17.86	14.29			8.10				30.86				1.22		
	P19	SCORES	0	100	40	40	40	60	43.33	20	60	56.00	50	80	30	50	57.04
		W. SCORES	0.00	14.29			6.19				18.00				2.04		
	P20	SCORES	70	60	40	40	50	100	52.92	40	10	13.00	100	60	100	50	75.56
		W. SCORES	25.00	8.57			7.56				4.18				2.70		
	P21	SCORES	100	70	40	100	20	60	60.00	80	30	35.00	20	100	50	40	55.56
		W. SCORES	35.71	10.00			8.57				11.25				1.98		
	P22	SCORES	70	50	30	70	30	20	43.33	100	100	100.00	90	40	40	60	59.26
		W. SCORES	25.00	7.14			6.19				32.14				2.12		
	P23	SCORES	90	40	20	40	40	0	30.00	90	30	36.00	100	50	0	40	55.19
		W. SCORES	32.14	5.71			4.29				11.57				1.97		
H_2 Production	P24	SCORES	40	30	20	80	70	90	68.75	40	0	4.00	30	50	60	100	56.67
			14.29	4.29			9.82				1.29				2.02		
	P25	SCORES	10	70	80	70	0	100	56.25	60	60	60.00	60	40	60	90	60.00
		W. SCORES	3.57	10.00			8.04				19.29				2.14		
	P26	SCORES	80	80	40	30	20	60	33.75	0	50	45.00	0	10	90	100	38.89
		W. SCORES	28.57	11.43			4.82				14.46				1.39		
	P27	SCORES	40	20	70	20	90	80	58.75	100	100	100.00	90	100	90	50	84.44
			14.29	2.86			8.39				32.14				1.88		
	P28	SCORES	90	30	50	40	90	100	66.25	80	80	80.00	20	40	90	60	45.93
		W. SCORES	32.14	4.29			9.46				25.71				1.64		
	P29	SCORES	40	40	30	50	30	90	47.50	30	70	66.00	60	80	70	80	72.59
		W. SCORES	14.29	5.71			6.79				21.21				2.59		
	P30	SCORES	30	50	80	20	40	40	39.17	40	90	85.00	20	90	70	70	61.85
		W. SCORES	10.71	7.14			5.60				27.32				2.21		

Scenario 1: TOPSIS

Project Scores

		ORIGINAL					NORMALISED					WEIGHTED NORMALISED				
		F	E	T	O	R	F	E	T	O	R	F	E	T	O	R
	WEIGHT	0.36	0.14	0.14	0.32	0.04	0.36	0.14	0.14	0.32	0.04					
Clean Fuels	P1	60.00	20.00	22.08	65.00	42.22	0.1744	0.0641	0.0767	0.1794	0.1427	0.0623	0.0092	0.0110	0.0577	0.0051
	P2	60.00	20.00	51.25	64.00	57.78	0.1744	0.0641	0.1779	0.1766	0.1953	0.0623	0.0092	0.0059	0.0568	0.0070
	P3	20.00	100.00	74.58	10.00	52.96	0.0581	0.3204	0.2589	0.0276	0.1791	0.0208	0.0458	0.0136	0.0089	0.0064
	P4	80.00	10.00	50.42	76.00	48.15	0.2325	0.0320	0.1750	0.2097	0.1628	0.0830	0.0046	0.0199	0.0674	0.0058
	P5	60.00	40.00	45.00	36.00	57.04	0.1744	0.1282	0.1562	0.0993	0.1928	0.0623	0.0183	0.0134	0.0319	0.0069
	P6	40.00	10.00	41.67	81.00	38.15	0.1162	0.0320	0.1447	0.2235	0.1290	0.0415	0.0046	0.0120	0.0718	0.0046
	P7	30.00	50.00	47.08	96.00	47.04	0.0872	0.1602	0.1635	0.2649	0.1590	0.0311	0.0229	0.0111	0.0851	0.0057
	P8	60.00	40.00	57.50	83.00	38.89	0.1744	0.1282	0.1996	0.2290	0.1315	0.0623	0.0183	0.0199	0.0736	0.0047
Upgrading Low Value Refined Products	P9	60.00	0.00	51.25	16.00	37.04	0.1744	0.0000	0.1779	0.0442	0.1252	0.0623	0.0000	0.0254	0.0142	0.0045
	P10	90.00	90.00	35.00	33.00	36.67	0.2616	0.2884	0.1215	0.0911	0.1240	0.0934	0.0412	0.0174	0.0293	0.0044
	P11	50.00	90.00	46.67	44.00	51.48	0.1453	0.2884	0.1620	0.1214	0.1740	0.0519	0.0412	0.0231	0.0390	0.0062
	P12	100.00	40.00	59.17	86.00	39.26	0.2906	0.1282	0.2054	0.2373	0.1327	0.1038	0.0183	0.0293	0.0763	0.0047
	P13	0.00	50.00	61.25	76.00	31.48	0.0000	0.1602	0.2126	0.2097	0.1064	0.0000	0.0229	0.0304	0.0674	0.0038
	P14	60.00	100.00	54.17	32.00	27.78	0.1744	0.3204	0.1881	0.0883	0.0939	0.0623	0.0458	0.0269	0.0284	0.0034
	P15	80.00	10.00	64.58	97.00	63.33	0.2325	0.0320	0.2242	0.2677	0.2141	0.0830	0.0046	0.0320	0.0860	0.0076
	P16	70.00	0.00	60.42	76.00	81.11	0.2034	0.0000	0.2097	0.2097	0.2742	0.0727	0.0000	0.0300	0.0674	0.0098

		ORIGINAL					NORMALISED					WEIGHTED NORMALISED				
		F	E	T	O	R	F	E	T	O	R	F	E	T	O	R
	WEIGHT	0.36	0.14	0.14	0.32	0.04	0.36	0.14	0.14	0.32	0.04					
Petrochemicals Feedstock and Chemicals from Refined Products	P17	70.00	10.00	59.17	43.00	55.93	0.2034	0.0320	0.2054	0.1187	0.1891	0.0727	0.0046	0.0293	0.0381	0.0068
	P18	50.00	100.00	56.67	96.00	34.07	0.1453	0.3204	0.1967	0.2649	0.1152	0.0519	0.0458	0.0281	0.0851	0.0041
	P19	0.00	100.00	43.33	56.00	57.04	0.0000	0.3204	0.1504	0.1545	0.1928	0.0000	0.0458	0.0215	0.0497	0.0069
	P20	70.00	60.00	52.92	13.00	75.56	0.2034	0.1923	0.1837	0.0359	0.2554	0.0727	0.0275	0.0262	0.0115	0.0091
	P21	100.00	70.00	60.00	35.00	55.56	0.2906	0.2243	0.2083	0.0966	0.1878	0.1038	0.0320	0.0298	0.0310	0.0067
	P22	70.00	50.00	43.33	100.00	59.26	0.2034	0.1602	0.1504	0.2759	0.2003	0.0727	0.0229	0.0215	0.0887	0.0072
	P23	90.00	40.00	30.00	36.00	55.19	0.2616	0.1282	0.1042	0.0993	0.1866	0.0934	0.0183	0.0149	0.0319	0.0067
H_2 Production	P24	40.00	30.00	68.75	4.00	56.67	0.1162	0.0961	0.2387	0.0110	0.1916	0.0415	0.0137	0.0341	0.0035	0.0068
	P25	10.00	70.00	56.25	60.00	60.00	0.0291	0.2243	0.1953	0.1656	0.2028	0.0104	0.0320	0.0279	0.0532	0.0072
	P26	80.00	80.00	33.75	45.00	38.89	0.2325	0.2563	0.1172	0.1242	0.1315	0.0830	0.0366	0.0167	0.0399	0.0047
	P27	40.00	20.00	58.75	100.00	84.44	0.1162	0.0641	0.2040	0.2759	0.2855	0.0415	0.0092	0.0291	0.0887	0.0102
	P28	90.00	30.00	66.25	80.00	45.93	0.2616	0.0961	0.2300	0.2208	0.1553	0.0934	0.0137	0.0329	0.0710	0.0055
	P29	40.00	40.00	47.50	66.00	72.59	0.1162	0.1282	0.1649	0.1821	0.2454	0.0415	0.0183	0.0236	0.0585	0.0088
	P30	30.00	50.00	39.17	85.00	61.85	0.0872	0.1602	0.1360	0.2345	0.2091	0.0311	0.0229	0.0194	0.0754	0.0075
	SQRT	344.09	312.09	288.04	362.40	295.79					MAX	0.1038	0.0458	0.0341	0.0887	0.0102
											MIN	0.0000	0.0000	0.0059	0.0035	0.0034

Scenario 1: TOPSIS

Project Ranks

	+	-	S^+	*RANK*	S^-	*RANK*	C^+	*RANK*	*SMART RANK*
P1	0.0046	0.0069	0.0677	*13*	0.0832	*17*	0.5511	***14***	*4*
P2	0.0049	0.0068	0.0699	*14*	0.0825	*19*	0.5412	***15***	*20*
P3	0.0137	0.0026	0.1170	*30*	0.0512	*30*	0.3044	***30***	*19*
P4	0.0028	0.0112	0.0529	*6*	0.1058	*8*	0.6665	***6***	*14*
P5	0.0061	0.0051	0.0783	*20*	0.0713	*25*	0.4766	***24***	*18*
P6	0.0064	0.0064	0.0799	*23*	0.0803	*21*	0.5013	***21***	*28*
P7	0.0064	0.0082	0.0798	*22*	0.0905	*14*	0.5314	***18***	*25*
P8	0.0029	0.0093	0.0542	*7*	0.0965	*13*	0.6404	***8***	*16*
P9	0.0095	0.0044	0.0974	*25*	0.0661	*27*	0.4045	***25***	*22*
P10	0.0040	0.0112	0.0630	*11*	0.1059	*7*	0.6269	***10***	*2*
P11	0.0053	0.0060	0.0729	*17*	0.0772	*22*	0.5142	***19***	*13*
P12	0.0010	0.0170	0.0310	*1*	0.1302	*1*	0.8077	***1***	*3*
P13	0.0118	0.0052	0.1086	*27*	0.0721	*24*	0.3990	***26***	*30*
P14	0.0055	0.0070	0.0739	*18*	0.0838	*16*	0.5316	***17***	*7*
P15	0.0021	0.0144	0.0463	*4*	0.1201	*2*	0.7216	***4***	*10*
P16	0.0035	0.0100	0.0595	*9*	0.0999	*9*	0.6269	***11***	*17*

	+	-	S^+	*RANK*	S^-	*RANK*	C^+	*RANK*	*SMART RANK*
P17	0.0053	0.0071	0.0725	*16*	0.0840	*15*	0.5368	***16***	*15*
P18	0.0028	0.0119	0.0527	*5*	0.1093	*6*	0.6746	***5***	*11*
P19	0.0125	0.0045	0.1117	*29*	0.0669	*26*	0.3748	***28***	*29*
P20	0.0073	0.0065	0.0856	*24*	0.0809	*20*	0.4860	***23***	*9*
P21	0.0035	0.0131	0.0595	*10*	0.1146	*5*	0.6582	***7***	*1*
P22	0.0017	0.0133	0.0408	*3*	0.1154	*4*	0.7389	***3***	*12*
P23	0.0045	0.0100	0.0668	*12*	0.0998	*10*	0.5989	***12***	*8*
P24	0.0122	0.0027	0.1103	*28*	0.0522	*29*	0.3211	***29***	*21*
P25	0.0102	0.0041	0.1011	*26*	0.0640	*28*	0.3878	***27***	*27*
P26	0.0032	0.0097	0.0568	*8*	0.0984	*11*	0.6340	***9***	*6*
P27	0.0052	0.0096	0.0724	*15*	0.0982	*12*	0.5756	***13***	*24*
P28	0.0015	0.0142	0.0384	*2*	0.1191	*3*	0.7564	***2***	*5*
P29	0.0057	0.0054	0.0752	*19*	0.0737	*23*	0.4948	***22***	*23*
P30	0.0062	0.0069	0.0788	*21*	0.0828	*18*	0.5125	***20***	*26*

Scenario 1: TOPSIS

Portfolio Scores

		ORIGINAL					NORMALISED					WEIGHTED NORMALISED				
		F	E	T	O	R	F	E	T	O	R	F	E	T	O	R
	WEIGHT	0.36	0.14	0.14	0.32	0.04	0.36	0.14	0.32	0.14	0.04					
PORTFOLIOS PT1	8-12-18-22-26-28	450	340	317	490	256	0.1484	0.1792	0.1578	0.1719	0.1454	0.0530	0.0256	0.0507	0.0246	0.0052
PT2	8-15-18-22-26-28	430	310	322	501	280	0.1418	0.1634	0.1605	0.1758	0.1591	0.0506	0.0233	0.0516	0.0251	0.0057
PT3	8-15-21-22-26-28	410	230	282	340	243	0.1352	0.1212	0.1406	0.1193	0.1377	0.0483	0.0173	0.0452	0.0170	0.0049
PT4	8-12-21-22-26-28	500	310	320	429	278	0.1649	0.1634	0.1595	0.1505	0.1576	0.0589	0.0233	0.0513	0.0215	0.0056
PT5	4-8-10-15-22-26	460	280	285	434	285	0.1517	0.1476	0.1418	0.1523	0.1618	0.0542	0.0211	0.0456	0.0218	0.0058
PT6	4-8-10-15-22-28	470	230	317	469	292	0.1550	0.1212	0.1580	0.1646	0.1658	0.0553	0.0173	0.0508	0.0235	0.0059
PT7	8-10-12-18-22-26	450	400	285	443	247	0.1484	0.2108	0.1423	0.1555	0.1402	0.0530	0.0301	0.0457	0.0222	0.0050
PT8	8-10-12-18-22-28	460	350	318	478	254	0.1517	0.1845	0.1585	0.1677	0.1442	0.0542	0.0264	0.0509	0.0240	0.0051
PT9	8-10-12-15-18-26	460	360	307	440	251	0.1517	0.1897	0.1528	0.1544	0.1425	0.0542	0.0271	0.0491	0.0221	0.0051
PT10	8-10-12-15-18-28	470	310	339	475	258	0.1550	0.1634	0.1690	0.1667	0.1465	0.0553	0.0233	0.0543	0.0238	0.0052

		ORIGINAL					NORMALISED					WEIGHTED NORMALISED				
		F	E	T	O	R	F	E	T	O	R	F	E	T	O	R
	WEIGHT	0.36	0.14	0.14	0.32	0.04	0.36	0.14	0.32	0.14	0.04					
PORTFOLIOS PT11	4-10-12-15-22-26	500	280	286	437	286	0.1649	0.1476	0.1427	0.1533	0.1620	0.0589	0.0211	0.0459	0.0219	0.0058
PT12	4-10-12-15-22-28	510	230	319	472	293	0.1682	0.1212	0.1589	0.1656	0.1660	0.0601	0.0173	0.0511	0.0237	0.0059
PT13	4-8-12-15-22-26	470	230	309	487	288	0.1550	0.1212	0.1539	0.1709	0.1633	0.0553	0.0173	0.0495	0.0244	0.0058
PT14	4-8-12-15-22-28	480	180	341	522	295	0.1583	0.0949	0.1701	0.1832	0.1673	0.0565	0.0136	0.0547	0.0262	0.0060
PT15	8-10-12-15-21-26	510	330	310	379	273	0.1682	0.1739	0.1545	0.1330	0.1547	0.0601	0.0248	0.0497	0.0190	0.0055
PT16	8-10-12-15-21-28	520	280	343	414	280	0.1715	0.1476	0.1707	0.1453	0.1587	0.0612	0.0211	0.0549	0.0208	0.0057
PT17	8-10-12-21-22-26	500	370	289	382	269	0.1649	0.1950	0.1439	0.1340	0.1524	0.0589	0.0279	0.0463	0.0191	0.0054
PT18	8-10-12-21-22-28	510	320	321	417	276	0.1682	0.1687	0.1601	0.1463	0.1564	0.0601	0.0241	0.0515	0.0209	0.0056
PT19	8-10-12-15-22-26	480	310	293	444	276	0.1583	0.1634	0.1462	0.1558	0.1568	0.0565	0.0233	0.0470	0.0223	0.0056
PT20	8-10-12-15-22-28	490	260	326	479	283	0.1616	0.1370	0.1624	0.1681	0.1608	0.0577	0.0196	0.0522	0.0240	0.0057

			ORIGINAL					NORMALISED					WEIGHTED NORMALISED				
			F	E	T	O	R	F	E	T	O	R	F	E	T	O	R
		WEIGHT	0.36	0.14	0.14	0.32	0.04	0.36	0.14	0.32	0.14	0.04					
PORTFOLIOS	PT21	8-10-12-21-26-28	520	350	312	362	255	0.1715	0.1845	0.1553	0.1270	0.1448	0.0612	0.0264	0.0499	0.0181	0.0052
	PT22	8-12-15-21-26-28	510	270	341	426	282	0.1682	0.1423	0.1701	0.1495	0.1599	0.0601	0.0203	0.0547	0.0214	0.0057
	PT23	8-10-15-21-26-28	500	320	317	373	279	0.1649	0.1687	0.1580	0.1309	0.1585	0.0589	0.0241	0.0508	0.0187	0.0057
	PT24	4-12-15-21-22-28	520	210	344	474	311	0.1715	0.1107	0.1713	0.1663	0.1767	0.0612	0.0158	0.0551	0.0238	0.0063
	PT25	4-12-15-21-22-26	510	260	311	439	304	0.1682	0.1370	0.1551	0.1540	0.1727	0.0601	0.0196	0.0499	0.0220	0.0062
	PT26	8-12-15-18-21-28	480	290	364	477	290	0.1583	0.1529	0.1815	0.1674	0.1646	0.0565	0.0218	0.0583	0.0239	0.0059
	PT27	8-12-15-18-21-26	470	340	332	442	270	0.1550	0.1792	0.1653	0.1551	0.1532	0.0553	0.0256	0.0531	0.0222	0.0055
	PT28	8-12-15-21-22-28	500	240	351	481	302	0.1649	0.1265	0.1749	0.1688	0.1715	0.0589	0.0181	0.0562	0.0241	0.0061
	PT29	8-12-15-21-22-26	490	290	318	446	295	0.1616	0.1529	0.1587	0.1565	0.1675	0.0577	0.0218	0.0510	0.0224	0.0060
	PT30	8-10-15-21-22-28	490	290	327	428	300	0.1616	0.1529	0.1628	0.1502	0.1700	0.0577	0.0218	0.0523	0.0215	0.0061

			ORIGINAL					NORMALISED					WEIGHTED NORMALISED				
			F	E	T	O	R	F	E	T	O	R	F	E	T	O	R
		WEIGHT	0.36	0.14	0.14	0.32	0.04	0.36	0.14	0.32	0.14	0.04					
PORTFOLIOS	PT31	8-10-15-21-22-26	480	340	294	393	293	0.1583	0.1792	0.1466	0.1379	0.1660	0.0565	0.0256	0.0471	0.0197	0.0059
	PT32	4-12-15-22-26-28	500	220	318	484	295	0.1649	0.1160	0.1582	0.1698	0.1673	0.0589	0.0166	0.0509	0.0243	0.0060
	PT33	8-12-15-18-26-28	460	300	338	487	260	0.1517	0.1581	0.1684	0.1709	0.1477	0.0542	0.0226	0.0541	0.0244	0.0053
	PT34	8-12-15-22-26-28	480	250	325	491	286	0.1583	0.1318	0.1618	0.1723	0.1620	0.0565	0.0188	0.0520	0.0246	0.0058
	PT35	8-10-15-22-26-28	470	300	300	438	283	0.1550	0.1581	0.1497	0.1537	0.1606	0.0553	0.0226	0.0481	0.0220	0.0057
	PT36	8-12-15-18-22-26	450	270	348	542	281	0.1484	0.1423	0.1732	0.1902	0.1593	0.0530	0.0203	0.0557	0.0272	0.0057
	PT37	8-12-15-18-22-28	440	320	315	507	274	0.1451	0.1687	0.1570	0.1779	0.1553	0.0518	0.0241	0.0505	0.0254	0.0055
	PT38	8-10-15-18-22-26	430	370	291	454	271	0.1418	0.1950	0.1450	0.1593	0.1538	0.0506	0.0279	0.0466	0.0228	0.0055
	PT39	8-10-15-18-22-28	440	320	320	489	278	0.1451	0.1687	0.1595	0.1716	0.1578	0.0518	0.0241	0.0513	0.0245	0.0056
	PT40	8-10-12-22-26-28	490	330	295	427	259	0.1616	0.1739	0.1470	0.1498	0.1469	0.0577	0.0248	0.0473	0.0214	0.0052
	SQRT		3033	1897	2006	2850	1762					MAX	0.0612	0.0301	0.0583	0.0272	0.0063
												MIN	0.0483	0.0136	0.0452	0.0170	0.0049

Scenario 1: TOPSIS

Portfolio Ranks

	+	-	S^+	RANK	S^-	RANK	C^+	RANK
PT1	0.0002	0.0003	0.0124	11	0.0160	18	0.5623	13
PT2	0.0002	0.0002	0.0144	24	0.0144	31	0.4999	30
PT3	0.0006	0.0000	0.0247	40	0.0038	40	0.1324	40
PT4	0.0001	0.0003	0.0116	7	0.0163	15	0.5845	9
PT5	0.0003	0.0001	0.0180	39	0.0107	39	0.3729	39
PT6	0.0003	0.0001	0.0164	34	0.0118	37	0.4177	37
PT7	0.0003	0.0003	0.0159	32	0.0180	4	0.5305	22
PT8	0.0001	0.0003	0.0114	5	0.0167	13	0.5939	6
PT9	0.0002	0.0003	0.0131	17	0.0161	16	0.5514	16
PT10	0.0001	0.0003	0.0104	3	0.0166	14	0.6137	3

	+	-	S^+	RANK	S^-	RANK	C^+	RANK
PT11	0.0003	0.0002	0.0165	35	0.0139	35	0.4582	36
PT12	0.0002	0.0002	0.0152	31	0.0152	23	0.5008	28
PT13	0.0003	0.0001	0.0169	37	0.0117	38	0.4098	38
PT14	0.0003	0.0002	0.0176	38	0.0156	21	0.4687	34
PT15	0.0002	0.0003	0.0131	19	0.0170	10	0.5652	12
PT16	0.0001	0.0003	0.0116	8	0.0182	3	0.6106	4
PT17	0.0002	0.0003	0.0149	27	0.0180	5	0.5468	18
PT18	0.0001	0.0003	0.0112	4	0.0175	8	0.6097	5
PT19	0.0002	0.0002	0.0149	26	0.0140	34	0.4838	32
PT20	0.0002	0.0002	0.0131	18	0.0149	26	0.5329	21

	+	-	S^+	RANK	S^-	RANK	C^+	RANK
PT21	0.0002	0.0004	0.0129	14	0.0189	2	0.5928	7
PT22	0.0001	0.0003	0.0120	9	0.0171	9	0.5874	8
PT23	0.0002	0.0003	0.0131	15	0.0161	17	0.5514	17
PT24	0.0002	0.0003	0.0151	30	0.0178	6	0.5419	19
PT25	0.0002	0.0002	0.0145	25	0.0149	27	0.5069	26
PT26	0.0001	0.0004	0.0101	1	0.0189	1	0.6523	1
PT27	0.0001	0.0003	0.0104	2	0.0169	11	0.6188	2
PT28	0.0002	0.0003	0.0128	13	0.0175	7	0.5767	11
PT29	0.0002	0.0002	0.0126	12	0.0148	29	0.5413	20
PT30	0.0001	0.0002	0.0122	10	0.0151	24	0.5529	15

	+	-	S^+	RANK	S^-	RANK	C^+	RANK
PT31	0.0002	0.0002	0.0150	29	0.0150	25	0.5004	29
PT32	0.0003	0.0002	0.0159	33	0.0144	32	0.4745	33
PT33	0.0001	0.0003	0.0115	6	0.0158	19	0.5786	10
PT34	0.0002	0.0002	0.0140	22	0.0141	33	0.5021	27
PT35	0.0002	0.0002	0.0149	28	0.0128	36	0.4623	35
PT36	0.0002	0.0003	0.0131	16	0.0168	12	0.5616	14
PT37	0.0002	0.0002	0.0138	21	0.0149	28	0.5189	25
PT38	0.0003	0.0002	0.0166	36	0.0157	20	0.4854	31
PT39	0.0002	0.0002	0.0135	20	0.0147	30	0.5214	24
PT40	0.0002	0.0002	0.0141	23	0.0155	22	0.5243	23

Scenario 1: ILP Model for Portfolio Ranking

Projects	Decision	Attractiveness	Budget	Class1	Class2	Class3	Class4
			Constraints				
1	0	49.84	1.2	1	0	0	0
2	0	33.67	1.5	1	0	0	0
3	0	33.97	2	1	0	0	0
4	0	38.92	2.5	1	0	0	0
5	0	35.61	1	1	0	0	0
6	0	23.03	1.5	1	0	0	0
7	0	26.26	2	1	0	0	0
8	0	36.75	1.6	1	0	0	0
9	0	30.07	2.4	0	1	0	0
10	0	51.31	1.6	0	1	0	0
11	0	39.22	1	0	1	0	0
12	0	51.28	1.2	0	1	0	0
13	0	17.02	1.7	0	1	0	0
14	0	44.44	1.5	0	1	0	0
15	0	41.49	1.1	0	1	0	0
16	0	36.53	1.3	0	1	0	0
17	0	36.88	1	0	0	1	0
18	0	41.46	2.2	0	0	1	0
19	0	22.51	2.1	0	0	1	0
20	0	43.83	1.8	0	0	1	0
21	0	56.27	2	0	0	1	0
22	0	40.45	1.4	0	0	1	0
23	0	44.11	1.4	0	0	1	0
24	0	30.42	2.3	0	0	0	1
25	0	23.75	2	0	0	0	1
26	0	46.21	1.8	0	0	0	1
27	0	27.41	1.6	0	0	0	1
28	0	47.53	1.8	0	0	0	1
29	0	29.38	2.1	0	0	0	1
30	0	25.66	2.5	0	0	0	1
	RHS		10	1	1	1	1
			0	0	0	0	0

	Available
Objective	0

SOLUTION

	Portfolios	#	tractivene	Budget	Rank
PT1	8-12-18-22-26-28	0	263.68	10	31
PT2	8-15-18-22-26-28	0	253.88	9.9	40
PT3	8-15-21-22-26-28	0	268.70	9.7	23
PT4	8-12-21-22-26-28	0	278.49	9.8	8
PT5	4-8-10-15-22-26	0	255.13	10	38
PT6	4-8-10-15-22-28	0	256.45	10	36
PT7	8-10-12-18-22-26	0	267.45	9.8	26
PT8	8-10-12-18-22-28	0	268.78	9.8	22
PT9	8-10-12-15-18-26	0	268.49	9.5	24
PT10	8-10-12-15-18-28	0	269.81	9.5	19
PT11	4-10-12-15-22-26	0	269.66	9.6	20
PT12	4-10-12-15-22-28	0	270.99	9.6	18
PT13	4-8-12-15-22-26	0	255.10	9.6	39
PT14	4-8-12-15-22-28	0	256.42	9.6	37
PT15	8-10-12-15-21-26	0	283.31	9.3	4
PT16	8-10-12-15-21-28	0	284.63	9.3	2
PT17	8-10-12-21-22-26	0	282.27	9.6	5
PT18	8-10-12-21-22-28	0	283.59	9.6	3
PT19	8-10-12-15-22-26	0	267.49	8.7	25
PT20	8-10-12-15-22-28	0	268.81	8.7	21

	Portfolios	#	Attractiveness	Budget	Rank
PT21	8-10-12-21-26-28	0	289.35	10	1
PT22	8-12-15-21-26-28	0	279.53	9.5	7
PT23	8-10-15-21-26-28	0	279.56	9.9	6
PT24	4-12-15-21-22-28	0	275.95	10	9
PT25	4-12-15-21-22-26	0	274.62	10	11
PT26	8-12-15-18-21-28	0	274.78	9.9	10
PT27	8-12-15-18-21-26	0	273.45	9.9	15
PT28	8-12-15-21-22-28	0	273.77	9.1	13
PT29	8-12-15-21-22-26	0	272.45	9.1	17
PT30	8-10-15-21-22-28	0	273.80	9.5	12
PT31	8-10-15-21-22-26	0	272.47	9.5	16
PT32	4-12-15-22-26-28	0	265.89	9.8	27
PT33	8-12-15-18-26-28	0	264.72	9.7	28
PT34	8-12-15-22-26-28	0	263.71	8.9	30
PT35	8-10-15-22-26-28	0	263.74	9.3	29
PT36	8-12-15-18-22-26	0	257.63	9.3	35
PT37	8-12-15-18-22-28	0	258.96	9.3	33
PT38	8-10-15-18-22-26	0	257.66	9.7	34
PT39	8-10-15-18-22-28	0	258.98	9.7	32
PT40	8-10-12-22-26-28	0	273.53	9.4	14

Scenario 2:

Random Numbers Generated for

Attribute Weights

And

Project Scores

Weights

F	E	T	O	R	G	TI	I	IPR	EF	P	RA	TS	B	S
95.3929	38.2733	37.1319	87.1517	9.7690	36.5307	84.4478	69.9118	34.4127	2.5941	89.8953	71.7612	87.0113	32.3069	52.5163

SCORES

Projects	F	E	G	TI	I	IPR	EF	P	RA	TS	B	S
1	53.2090	13.4678	36.5123	1.1628	1.4422	32.1818	17.2643	64.0614	18.1097	38.9569	41.9782	61.3788
2	54.7533	19.0619	4.9043	42.8602	97.1801	15.7537	7.1596	66.3045	65.7125	56.1998	1.4806	68.0624
3	2.9444	93.7773	98.2299	79.5038	80.4407	3.7197	95.4009	1.0346	58.5894	21.8635	48.4939	71.3340
4	86.7038	94.2668	88.2337	86.6805	96.8523	97.6374	90.3803	92.3675	91.7238	97.2954	93.3833	93.0418
5	58.2995	39.3353	9.5157	8.2705	86.5963	70.3726	85.2138	24.9519	63.6555	57.7349	16.0985	57.6128
6	36.9945	0.8025	25.9590	0.6470	76.3817	74.1508	82.8455	70.0583	3.0204	49.3912	44.2274	0.7183
7	21.8329	44.6211	69.1549	13.3030	88.3084	8.8656	56.7186	95.8708	92.0835	2.0927	13.0222	47.2854
8	96.5638	87.7082	98.5099	94.2540	85.8213	97.4868	87.5878	96.8867	92.9987	91.6945	99.8439	99.1842
9	58.8427	1.8159	81.8690	1.1571	22.1473	25.1167	60.7898	3.1030	1.2397	37.9284	2.7741	70.7083
10	85.9210	94.9104	95.8992	96.4513	99.5871	97.2712	86.0414	97.4657	97.8700	96.4788	97.1398	95.3453
11	47.3708	88.1558	25.5959	40.4950	44.3373	46.5102	70.9189	38.8653	28.5928	61.4551	93.0265	11.5085
12	89.7151	92.8271	99.2877	94.7676	94.5007	97.0171	91.1081	91.0459	85.7050	92.4915	94.7932	87.5457
13	1.2024	40.8856	46.4980	75.1549	44.2610	47.0687	3.8976	74.1020	9.2532	45.9029	16.9164	38.5022
14	56.1083	91.0794	70.9616	67.3208	49.0982	4.6144	45.2101	22.8278	29.9234	1.7675	85.9493	0.2100
15	93.9766	98.6706	97.6974	91.2546	86.2799	98.7828	92.0260	92.0754	93.9894	85.3635	87.4821	92.1299
16	61.7939	3.1343	1.0404	92.4467	3.1484	92.4436	38.0932	77.3553	78.4295	82.0856	70.1773	64.5375
17	60.9729	3.6112	54.7838	0.4577	54.2589	98.7945	62.1570	38.1573	3.0671	66.7470	91.1039	75.1274
18	86.7217	97.7194	95.6310	91.4167	91.3082	89.9481	91.4029	95.4625	93.8630	86.8691	90.8934	99.1884
19	2.7680	95.3551	38.0902	37.8216	36.6008	50.9781	2.4244	59.2395	44.2915	78.5730	23.6335	49.9588
20	66.7928	58.7848	38.9874	38.5754	42.9884	98.8800	37.8430	2.1622	98.0407	53.7339	98.7487	43.3973
21	98.2380	94.6559	87.6029	92.9516	99.4552	94.4394	97.0785	85.6542	95.1352	89.4990	95.1979	97.5985
22	88.7130	90.5940	90.5844	87.9472	98.6619	96.1872	87.8707	97.7464	97.7189	93.3732	99.0913	98.2014
23	81.8628	31.9468	3.6129	35.1451	2.1088	0.5676	83.0500	24.2714	97.3144	2.3857	3.3906	2.9395
24	32.4442	25.6478	0.0707	72.2709	69.5486	85.3053	33.1706	0.4120	26.2734	41.5601	55.7756	96.5300
25	0.6101	62.7155	77.0013	66.9698	4.9837	97.9888	55.3972	51.2192	52.0585	1.3529	0.7215	89.5840
26	89.7641	91.1814	85.0375	86.1385	91.3411	98.1689	99.0258	89.0010	99.2410	97.1082	87.9943	93.6305
27	38.2550	1.0308	61.5131	1.9874	88.6807	77.5719	94.0733	94.5860	87.3226	93.5453	83.6512	3.4380
28	94.8202	93.8241	92.2095	91.2226	88.0854	89.0651	94.0992	99.5454	90.6668	90.1097	90.2937	95.8928
29	30.5826	33.5215	28.5989	41.7707	26.7312	89.4101	1.2542	62.0258	59.3402	73.5130	68.4683	76.7968
30	26.5511	42.5489	77.3522	18.0639	30.0424	1.9487	31.2418	88.2168	1.9844	83.2759	63.0207	60.5457

	ATTRIBUTES		FINANCE (F)	EMPLOYMENT (E)	TECHNOLOGY (T)					OPPORTUNITY (O)			RISK (R)				TOTAL
	WEIGHTS		100	40	40					90			10				280
	N. WEIGHTS		0.36	0.14	0.14					0.32			0.04				1.00
	SUB-ATTRIBUTES				G	TI	I	IPR	TOTAL	EF	IPR	TOTAL	RA	TS	B	S	TOTAL
	WEIGHTS				40	90	70	40	240	10	90	100	80	90	40	60	270
	N. WEIGHTS				0.17	0.38	0.29	0.17	1.00	0.10	0.90	1.00	0.30	0.33	0.15	0.22	1.00
Clean Fuels	P1	SCORES	60	20	40	0	0	40	13.33	20	70	65.00	20	40	50	70	42.22
		W. SCORES	21.43	2.86			1.90				20.89				1.51		
	P2	SCORES	60	20	0	50	100	20	51.25	10	70	64.00	70	60	0	70	56.30
		W. SCORES	21.43	2.86			7.32				20.57				2.01		
	P3	SCORES	0	100	100	80	90	0	72.92	100	0	10.00	60	30	50	80	52.96
		W. SCORES	0.00	14.29			10.42				3.21				1.89		
	P4	SCORES	90	100	90	90	100	100	94.58	100	100	100.00	100	100	100	100	100.00
		W. SCORES	32.14	14.29			13.51				32.14				3.57		
	P5	SCORES	60	40	10	10	90	80	45.00	90	30	36.00	70	60	20	60	57.04
		W. SCORES	21.43	5.71			6.43				11.57				2.04		
	P6	SCORES	40	0	30	0	80	80	41.67	90	80	81.00	0	50	50	0	24.07
		W. SCORES	14.29	0.00			5.95				26.04				0.86		
	P7	SCORES	30	50	70	20	90	10	47.08	60	100	96.00	100	0	20	50	43.70
		W. SCORES	10.71	7.14			6.73				30.86				1.56		
	P8	SCORES	100	90	100	100	90	100	97.08	90	100	99.00	100	100	100	100	100.00
		W. SCORES	35.71	12.86			13.87				31.82				3.57		
Upgrading Low Value Refined Products	P9	SCORES	60	0	90	0	30	30	28.75	70	0	7.00	0	40	0	80	31.11
		W. SCORES	21.43	0.00			4.11				2.25				1.11		
	P10	SCORES	90	100	100	100	100	100	100.00	90	100	99.00	100	100	100	100	100.00
		W. SCORES	32.14	14.29			14.29				31.82				3.57		
	P11	SCORES	50	90	30	50	50	50	46.67	80	40	44.00	30	70	100	20	51.48
		W. SCORES	17.86	12.86			6.67				14.14				1.84		
	P12	SCORES	90	100	100	100	100	100	100.00	100	100	100.00	90	100	100	90	94.81
		W. SCORES	32.14	14.29			14.29				32.14				3.39		
	P13	SCORES	0	50	50	80	50	50	61.25	0	80	72.00	10	50	20	40	31.48
		W. SCORES	0.00	7.14			8.75				23.14				1.12		
	P14	SCORES	60	100	80	70	50	0	54.17	50	30	32.00	30	0	90	0	22.22
		W. SCORES	21.43	14.29			7.74				10.29				0.79		
	P15	SCORES	100	100	100	100	90	100	97.08	100	100	100.00	100	90	90	100	95.19
		W. SCORES	35.71	14.29			13.87				32.14				3.40		
	P16	SCORES	70	0	0	100	0	100	54.17	40	80	76.00	80	90	80	70	81.11
		W. SCORES	25.00	0.00			7.74				24.43				2.90		

	ATTRIBUTES		FINANCE (F)	EMPLOYMENT (E)	TECHNOLOGY (T)					OPPORTUNITY (O)			RISK (R)				TOTAL
	WEIGHTS		100	40	40					90			10				280
	N. WEIGHTS		0.36	0.14	0.14					0.32			0.04				1.00
	SUB-ATTRIBUTES				G	TI	I	IPR	TOTAL	EF	IPR	TOTAL	RA	TS	B	S	TOTAL
	WEIGHTS				40	90	70	40	240	10	90	100	80	90	40	60	270
	N. WEIGHTS				0.17	0.38	0.29	0.17	1.00	0.10	0.90	1.00	0.30	0.33	0.15	0.22	1.00
Petrochemicals Feedstock and Chemicals from Refined Products	P17	SCORES	70	0	60	0	60	100	44.17	70	40	43.00	0	70	100	80	55.93
		W. SCORES	25.00	0.00			6.31				13.82				2.00		
	P18	SCORES	90	100	100	100	100	90	98.33	100	100	100.00	100	90	100	100	96.67
		W. SCORES	32.14	14.29			14.05				32.14				3.45		
	P19	SCORES	0	100	40	40	40	60	43.33	0	60	54.00	50	80	30	50	57.04
		W. SCORES	0.00	14.29			6.19				17.36				2.04		
	P20	SCORES	70	60	40	40	50	100	52.92	40	0	4.00	100	60	100	50	75.56
		W. SCORES	25.00	8.57			7.56				1.29				2.70		
	P21	SCORES	100	100	90	100	100	100	98.33	100	90	91.00	100	90	100	100	96.67
		W. SCORES	35.71	14.29			14.05				29.25				3.45		
	P22	SCORES	90	100	100	90	100	100	96.25	90	100	99.00	100	100	100	100	100.00
		W. SCORES	32.14	14.29			13.75				31.82				3.57		
	P23	SCORES	90	40	0	40	0	0	15.00	90	30	36.00	100	0	0	0	29.63
		W. SCORES	32.14	5.71			2.14				11.57				1.06		
H_2 Production	P24	SCORES	40	30	0	80	70	90	65.42	40	0	4.00	30	50	60	100	56.67
			14.29	4.29			9.35				1.29				2.02		
	P25	SCORES	0	70	80	70	0	100	56.25	60	60	60.00	60	0	0	90	37.78
		W. SCORES	0.00	10.00			8.04				19.29				1.35		
	P26	SCORES	90	100	90	90	100	100	94.58	100	90	91.00	100	100	90	100	98.52
		W. SCORES	32.14	14.29			13.51				29.25				3.52		
	P27	SCORES	40	0	70	0	90	80	51.25	100	100	100.00	90	100	90	0	73.33
			14.29	0.00			7.32				32.14				1.88		
	P28	SCORES	100	100	100	100	90	90	95.42	100	100	100.00	100	100	100	100	100.00
		W. SCORES	35.71	14.29			13.63				32.14				3.57		
	P29	SCORES	40	40	30	50	30	90	47.50	0	70	63.00	60	80	70	80	72.59
		W. SCORES	14.29	5.71			6.79				20.25				2.59		
	P30	SCORES	30	50	80	20	40	0	32.50	40	90	85.00	0	90	70	70	55.93
		W. SCORES	10.71	7.14			4.64				27.32				2.00		

Scenario 2: TOPSIS

Project Scores

		ORIGINAL					NORMALISED					WEIGHTED NORMALISED				
		F	E	T	O	R	F	E	T	O	R	F	E	T	O	R
	WEIGHT	0.36	0.14	0.14	0.32	0.04	0.36	0.14	0.14	0.32	0.04					
Clean Fuels	P1	60.00	20.00	13.33	65.00	42.22	0.3386	0.1101	0.0740	0.3054	0.2307	0.1209	0.0157	0.0106	0.0982	0.0082
	P2	60.00	20.00	51.25	64.00	56.30	0.3386	0.1101	0.2844	0.3007	0.3076	0.1209	0.0157	0.0055	0.0967	0.0110
	P3	0.00	100.00	72.92	10.00	52.96	0.0000	0.5505	0.4047	0.0470	0.2894	0.0000	0.0786	0.0210	0.0151	0.0103
	P4	90.00	100.00	94.58	100.00	100.00	0.5079	0.5505	0.5249	0.4699	0.5464	0.1814	0.0786	0.0299	0.1510	0.0195
	P5	60.00	40.00	45.00	36.00	57.04	0.3386	0.2202	0.2497	0.1692	0.3116	0.1209	0.0315	0.0388	0.0544	0.0111
	P6	40.00	0.00	41.67	81.00	24.07	0.2257	0.0000	0.2312	0.3806	0.1315	0.0806	0.0000	0.0185	0.1223	0.0047
	P7	30.00	50.00	47.08	96.00	43.70	0.1693	0.2752	0.2613	0.4511	0.2388	0.0605	0.0393	0.0171	0.1450	0.0085
	P8	100.00	90.00	97.08	99.00	100.00	0.5643	0.4954	0.5388	0.4652	0.5464	0.2015	0.0708	0.0299	0.1495	0.0195
	SQRT	177.20	181.66	180.20	212.83	183.03										

		ORIGINAL					NORMALISED					WEIGHTED NORMALISED				
		F	E	T	O	R	F	E	T	O	R	F	E	T	O	R
	WEIGHT	0.36	0.14	0.14	0.32	0.04	0.36	0.14	0.14	0.32	0.04					
Upgrading Low Value Refined Products	P9	60.00	0.00	28.75	7.00	31.11	0.2970	0.0000	0.1402	0.0335	0.1561	0.1061	0.0000	0.0200	0.0108	0.0056
	P10	90.00	100.00	100.00	99.00	100.00	0.4456	0.4446	0.4877	0.4732	0.5017	0.1591	0.0635	0.0697	0.1521	0.0179
	P11	50.00	90.00	46.67	44.00	51.48	0.2475	0.4001	0.2276	0.2103	0.2583	0.0884	0.0572	0.0325	0.0676	0.0092
	P12	90.00	100.00	100.00	100.00	94.81	0.4456	0.4446	0.4877	0.4780	0.4757	0.1591	0.0635	0.0697	0.1536	0.0170
	P13	0.00	50.00	61.25	72.00	31.48	0.0000	0.2223	0.2987	0.3441	0.1579	0.0000	0.0318	0.0427	0.1106	0.0056
	P14	60.00	100.00	54.17	32.00	22.22	0.2970	0.4446	0.2642	0.1530	0.1115	0.1061	0.0635	0.0377	0.0492	0.0040
	P15	100.00	100.00	97.08	100.00	95.19	0.4951	0.4446	0.4734	0.4780	0.4775	0.1768	0.0635	0.0676	0.1536	0.0171
	P16	70.00	0.00	54.17	76.00	81.11	0.3466	0.0000	0.2642	0.3633	0.4069	0.1238	0.0000	0.0377	0.1168	0.0145
	SQRT	201.99	224.94	205.06	209.21	199.33										

		ORIGINAL					NORMALISED					WEIGHTED NORMALISED				
		F	E	T	O	R	F	E	T	O	R	F	E	T	O	R
	WEIGHT	0.36	0.14	0.14	0.32	0.04	0.36	0.14	0.14	0.32	0.04					
Petrochemicals Feedstock and Chemicals from Refined Products	P17	70.00	0.00	44.17	43.00	55.93	0.3333	0.0000	0.2346	0.2327	0.2740	0.1190	0.0000	0.0335	0.0748	0.0098
	P18	90.00	100.00	98.33	100.00	96.67	0.4286	0.4704	0.5222	0.5411	0.4736	0.1531	0.0672	0.0746	0.1739	0.0169
	P19	0.00	100.00	43.33	54.00	57.04	0.0000	0.4704	0.2301	0.2922	0.2795	0.0000	0.0672	0.0329	0.0939	0.0100
	P20	70.00	60.00	52.92	4.00	75.56	0.3333	0.2822	0.2810	0.0216	0.3702	0.1190	0.0403	0.0401	0.0070	0.0132
	P21	100.00	100.00	98.33	91.00	96.67	0.4762	0.4704	0.5222	0.4924	0.4736	0.1701	0.0672	0.0746	0.1583	0.0169
	P22	90.00	100.00	96.25	99.00	100.00	0.4286	0.4704	0.5112	0.5357	0.4900	0.1531	0.0672	0.0730	0.1722	0.0175
	P23	90.00	40.00	15.00	36.00	29.63	0.4286	0.1881	0.0797	0.1948	0.1452	0.1531	0.0269	0.0114	0.0626	0.0052
	SQRT	210.00	212.60	188.30	184.82	204.10										

		ORIGINAL					NORMALISED					WEIGHTED NORMALISED				
		F	E	T	O	R	F	E	T	O	R	F	E	T	O	R
	WEIGHT	0.36	0.14	0.14	0.32	0.04	0.36	0.14	0.14	0.32	0.04					
H_2 Production	P24	40.00	30.00	65.42	4.00	56.67	0.2240	0.0753	0.1740	0.0098	0.1449	0.0800	0.0108	0.0249	0.0032	0.0052
	P25	0.00	70.00	56.25	60.00	37.78	0.0000	0.1757	0.1496	0.1471	0.0966	0.0000	0.0251	0.0214	0.0473	0.0034
	P26	90.00	100.00	94.58	91.00	98.52	0.5039	0.2510	0.2515	0.2231	0.2519	0.1800	0.0359	0.0359	0.0717	0.0090
	P27	40.00	0.00	51.25	100.00	73.33	0.2240	0.0000	0.1363	0.2452	0.1875	0.0800	0.0000	0.0195	0.0788	0.0067
	P28	100.00	100.00	95.42	100.00	100.00	0.5599	0.2510	0.2537	0.2452	0.2556	0.2000	0.0359	0.0362	0.0788	0.0091
	P29	40.00	40.00	47.50	63.00	72.59	0.2240	0.1004	0.1263	0.1545	0.1856	0.0800	0.0143	0.0180	0.0497	0.0066
	P30	30.00	50.00	32.50	85.00	55.93	0.1680	0.1255	0.0864	0.2084	0.1430	0.0600	0.0179	0.0123	0.0670	0.0051
	SQRT	178.61	398.37	376.04	407.82	391.16										

Scenario 2: TOPSIS

Project Ranks

	+	-	s^+	RANK	s^-	RANK	c^+	RANK	SMART RANK
P1	0.0142	0.0218	0.1191	3	0.1477	4	0.5536	3	3
P2	0.0146	0.0216	0.1208	4	0.1468	5	0.5486	4	5
P3	0.0595	0.0065	0.2439	8	0.0804	8	0.2478	8	6
P4	0.0005	0.0584	0.0220	2	0.2416	2	0.9164	2	2
P5	0.0181	0.0183	0.1347	5	0.1353	6	0.5012	5	4
P6	0.0223	0.0182	0.1492	7	0.1348	7	0.4746	7	8
P7	0.0221	0.0222	0.1486	6	0.1491	3	0.5008	6	7
P8	0.0001	0.0645	0.0120	1	0.2540	1	0.9550	1	1

	+	-	s^+	RANK	s^-	RANK	c^+	RANK	SMART RANK
P9	0.0321	0.0113	0.1791	7	0.1061	8	0.3721	7	7
P10	0.0003	0.0520	0.0177	3	0.2280	3	0.9278	3	2
P11	0.0167	0.0145	0.1293	5	0.1204	6	0.4822	6	5
P12	0.0003	0.0524	0.0177	2	0.2289	2	0.9282	2	3
P13	0.0350	0.0115	0.1871	8	0.1072	7	0.3643	8	8
P14	0.0171	0.0171	0.1309	6	0.1307	5	0.4996	5	4
P15	0.0000	0.0581	0.0022	1	0.2411	1	0.9909	1	1
P16	0.0092	0.0270	0.0961	4	0.1643	4	0.6309	4	6

	+	-	s^+	*RANK*	s^-	*RANK*	c^+	*RANK*	*SMART RANK*
P17	0.0187	0.0193	0.1367	*5*	0.1389	*5*	0.5039	***5***	*6*
P18	0.0003	0.0600	0.0170	*2*	0.2449	*2*	0.9350	***2***	*2*
P19	0.0371	0.0126	0.1927	*7*	0.1121	*7*	0.3678	***7***	*7*
P20	0.0324	0.0167	0.1800	*6*	0.1292	*6*	0.4178	***6***	*4*
P21	0.0002	0.0605	0.0157	*1*	0.2459	*1*	0.9401	***1***	*1*
P22	0.0003	0.0592	0.0172	*3*	0.2433	*3*	0.9341	***3***	*3*
P23	0.0185	0.0272	0.1358	*4*	0.1651	*4*	0.5486	***4***	*5*

	+	-	s^+	*RANK*	s^-	*RANK*	c^+	*RANK*	*SMART RANK*
P24	0.0209	0.0067	0.1446	*6*	0.0817	*6*	0.3611	***6***	*3*
P25	0.0413	0.0027	0.2033	*7*	0.0516	*7*	0.2023	***7***	*7*
P26	0.0005	0.0390	0.0212	*2*	0.1974	*2*	0.9029	***2***	*2*
P27	0.0160	0.0122	0.1264	*3*	0.1104	*3*	0.4662	***3***	*6*
P28	0.0000	0.0476	0.0000	*1*	0.2182	*1*	1.0000	***1***	*1*
P29	0.0160	0.0088	0.1267	*4*	0.0939	*4*	0.4256	***4***	*4*
P30	0.0206	0.0080	0.1437	*5*	0.0894	*5*	0.3837	***5***	*5*

Scenario 2: TOPSIS

Portfolio Scores

		ORIGINAL					NORMALISED					WEIGHTED NORMALISED				
		F	E	T	O	R	F	E	T	O	R	F	E	T	O	R
	WEIGHT	0.36	0.14	0.14	0.32	0.04	0.36	0.14	0.32	0.14	0.04					
PORTFOLIOS PT1	8-12-18-22-26-28	560	590	582	589	590	0.1566	0.1584	0.1582	0.1589	0.1590	0.0559	0.0226	0.0509	0.0227	0.0057
PT2	8-15-18-22-26-28	570	590	579	589	590	0.1594	0.1584	0.1574	0.1589	0.1591	0.0569	0.0226	0.0506	0.0227	0.0057
PT3	8-15-21-22-26-28	490	490	483	481	490	0.1370	0.1315	0.1312	0.1298	0.1321	0.0489	0.0188	0.0422	0.0185	0.0047
PT4	8-12-21-22-26-28	570	590	582	580	590	0.1594	0.1584	0.1582	0.1565	0.1590	0.0569	0.0226	0.0509	0.0224	0.0057
PT5	4-8-10-15-22-26	560	590	580	588	594	0.1566	0.1584	0.1576	0.1587	0.1600	0.0559	0.0226	0.0507	0.0227	0.0057
PT6	4-8-10-15-22-28	570	590	580	597	595	0.1594	0.1584	0.1579	0.1611	0.1604	0.0569	0.0226	0.0507	0.0230	0.0057
PT7	8-10-12-18-22-26	550	590	586	588	590	0.1538	0.1584	0.1595	0.1587	0.1590	0.0549	0.0226	0.0513	0.0227	0.0057
PT8	8-10-12-18-22-28	560	590	587	597	591	0.1566	0.1584	0.1597	0.1611	0.1594	0.0559	0.0226	0.0513	0.0230	0.0057
PT9	8-10-12-15-18-26	560	590	587	589	585	0.1566	0.1584	0.1597	0.1589	0.1577	0.0559	0.0226	0.0513	0.0227	0.0056
PT10	8-10-12-15-18-28	570	590	588	598	587	0.1594	0.1584	0.1599	0.1614	0.1581	0.0569	0.0226	0.0514	0.0231	0.0056

		ORIGINAL					NORMALISED					WEIGHTED NORMALISED				
		F	E	T	O	R	F	E	T	O	R	F	E	T	O	R
	WEIGHT	0.36	0.14	0.14	0.32	0.04	0.36	0.14	0.32	0.14	0.04					
PORTFOLIOS PT11	4-10-12-15-22-26	550	600	583	589	589	0.1538	0.1611	0.1584	0.1589	0.1586	0.0549	0.0230	0.0509	0.0227	0.0057
PT12	4-10-12-15-22-28	560	600	583	598	590	0.1566	0.1611	0.1587	0.1614	0.1590	0.0559	0.0230	0.0510	0.0231	0.0057
PT13	4-8-12-15-22-26	560	590	580	589	589	0.1566	0.1584	0.1576	0.1589	0.1586	0.0559	0.0226	0.0507	0.0227	0.0057
PT14	4-8-12-15-22-28	570	590	580	598	590	0.1594	0.1584	0.1579	0.1614	0.1590	0.0569	0.0226	0.0507	0.0231	0.0057
PT15	8-10-12-15-21-26	570	590	587	580	585	0.1594	0.1584	0.1597	0.1565	0.1577	0.0569	0.0226	0.0513	0.0224	0.0056
PT16	8-10-12-15-21-28	580	590	588	589	587	0.1622	0.1584	0.1599	0.1589	0.1581	0.0579	0.0226	0.0514	0.0227	0.0056
PT17	8-10-12-21-22-26	560	590	586	579	590	0.1566	0.1584	0.1595	0.1562	0.1590	0.0559	0.0226	0.0513	0.0223	0.0057
PT18	8-10-12-21-22-28	570	590	587	588	591	0.1594	0.1584	0.1597	0.1587	0.1594	0.0569	0.0226	0.0513	0.0227	0.0057
PT19	8-10-12-15-22-26	560	590	585	588	589	0.1566	0.1584	0.1591	0.1587	0.1586	0.0559	0.0226	0.0511	0.0227	0.0057
PT20	8-10-12-15-22-28	570	590	586	597	590	0.1594	0.1584	0.1593	0.1611	0.1590	0.0569	0.0226	0.0512	0.0230	0.0057

PORTFOLIOS		ORIGINAL					NORMALISED					WEIGHTED NORMALISED				
		F	E	T	O	R	F	E	T	O	R	F	E	T	O	R
	WEIGHT	0.36	0.14	0.14	0.32	0.04	0.36	0.14	0.32	0.14	0.04					
PT21	8-10-12-21-26-28	570	590	585	580	590	0.1594	0.1584	0.1592	0.1565	0.1590	0.0569	0.0226	0.0512	0.0224	0.0057
PT22	8-12-15-21-26-28	580	590	583	581	585	0.1622	0.1584	0.1584	0.1568	0.1577	0.0579	0.0226	0.0509	0.0224	0.0056
PT23	8-10-15-21-26-28	580	590	583	580	590	0.1622	0.1584	0.1584	0.1565	0.1591	0.0579	0.0226	0.0509	0.0224	0.0057
PT24	4-12-15-21-22-28	570	600	582	590	587	0.1594	0.1611	0.1582	0.1592	0.1581	0.0569	0.0230	0.0509	0.0227	0.0056
PT25	4-12-15-21-22-26	560	600	581	581	585	0.1566	0.1611	0.1580	0.1568	0.1577	0.0559	0.0230	0.0508	0.0224	0.0056
PT26	8-12-15-18-21-28	580	590	586	590	590	0.1622	0.1584	0.1595	0.1592	0.1590	0.0579	0.0226	0.0513	0.0227	0.0057
PT27	8-12-15-18-21-26	570	590	585	581	582	0.1594	0.1584	0.1592	0.1568	0.1568	0.0569	0.0226	0.0512	0.0224	0.0056
PT28	8-12-15-21-22-28	580	590	584	589	587	0.1622	0.1584	0.1589	0.1589	0.1581	0.0579	0.0226	0.0511	0.0227	0.0056
PT29	8-12-15-21-22-26	570	590	583	580	585	0.1594	0.1584	0.1587	0.1565	0.1577	0.0569	0.0226	0.0510	0.0224	0.0056
PT30	8-10-15-21-22-28	580	590	584	588	592	0.1622	0.1584	0.1589	0.1587	0.1595	0.0579	0.0226	0.0511	0.0227	0.0057

		ORIGINAL					NORMALISED					WEIGHTED NORMALISED				
		F	E	T	O	R	F	E	T	O	R	F	E	T	O	R
	WEIGHT	0.36	0.14	0.14	0.32	0.04	0.36	0.14	0.32	0.14	0.04					
PORTFOLIOS PT31	8-10-15-21-22-26	570	590	583	579	590	0.1594	0.1584	0.1587	0.1562	0.1591	0.0569	0.0226	0.0510	0.0223	0.0057
PT32	4-12-15-22-26-28	560	600	578	590	589	0.1566	0.1611	0.1572	0.1592	0.1586	0.0559	0.0230	0.0505	0.0227	0.0057
PT33	8-12-15-18-26-28	570	590	583	590	585	0.1594	0.1584	0.1584	0.1592	0.1577	0.0569	0.0226	0.0509	0.0227	0.0056
PT34	8-12-15-22-26-28	570	590	580	589	589	0.1594	0.1584	0.1579	0.1589	0.1586	0.0569	0.0226	0.0507	0.0227	0.0057
PT35	8-10-15-22-26-28	570	590	580	588	594	0.1594	0.1584	0.1579	0.1587	0.1600	0.0569	0.0226	0.0507	0.0227	0.0057
PT36	8-12-15-18-22-26	570	590	584	598	587	0.1594	0.1584	0.1589	0.1614	0.1581	0.0569	0.0226	0.0511	0.0231	0.0056
PT37	8-12-15-18-22-28	560	590	583	589	585	0.1566	0.1584	0.1587	0.1589	0.1577	0.0559	0.0226	0.0510	0.0227	0.0056
PT38	8-10-15-18-22-26	560	590	583	588	590	0.1566	0.1584	0.1587	0.1587	0.1591	0.0559	0.0226	0.0510	0.0227	0.0057
PT39	8-10-15-18-22-28	570	590	590	597	592	0.1594	0.1584	0.1605	0.1611	0.1595	0.0569	0.0226	0.0516	0.0230	0.0057
PT40	8-10-12-22-26-28	560	590	583	588	593	0.1566	0.1584	0.1587	0.1587	0.1599	0.0559	0.0226	0.0510	0.0227	0.0057
	SQRT	3576	3725	3676	3706	3711					MAX	0.0579	0.0230	0.0516	0.0231	0.0057
											MIN	0.0489	0.0188	0.0422	0.0185	0.0047

Scenario 2: TOPSIS

Portfolio Ranks

	+	-	S^+	RANK	S^-	RANK	C^+	RANK	IP RANK	SMART	SMART RANK
PT1	0.000005	0.000157	0.0022	**33**	0.0125	**33**	**0.8513**	**33**	36	388	36
PT2	0.000002	0.000168	0.0015	**24**	0.0129	**25**	**0.8965**	**24**	25	392	25
PT3	0.000208	0.000000	0.0144	**40**	0.0000	**40**	**0.0000**	**40**	7	395	7
PT4	0.000002	0.000169	0.0015	**23**	0.0130	**23**	**0.8985**	**23**	20	392	20
PT5	0.000005	0.000154	0.0023	**36**	0.0124	**37**	**0.8457**	**36**	37	388	37
PT6	0.000002	0.000173	0.0014	**17**	0.0131	**18**	**0.9063**	**18**	19	392	19
PT7	0.000009	0.000151	0.0031	**38**	0.0123	**38**	**0.8004**	**38**	40	386	40
PT8	0.000004	0.000168	0.0021	**25**	0.0130	**24**	**0.8635**	**25**	29	389	29
PT9	0.000004	0.000165	0.0021	**26**	0.0129	**27**	**0.8607**	**27**	31	389	31
PT10	0.000001	0.000185	0.0011	**8**	0.0136	**8**	**0.9259**	**8**	10	393	10

	+	-	S^+	RANK	S^-	RANK	C^+	RANK	IP RANK	SMART	SMART RANK
PT11	0.000010	0.000148	0.0031	39	0.0122	39	0.7978	39	39	386	39
PT12	0.000004	0.000166	0.0021	27	0.0129	26	0.8608	26	26	390	26
PT13	0.000005	0.000154	0.0023	35	0.0124	36	0.8461	35	38	388	38
PT14	0.000002	0.000173	0.0014	18	0.0132	17	0.9063	17	23	392	23
PT15	0.000002	0.000178	0.0013	14	0.0133	12	0.9109	13	11	393	11
PT16	0.000000	0.000199	0.0006	1	0.0141	1	0.9622	1	1	396	1
PT17	0.000005	0.000161	0.0022	32	0.0127	29	0.8530	32	30	389	30
PT18	0.000001	0.000180	0.0012	10	0.0134	10	0.9201	10	9	393	9
PT19	0.000004	0.000162	0.0021	28	0.0127	28	0.8573	28	32	389	32
PT20	0.000001	0.000181	0.0011	9	0.0135	9	0.9224	9	12	393	12

	+	-	S^+	RANK	S^-	RANK	C^+	RANK	IP RANK	SMART	SMART RANK
PT21	0.000002	0.000175	0.0013	16	0.0132	15	0.9082	16	13	393	13
PT22	0.000001	0.000188	0.0010	5	0.0137	6	0.9315	5	6	396	6
PT23	0.000001	0.000187	0.0010	6	0.0137	7	0.9300	6	5	396	5
PT24	0.000002	0.000175	0.0013	12	0.0132	13	0.9121	12	8	393	8
PT25	0.000005	0.000156	0.0023	34	0.0125	34	0.8474	34	27	390	27
PT26	0.000000	0.000196	0.0006	2	0.0140	2	0.9594	2	3	396	3
PT27	0.000002	0.000175	0.0013	15	0.0132	14	0.9091	15	16	392	16
PT28	0.000001	0.000193	0.0007	3	0.0139	3	0.9500	3	4	396	4
PT29	0.000002	0.000172	0.0014	20	0.0131	19	0.9031	19	18	392	18
PT30	0.000001	0.000192	0.0007	4	0.0139	4	0.9490	4	2	396	2

	+	-	S^+	RANK	S^-	RANK	C^+	RANK	IP RANK	SMART	SMART RANK
PT31	0.000002	0.000171	0.0014	22	0.0131	20	0.9020	22	15	392	15
PT32	0.000005	0.000155	0.0023	37	0.0124	35	0.8451	37	28	389	28
PT33	0.000002	0.000173	0.0013	13	0.0132	16	0.9104	14	22	392	22
PT34	0.000002	0.000170	0.0014	19	0.0130	21	0.9028	20	24	392	24
PT35	0.000002	0.000170	0.0014	21	0.0130	22	0.9022	21	21	392	21
PT36	0.000001	0.000179	0.0012	11	0.0134	11	0.9184	11	35	389	35
PT37	0.000005	0.000159	0.0021	29	0.0126	30	0.8547	29	17	392	17
PT38	0.000005	0.000159	0.0022	31	0.0126	32	0.8544	31	34	389	34
PT39	0.000001	0.000188	0.0011	7	0.0137	5	0.9275	7	14	392	14
PT40	0.000005	0.000159	0.0022	30	0.0126	31	0.8544	30	33	389	33

Scenario 2: ILP Model for Portfolio Ranking

			Constraints				
Projects	Decision	Attractiveness	Budget	Class1	Class2	Class3	Class4
1	0	48.59	1.2	1	0	0	0
2	0	33.62	1.5	1	0	0	0
3	0	26.59	2	1	0	0	0
4	0	63.51	2.5	1	0	0	0
5	0	35.61	1	1	0	0	0
6	0	21.10	1.5	1	0	0	0
7	0	26.14	2	1	0	0	0
8	0	66.01	1.6	1	0	0	0
9	0	26.65	2.4	0	1	0	0
10	0	64.29	1.6	0	1	0	0
11	0	39.22	1	0	1	0	0
12	0	64.10	1.2	0	1	0	0
13	0	17.02	1.7	0	1	0	0
14	0	44.25	1.5	0	1	0	0
15	0	67.27	1.1	0	1	0	0
16	0	35.63	1.3	0	1	0	0
17	0	33.31	1	0	0	1	0
18	0	63.93	2.2	0	0	1	0
19	0	22.51	2.1	0	0	1	0
20	0	43.83	1.8	0	0	1	0
21	0	67.50	2	0	0	1	0
22	0	63.75	1.4	0	0	1	0
23	0	41.06	1.4	0	0	1	0
24	0	29.94	2.3	0	0	0	1
25	0	19.38	2	0	0	0	1
26	0	63.46	1.8	0	0	0	1
27	0	23.49	1.6	0	0	0	1
28	0	67.20	1.8	0	0	0	1
29	0	29.38	2.1	0	0	0	1
30	0	24.50	2.5	0	0	0	1
	RHS		10	1	1	1	1
		Available	0	0	0	0	0

Objective 0

SOLUTION

	Portfolios	#	Attractiveness	Budget	Rank		Portfolios	#	Attractiveness	Budget	Rank
PT1	8-12-18-22-26-28	0	388.45	10	36	PT21	8-10-12-21-26-28	0	392.56	10	13
PT2	8-15-18-22-26-28	0	391.62	9.9	25	PT22	8-12-15-21-26-28	0	395.54	9.5	6
PT3	8-15-21-22-26-28	0	395.19	9.7	7	PT23	8-10-15-21-26-28	0	395.73	9.9	5
PT4	8-12-21-22-26-28	0	392.02	9.8	20	PT24	4-12-15-21-22-28	0	393.33	10	8
PT5	4-8-10-15-22-26	0	388.29	10	37	PT25	4-12-15-21-22-26	0	389.59	10	27
PT6	4-8-10-15-22-28	0	392.03	10	19	PT26	8-12-15-18-21-28	0	396.01	9.9	3
PT7	8-10-12-18-22-26	0	385.54	9.8	40	PT27	8-12-15-18-21-26	0	392.27	9.9	16
PT8	8-10-12-18-22-28	0	389.28	9.8	29	PT28	8-12-15-21-22-28	0	395.83	9.1	4
PT9	8-10-12-15-18-26	0	389.05	9.5	31	PT29	8-12-15-21-22-26	0	392.09	9.1	18
PT10	8-10-12-15-18-28	0	392.80	9.5	10	PT30	8-10-15-21-22-28	0	396.02	9.5	2
PT11	4-10-12-15-22-26	0	386.38	9.6	39	PT31	8-10-15-21-22-26	0	392.28	9.5	15
PT12	4-10-12-15-22-28	0	390.12	9.6	26	PT32	4-12-15-22-26-28	0	389.29	9.8	28
PT13	4-8-12-15-22-26	0	388.10	9.6	38	PT33	8-12-15-18-26-28	0	391.97	9.7	22
PT14	4-8-12-15-22-28	0	391.85	9.6	23	PT34	8-12-15-22-26-28	0	391.79	8.9	24
PT15	8-10-12-15-21-26	0	392.63	9.3	11	PT35	8-10-15-22-26-28	0	391.98	9.3	21
PT16	8-10-12-15-21-28	0	396.37	9.3	1	PT36	8-12-15-18-22-26	0	388.52	9.3	35
PT17	8-10-12-21-22-26	0	389.11	9.6	30	PT37	8-12-15-18-22-28	0	392.26	9.3	17
PT18	8-10-12-21-22-28	0	392.85	9.6	9	PT38	8-10-15-18-22-26	0	388.70	9.7	34
PT19	8-10-12-15-22-26	0	388.88	8.7	32	PT39	8-10-15-18-22-28	0	392.45	9.7	14
PT20	8-10-12-15-22-28	0	392.62	8.7	12	PT40	8-10-12-22-26-28	0	388.81	9.4	33

Appendix D ILP Model for Portfolio Generation

		Constraints				
Projects	Decision	Budget	Class1	Class2	Class3	Class4
1	0	1.2	1	0	0	0
2	0	1.5	1	0	0	0
3	0	2	1	0	0	0
4	0	2.5	1	0	0	0
5	0	1	1	0	0	0
6	0	1.5	1	0	0	0
7	0	2	1	0	0	0
8	0	1.6	1	0	0	0
9	0	2.4	0	1	0	0
10	0	1.6	0	1	0	0
11	0	1	0	1	0	0
12	0	1.2	0	1	0	0
13	0	1.7	0	1	0	0
14	0	1.5	0	1	0	0
15	0	1.1	0	1	0	0
16	0	1.3	0	1	0	0
17	0	1	0	0	1	0
18	0	2.2	0	0	1	0
19	0	2.1	0	0	1	0
20	0	1.8	0	0	1	0
21	0	2	0	0	1	0
22	0	1.4	0	0	1	0
23	0	1.4	0	0	1	0
24	0	2.3	0	0	0	1
25	0	2	0	0	0	1
26	0	1.8	0	0	0	1
27	0	1.6	0	0	0	1
28	0	1.8	0	0	0	1
29	0	2.1	0	0	0	1
30	0	2.5	0	0	0	1
	RHS	10	1	1	1	1
	Available	0	0	0	0	0
Objective	0					

	Prtfolio	#	Budget		Prtfolio	#	Budget
PT1	8-12-18-22-26-28	0	10	PT37	4-15-18-22-28	0	9
PT2	8-15-18-22-26-28	0	9.9	PT38	8-15-21-22-26	0	7.9
PT3	8-15-21-22-26-28	0	9.7	PT39	8-15-21-22-28	0	7.9
PT4	8-12-21-22-26-28	0	9.8	PT40	8-15-22-26-28	0	7.7
PT5	4-15-18-26-28	0	9.4	PT41	4-15-18-22-26	0	9
PT6	8-15-18-26-28	0	8.5	PT42	4-15-22-26-28	0	8.6
PT7	8-15-18-22-28	0	8.1	PT43	4-15-21-22-26	0	8.8
PT8	8-15-18-22-26	0	8.1	PT44	4-15-21-22-28	0	8.8
PT9	8-15-18-21-28	0	8.7	PT45	8-10-21-26-28	0	8.8
PT10	4-15-18-21-26	0	9.6	PT46	4-10-18-26-28	0	9.9
PT11	4-15-18-21-28	0	9.6	PT47	4-10-21-26-28	0	9.7
PT12	8-15-18-21-26	0	8.7	PT48	8-10-21-22-28	0	8.4
PT13	8-15-21-26-28	0	8.3	PT49	4-8-10-15-22-26	0	10
PT14	4-15-21-26-28	0	9.2	PT50	4-8-10-15-22-28	0	10
PT15	8-10-12-18-22-26	0	9.8	PT51	8-10-12-22-26-28	0	9.4
PT16	8-10-12-18-22-28	0	9.8	PT52	4-8-10-18-28	0	9.7
PT17	8-10-12-15-18-26	0	9.5	PT53	4-8-10-18-26	0	9.7
PT18	8-10-12-15-18-28	0	9.5	PT54	4-12-18-21-28	0	9.7
PT19	4-10-12-15-22-26	0	9.6	PT55	4-12-18-21-26	0	9.7
PT20	4-10-12-15-22-28	0	9.6	PT56	4-8-10-21-26	0	9.5
PT21	4-8-12-15-22-26	0	9.6	PT57	4-12-18-26-28	0	9.5
PT22	4-8-12-15-22-28	0	9.6	PT58	4-10-12-21-26	0	9.1
PT23	8-10-12-15-21-26	0	9.3	PT59	4-10-12-18-26	0	9.3
PT24	8-10-12-15-21-28	0	9.3	PT60	4-10-18-22-26	0	9.5
PT25	8-10-12-21-22-26	0	9.6	PT61	4-10-18-22-28	0	9.5
PT26	8-10-12-21-22-28	0	9.6	PT62	4-10-15-18-26	0	9.2
PT27	8-10-12-15-22-26	0	8.7	PT63	4-10-15-18-28	0	9.2
PT28	8-10-12-15-22-28	0	8.7	PT64	4-10-15-21-26	0	9
PT29	8-10-12-21-26-28	0	10	PT65	8-10-21-22-26	0	8.4
PT30	4-10-15-21-28	0	9	PT66	8-10-21-22-28	0	8.4
PT31	4-10-15-22-26	0	8.4	PT67	8-10-18-21-26	0	9.2
PT32	4-10-15-22-28	0	8.4	PT68	8-10-18-21-28	0	9.2
PT33	8-10-15-18-26	0	8.3	PT69	8-10-12-21-26	0	8.2
PT34	8-10-15-18-28	0	8.3	PT70	8-10-12-21-26	0	8.2
PT35	8-10-15-21-26	0	8.1	PT71	8-10-15-22-28	0	7.5
PT36	8-10-15-21-28	0	8.1	PT72	8-10-15-22-26	0	7.5

Appendix E Attribute Weighting Methods

A number of attribute weighting procedures based on the judgments of decision makers have been proposed in the Multi-attribute decision literature. The purpose of attribute weighting is to express the importance of each attribute relative to other attributes. The procedures presented in this report differ in term of their accuracy, degree of easiness to use, the degree of easiness of understanding on the part of the decision makers, and the theoretical foundation. At the end of this appendix, the methods are compared according to different criteria.

1. Ranking Methods

Arranging attributes in rank order is the simplest method for assessing the importance of weights; that is, every attribute under consideration is ranked in the order of the decision maker's preference. Either straight ranking (the most important = 1, second important = 2, etc.), inverse ranking (the least important = 1, next least important = 2, etc.), or using the dominance count method (See Table C-1). Once the ranking is established for a set of attributes, several procedures for generating numerical weights from rank-order information are available. The focus in this report is on the most popular approaches: rank sum, rank reciprocal, rank exponent, and rank order centroid.

Table C-1: Matrix of Attributes Showing Dominance Count

Attributes	***A***	***B***	***C***	***D***	***E***	***Count***	***Rank***
A	1	0	0	1	1	3	**3**
B	1	1	0	1	1	4	**2**
C	1	1	1	1	1	5	**1**
D	0	0	0	1	1	2	**4**
E	0	0	0	0	1	1	**5**

a) Rank Sum Weights (RS): In the RS procedure the weights, w_i, are the individual ranks normalised by dividing by the sum of the ranks. The formula producing the weights, in its simplest form can be written as:

$$w_i = 2(n + 1 - r_i) / n(n + 1), \quad i = 1, 2, \ldots, n$$

where the ith rank is denoted by r_i.

b) Rank Reciprocal Weights (RR): RR weights are derived from the normalised reciprocals of an attribute's rank by dividing each attribute by the sum of the reciprocals. The formula used to calculate the weights is:

$$w_i = (1/\, i) / \sum(1/\, j), \quad i \text{ (rank)} = 1, 2, \ldots, n$$
$$j \text{ (attributes)} = 1, 2, \ldots, n$$

c) Rank Exponent Weights (RE): RE requires an additional piece of information. The decision maker is required to specify the weight of the most important attribute on a 0-1 scale. This weight is entered into the formula:

$$w_i = (n - r_i + 1)^p / \sum (n - r_i + 1)^p, \quad i, j = 1, 2, \ldots, n$$

which may then be solved for *p* by an iterative procedure. Once *p* is determined, weights for the remaining attributes can be calculated. This approach is has some interesting properties. For $p = 0$, the formula assigns equal weights to the evaluation attributes. For $p = 1$, the method results in rank sum weights. As *p* increases, normalised weights get steeper and steeper.

d) Rank Order Centroid Weights (ROC): The basic idea of ROC is easy to understand. The formula is:

$$w_i = 1/n \sum_{j=i}^{n} 1/j, \qquad i = 1, 2, \ldots, n$$

Edwards and Barron (1994) report the results of extensive simulations which suggested that ROC and 'true' weights will agree on best alternative, which has the highest aggregate benefits, 75-87% of cases. When ROC weights did not pick the best option, the one they do pick is not too bad. Decision makers can use ready-made tables to find attribute weights.

1.1 Example

Assume that we have 5 attributes already ranked and needs to be weighted. The following table shows the calculation of the four ranking methods illustrated before:

Attribute	***Rank***	***RS***	***RR***	***RE***	***ROC***
A	4	0.133	0.109	0.073	0.090
B	2	0.267	0.219	0.291	0.257
C	5	0.067	0.088	0.018	0.040
D	1	0.333	0.438	0.454	0.457
E	3	0.200	0.146	0.164	0.157
	Total	1.000	1.000	1.000	1.000

2. Rating Methods

The rating methods require the decision maker to estimate weights on the basis of a predetermined scale; for example, a scale of 0 to 100 can be used. The most popular approaches are: direct rating and point allocation.

a) Direct Rating Method: The direct rating method, discussed by von Winterfeldt and Edwards (1986), uses 'direct numerical ratio judgments of relative attribute importance'. There are a number of ways of implementing this method.

In one approach the decision maker assigns in arbitrary importance of (say) 10 to the least important attribute. Then the next most important attribute is identified and a decision is made about how much more important it is than the previous attribute and so on. The raw weights are then normalised using the formula:

$$w_i = w_i^* / \sum_{i=1}^{n} w_i^*, \quad i = 1, 2, \ldots, n$$

where w_i^* is the ith raw weight and w_i is the ith normalise weight.

One way to obtain weights is by using swing weights. These are derived by asking the decision maker to compare a change (or swing) from the least-preferred to the most-preferred value on one attribute to a similar change in another attribute within the same group. The alternative approach involves arbitrarily assigning a raw weight of 100 to the attribute where switching from the worst to the best option on that attribute is most desirable. The desirability of making similar worst-to-best switches on each of the other attributes is then assessed relative to this, yielding raw weights on a scale with a maximum of 100. Finally the weights are normalised to sum either 1 or 100.

2.1 Example

Assume that there are four attributes that have been identified before: Probability of technical success, Budget, Competence and Time. The decision maker is asked to imagine a hypothetical project with all these attributes at their least-preferred levels, that is, a project which has the least probability of technical success, the least probability of budget, the least probability of time, and the worst level of competence. Then he is asked; if just one of these attributes could be moved to its best level, which would he choose? The decision maker may select ‘probability of technical success’. After this change has been made, he is asked which attribute he would next choose to move to its best level, and so on until all the attributes have been ranked. Assume that the decision maker's rankings are:

(1) Probability of technical success

(2) Budget

(3) Competence

(4) Time

We can now give ‘probability of technical success’ a weight of 100. The other weights are assessed as follows. The decision maker is asked to compare a swing from the least project in budget to the most one in budget, with a swing from the project with smallest probability of technical success to the largest one. He may decide that the swing in 'budget' is 80% as important as the swing in 'probability of technical success', so budget is given a weight of 80. Similarly, a swing from the worst 'competence' to the best is considered to be 60% as important as a swing from the smallest to the largest probability of technical success, so 'competence' is assigned a weight of 60. The same is done with ‘time’ and the weight assigned can be 20. Figure C-1 illustrates the results.

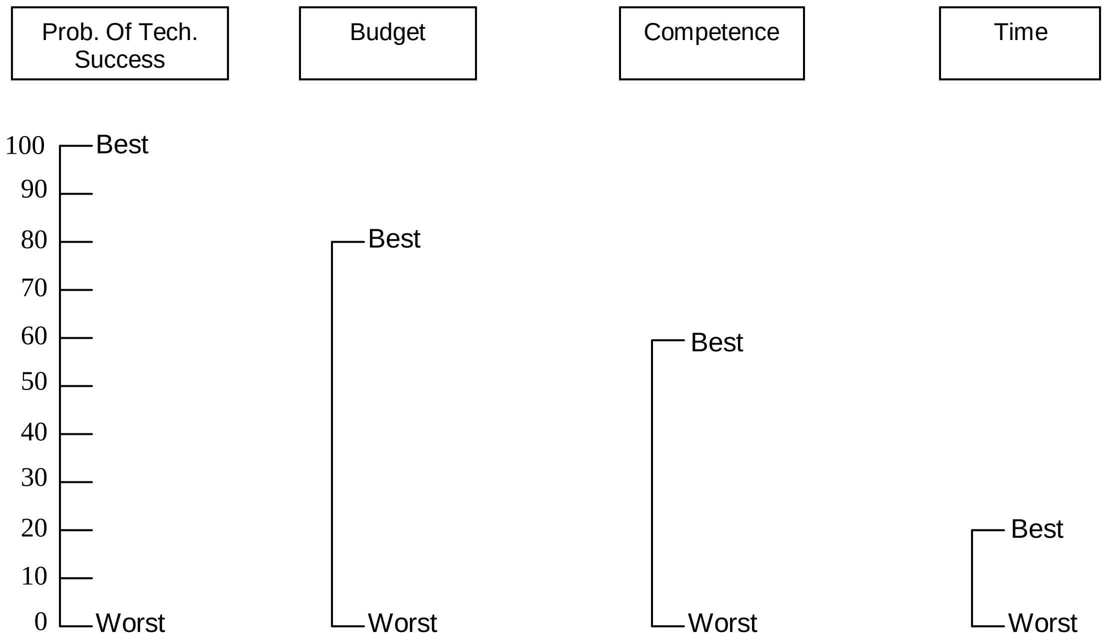

Figure C-1: Swing Weights for the Example

As shown below, the four weights obtained sum to 260, and it is better to 'normalize' them so that they add up to 100 (this will make later stages of the analysis easier to understand). Normalization is achieved by simply dividing each weight by the sum of the weights (260) and multiplying by 100.

Attribute	Original weights	Normalised weights (to nearest whole number)
Probability of technical success	100	38
Budget	80	31
Competence	60	23
Time	20	8
	260	100

b) Point Allocation Method: This method requires the decision maker to allocate 100 points across the attributes of interest. Specifically, it is based on allocating points ranging from 0 to 100, where 0 indicates that the attribute can be ignored and 100 represents the situation where only one attribute need be considered in a given decision situation. The more points an attribute receives, the greater its relevant importance.

2.2 Example

Consider a plant allocation problem involving three attributes. The decision maker might assign a weight of 30 points to accessibility to the transportation system, 50 points to the cost of establishing the plant, and 20 points to the availability of water. Consequently, weights of 0.3, 0.5, and 0.2 can be assigned to the three attributes, respectively.

An alternative to the point allocation method is a *ratio estimation procedure* (Easton 1973), a modification of the point allocation method. It starts by one of the ranking methods. A score of 100 is assigned to the most important attribute. Proportionately smaller weights are then given to attributes lower in the order. The procedure is continued until a score is assigned to the least important attribute. Then the score assigned to the least important attribute is taken as an anchor point for calculating the ratios. Specifically, the score for the least important attribute is divided by the score for each attribute; that is, the ratio is equal to w_i / w^*, where w^* is the lowest score and w_i is the score for the ith attribute. This ratio expresses the relative desirability of a change from the worst level of that attribute to its best value, in comparison with a change from the worst level to the best level of the first attribute. This procedure is repeated for the next most important attribute until weights are assigned to all attributes. Finally, the weights are normalised by dividing each weight by the total.

2.3 Example

Consider the table used in the ranking methods example. Weights using ratio estimation procedure are shown in the following table:

Attribute	***Straight***	***Ratio***	***Original***	***Normalised***
A	4	50	5.0	0.168
B	2	75	7.5	0.252
C	5	10	1.0	0.034
D	1	100	10.0	0.335
E	3	63	6.3	0.211
		Total	29.8	1.000

3. Pairwise Comparison Method

The pairwise comparison method was developed by Saaty (1980) in the context of the *analytic hierarchy process* (AHP). This method involves pairwise comparisons to create a ratio matrix. It takes as an input the pairwise comparisons and produces the relative weights as output. AHP uses a fundamental scale of absolute values for representing the strength of judgments (See Table C-2). The method can be best be described by an example.

3.1 Example

Take the example of a job seeker (Winston 1994) who needs to choose between job offers. The job seeker (call her Jane) might choose between the offers by determining how well each offer meets the following four objectives:

Objective 1: High starting salary (SAL)

Objective 2: Quality of life in city where job is located (QL)

Objective 3: Interest in work (IW)

Objective 4: Job location near family and relatives (NF)

The difficulty of choosing between offers is the importance of the multiple objectives to the decision maker (Jane). For example, one job offer may give the nearest location to family and relatives, but the same job offer may score poorly in the other three objectives. Another offer may provide a higher starting salary and higher quality of life in city where job is located, but it is so far from family and relatives.

For the ith objective (i.e. i = 1, 2, 3, 4), the AHP generates a weight w_i for each objective using the following method:

- Start by writing down an n X n matrix A (known as the pairwise comparison matrix). The entry row i and column j of A (call it a_{ij}) indicates how much important objective i is than objective j. 'importance' is to be measured on an integer-valued 1 – 9 scale (the fundamental scale), where a_{ii} = 1. If, for example, a_{13} = 3, objective 1 is weakly more important than objective 3 and a_{31} = 1/3.

- Suppose that Jane identified the following pairwise comparison matrix for her four objectives:

$$A = \begin{array}{c} \\ SAL \\ QL \\ IW \\ NF \end{array} \begin{array}{c} \begin{array}{cccc} SAL & QL & IW & NF \end{array} \\ \begin{pmatrix} 1 & 5 & 2 & 4 \\ 1/5 & 1 & 1/2 & 1/2 \\ 1/2 & 2 & 1 & 2 \\ 1/4 & 2 & 1/2 & 1 \end{pmatrix} \end{array}$$

- Unfortunately, some of Jane's pairwise comparisons are inconsistent. Jane feels SAL is twice as important as IW (a_{13} = 2). Since a_{32} = 2, Jane also believes that IW is twice as important as QL. Consistency of preferences would imply that Jane should feel that SAL is 2*2 = 4 times as important as QL. Since a_{12} = 5, Jane believes that SAL is 5 times as important as QL which shows that Jane's comparisons have a slight inconsistency. Slight inconsistencies are common and do not cause serious difficulties.

- For each of *A*'s columns, divide each entry in column *i* of *A* by the sum of the entries in column *i*. This will yield to a new matrix in which the sum of the entries in each column is 1 and we call it normalised *A*:

$$\text{Norm. } A = \begin{pmatrix} .5128 & .5000 & .5000 & .5333 \\ .1026 & .1000 & .1250 & .0667 \\ .2564 & .2000 & .2500 & .2667 \\ .1282 & .2000 & .1250 & .1333 \end{pmatrix}$$

- Estimate w_i as the average of the entries in row *i* of Norm. *A* as follows:

$$w_1 = \frac{.5128 + .5000 + .5000 + .5333}{4} = 0.5115$$

$$w_2 = \frac{.1026 + .1000 + .1250 + .0667}{4} = 0.0986$$

$$w_3 = \frac{.2564 + .2000 + .2500 + .2667}{4} = 0.2433$$

$$w_4 = \frac{.1282 + .2000 + .1250 + .1333}{4} = 0.1466$$

Now, a four-step procedure is used to check for the consistency of the decision maker's comparisons:

5. Compute *Aw* as follows:

$$\text{Norm. } Aw = \begin{bmatrix} .5128 & .5000 & .5000 & .5333 \\ .1026 & .1000 & .1250 & .0667 \\ .2564 & .2000 & .2500 & .2667 \\ .1282 & .2000 & .1250 & .1333 \end{bmatrix} \begin{bmatrix} .5115 \\ .0986 \\ .2433 \\ .1466 \end{bmatrix} = \begin{bmatrix} 2.0775 \\ 0.3959 \\ 0.9894 \\ 0.5933 \end{bmatrix}$$

6. Compute

$$1/n \sum_{i=1}^{i=n} \frac{i\text{th entry in } Aw}{i\text{th entry in } w}$$

$$= (1/4)\left\{\frac{2.0775}{.5115} + \frac{.3959}{.0986} + \frac{.9894}{.2433} + \frac{.5933}{.1466}\right\}$$

$$= 4.05$$

7. Compute the consistency index *CI* as follows:

$$CI = \frac{(\text{Result from step 2}) - n}{n - 1} = \frac{4.05 - 4}{3} = 0.017$$

8. Compare *CI* to the random index (*RI*), which is the consistency index of a randomly generated pairwise comparison matrix, in Table C-3. It has been shown that if (*CI*/*RI*) < 0.10, the degree of consistency is satisfactory, but if (*CI*/*RI*) > 0.10, serious inconsistency may exist and the AHP may not yield to meaningful results. For the example, (*CI*/*RI*) = (0.017 / 0.9) = 0.019 < 0.10.

Table C-3: Values of the Random Index (RI) (Source: Winston 1994)

n	RI
2	0
3	0.58
4	0.9
5	1.12
6	1.24
7	1.32
8	1.41
9	1.45
10	1.51

4. Comparing the Methods

Table C-4 summarises the major features of the three methods for assessing attribute weights modified from Malczewski's (1999) comparison table.

Table C-4: Comparison of Methods for Assessing Attribute Weights

	Method		
Feature	***Ranking***	***Rating***	***Pairwise***
No. of Judgments	n	n	$n(n-1)/2$
Response Scale	Ordinal	Interval	Ratio
Hierarchical	Possible	Possible	Yes
Underlying Theory	None	None	Statistics/Heuristic
Ease of Use	Very Easy	Very Easy	Easy
Trustworthiness	Low	High	High
Precision	Approximations	Quite Precise	Quite Precise
Software	Spreadsheets	Spreadsheets	Expert Choice

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