R&D PROJECT PRIORITIZATION USING ANALYTICAL HIERARCHY PROCESS

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Abstract

Research refers to the activities that aim to either discover or develop scientific techniques that enable us to improve the living standards of mankind. In a financially constricted economy, the goal of funding relevant R&D projects becomes a vital consideration for any funding organization. The shortlisted project has to satisfy certain parameters that fulfill the organization's vision and objectives. The aim of this thesis is to investigate the criteria for ranking research projects, and eventually, to propose a hierarchical framework for projects evaluations.

Analytic Hierarchy Process (AHP) is a decision making approach wherein the available alternatives are ranked using a hierarchy of criteria. The method of pairwise comparisons is used to gauge relative importance of these criteria and alternatives. The main advantage of using AHP is to combine both qualitative and quantitative judgments according to their relative weights of importance.

To begin with, a comprehensive hierarchy of criteria was developed for short-listing research projects, based on the related literature survey. This hierarchy was then converted into a survey form to ask experts about each criterion and it importance for selecting research project. Then, a nation-wide survey was conducted to obtain feedback for this hierarchy from academia and R&D organizations. The objective of this survey was two-fold; first, (1) to determine the relative weights of all the criteria whilst selecting the research projects, and then (2) to trim down the criteria of low-importance by using data analysis techniques. The second objective is of high significance due to the fact that too many criteria may lead to an information overload for the decision maker. From the data analysis, a final abridged hierarchy was proposed that was then tested against empirical data drawn from R&D projects sponsored by a local defense organization.

DEDICATION

To,

My Nephew & Niece
Muhammad Shaheer Kamran & Hamnah Kamran

Without their presence, life would have been dull and I would not have been able to complete my research.

Waqas Idrees

Acknowledgements

Acknowledgments are not formal but a genuine expression of gratitude. All praises and thanks are attributed to “**The Almighty ALLAH”,** the compassionate; the merciful, the source of all knowledge and wisdom, who gave me enough strength and knowledge to understand things better and enabled me to complete my research work. An incredible respect for our beloved **Holy Prophet Muhammad (Peace be upon Him**), the symbol of knowledge and savior of mankind. I would like to express my sincere gratitude to **Professor Dr. Akhtar Nawaz Malik** and **Dr. Sajid Siraj** for their kind supervision. Without their generous encouragement, inspiring guidance and remarkable suggestions, I would not have been able to complete this dissertation.

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CHAPTER 01
INTRODUCTION

Research refers to the activities that aim to either discover or develop scientific techniques that enable us to improve the living standards of mankind. Due to the involvement of uncertainty in their outcome, research-based projects generally do not attract the business community in developing nations. In such a situation, the government sector has a serious role in promoting such activities that may lead to a break-through and, in turn, improving the socio-economic standing of the nation. However, due to economic hardship, the developing countries have to invest more in the physiological needs of public and, therefore, research and development is considered to be a low-priority activity. For example, in case of Pakistan, the research and development expenditure is only 0.7% of the total GDP, as reported in 2010 (World Bank Indicators)[1].

In such a financially-constraint situation, prioritizing the available research projects becomes a hard task and these types of projects are generally selected on weak heuristics. When lacking a proper mechanism to grade candidate projects, the chances of inducing judgmental biases are increased manifold. In such cases, it is the right of citizens to know how their government is handling their tax money. It has been highlighted that this idea is not something new; even Aristotle was advocating this in 350 BC in his statements like "let all money be issued openly in front of the whole city..." (Shah, 2007)[2]

In our daily settings, we are faced with multiple conflicting criteria that warrant evaluation for making decisions. Where some criteria are objective in nature like cost, labor, equipment other aspects are more subjective like safety, comfort and hence difficult to quantify. One of the most common criteria that is used in the decision making process is cost. However, at times there is a conflicting criterion against that of cost which is quality. People usually require the best quality at the least cost. This is where decision making process comes in. Consider the following examples that warrant the need for multi-criteria decision making.

1. While thinking of purchasing a car, the most common criteria that we would consider are cost, comfort, safety, and fuel economy. However, it is illogical to think of buying the cheapest car to be the most comfortable and the safest.
2. Consider another example of Portfolio management. When it comes to portfolio management, managers strive for high returns against reduced risks. Stocks having a higher beta or which are riskier have the possibility of bringing high returns.

[1] http://www.tradingeconomics.com/pakistan/high-technology-exports-us-dollar-wb-data.html
[2] https://openknowledge.worldbank.org/handle/10986/6732. Shah, Anwar. 2007. Performance Accountability and Combating Corruption. Washington, DC: World Bank.

3. A service industry focuses on customer satisfaction. The cost of providing a service and providing it at a desired level is two conflicting criterion that would be required by a manager to make effective decisions.

Multiple-criteria decision-making (MCDM), a sub-discipline of operations research explicitly considers multiple criteria in a decision-making environment. These decisions are always made as a result of a structured process that requires the decision maker to analyze the situation, formulate an action plan, discover and evaluate the alternatives to reach a final decision (fig 01).

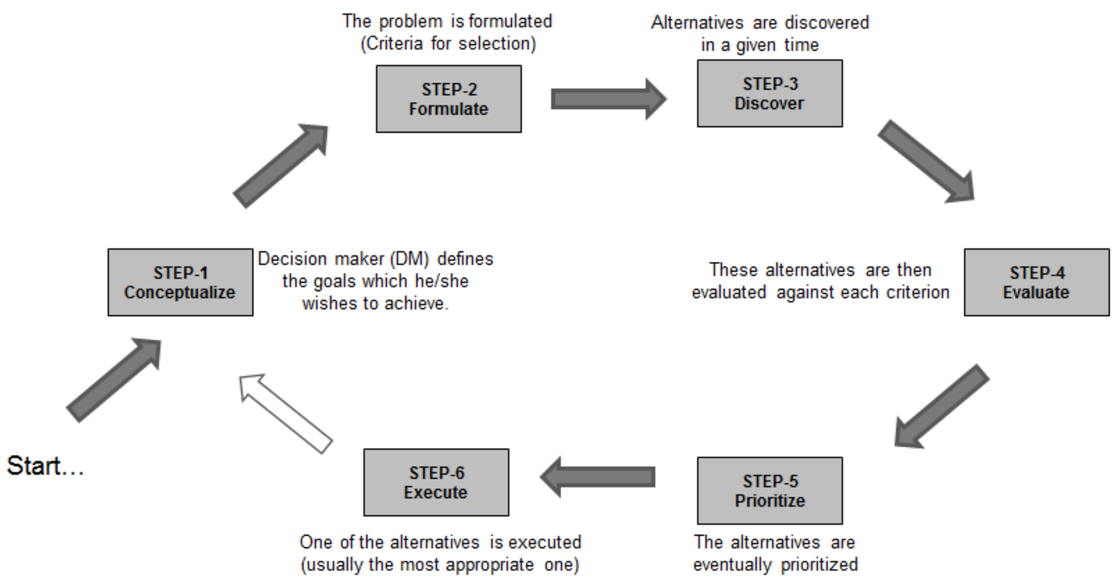


Figure 01-MCDM Process

On a daily basis, we usually weigh multiple criteria subliminally and are usually comfortable with the consequences of our decisions that are made founded on intuition alone. However, it becomes imperative to appropriately structure the problem and clearly assess multiple criteria when stakes are high like in R&D projects or engineering decisions. As an example how MCDM can used in a complex consider the following case:

The decision of implementing alternate energy sources to produce power in Pakistan may seem like an effective decision that should be readily implemented however; there are a number of criteria to consider before reaching a decision. Some of these criteria include:

- *Choice of energy source to use:* What source of energy would be the most effective in generating the maximum power to supply the desired load to a given area? Choice of systems includes wind, solar, nuclear, tidal, etc.
- *Choice of area to implement the power system:* Where should the power system be built? Depending on the nature of the energy source, the power plant can be near a coastal region or a mountainous area.

- *Economic viability:* how economically viable is the power system going to be? The total costs of building the plant along with its regular maintenance costs versus the generated output power is a main concern when deciding on a power system.
- *Environmental impact:* How eco-friendly is the power system going to be? What is the carbon footprint of it? What is the land footprint associated with the power plant?
- *Stakeholders' happiness:* In addition to various technical criteria, decision makers have to consider impact of their decisions on multiple parties that are affected by the consequences of these decisions.

The field of decision making has seen an immense growth since the advent of MCDM in the early 1960. There have been a variety of approaches that are used by decision makers, many of which are implemented using specialized decision-making software. Some of these methods are:

- Weighted Sum Model (WSM)
- Weighted Product Model (WPM)
- Analytical Hierarchy Process (AHP)
- Analytical Network Process (ANP)
- PROMETHEE
- ELECTRE
- TOPSIS

Each of these methods provides the decision maker with a solution based on a distinct mathematical process. The most widely used of these methods is however the Analytical Hierarchy Process (AHP). AHP is a structured procedure for consolidating and investigating complex decisions with the help of mathematics and psychology. It was developed by Thomas L. Saaty in 1970 and is the most extensively studied and continually refined area of research in MCDM.

The technique of Analytical Hierarchy Process has particular application in group decision making. It is extensively used around the world in a plethora of decision situations; from government to business, from industry to healthcare, from research to education.

The basic approach of AHP is that it does not generate a "correct" decision. Rather, AHP assists the decision maker in reaching a decision that best suits their goal and their understanding of the problem. It provides an all-inclusive coherent framework for organizing any decision problem, for computing its criteria, for linking those criteria to the general desired goals, and for assessing alternate results. AHP is based on the following three principles:

1. Decomposition
2. Comparative judgments

3. Hierarchic composition

The first step in AH is the decomposition of the problem into a hierarchical structure. Decision Makers split the decision problem into a process flow of easily grasped sub-problems. These sub problems are then analyzed independently. Each of the the element in the hierarchy relates to any number of aspect of the main decision problem; tangible or intangible, cautiously measured or coarsely assessed; anything that applies to the decision at hand.

Once the hierarchy is built, the decision makers systematically evaluate its various elements by comparing them to one another two at a time, with respect to their impact on an element above them in the hierarchy. When the comparisons are made, sound and cogent date can be used by the decision makers to make a decision but may a times decisin makers also use their subjective judgments pertaining to the meaning of a criterion and its relative importance. The core essence of AHP is that is not only depends on objective data and factual information but also the underlying human judgments.

These judgments are then converted to numerical values in a matrix which is that evaluated over the entire decision problem. Based on geometric mean calculations, a weight is calculated for each criterion in the decision hierarchy. This results in the otherwise diverse and incommensurable criteria to be associated to one another in a coherent and reliable way. This capability differentiates Analytical Hierarchy Process from various other decision making procedures.

The last step in this analytical hierarchy process calculation is that the mathematical precedence is evaluated for each alternative. This precedence represents the possible order of which alternative should be implemented based on the decision makers choices. A typical AHP network based on the above explained three principles can be drawn as follows:

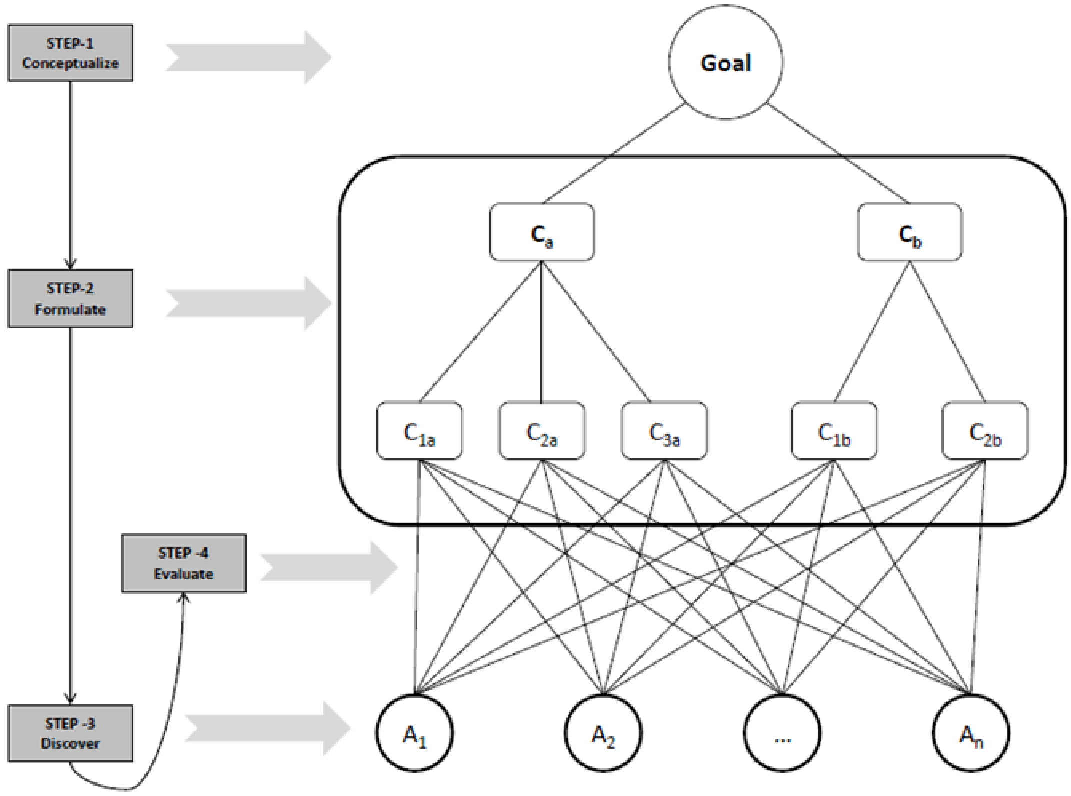


Figure 02: AHP Process

The focus of this thesis is to investigate the process behind decision making as it relates to research and development both from an academic and industrial perspective. This includes proposing a hierarchy for academia and organizations to facilitate them in funding of R&D projects using Analytical Hierarchy Process (AHP). The thesis identifies key criteria that effectively structure complex problems that arise during a decision making process and then considers these multiple-criteria to develop an informed and objective decision free from the decision maker's bias. The thesis develops a case study from a leading R&D defense organization (whose name has been hidden due to the sensitive nature of the industry that it operates in). A thesis takes a list of possible R&D projects from the organization. These projects are meted against a set of criteria and an objective decision is generated for the decision maker based on MCDM.

CHAPTER 02
BACKGROUND

Some of the more significant events that have happened and tendencies that have developed in MCDM over the years can be traced back to the literature that is present. A few highlights highlights that have taken place in MCDM are:

- The gobal usage of the Internet has increased manifold and calculating power has seen an increased growth, as suggested by Moore's Law. These days, users have the access to various web-based softwares that assist users and consumers in the application of MCDM approaches.
- Substantial growth in applications of MCDM has occurred. See the website for expert choice (http://www.expertchoice.com), the recent reviews of applications of decision analysis by Keefer et al. (2004) and Hämäläinen (2004), the survey of applications of multiobjective evolutionary algorithms by Coello and Lamont (2004), and the results of our bibliometric analysis of published papers.
- The importance of MCDM has been recognized in professional management journals. See the article about Thomas Saaty in *Fortune* (1999) and the article on "even swaps" as a rational way of making trade-offs in the *Harvard Business Review* (Hammond et al. 1998). The importance of behavioral aspects of decision making has grown, and this was recognized by the award of the 2002 Nobel Prize in Economics to Daniel Kahneman. It is widely believed that his late colleague Amos Tversky would have shared this honor.
- Data envelopment analysis (DEA) has grown in importance and its relationship with multiple objective linear programming (MOLP) has been explored.
- Evolutionary multiobjective optimization (EMO) has emerged as a new field with strong ties to MCDM.
- Heuristics in MCDM have become more important.
- MCDM has begun to penetrate many new areas of research and applications. Such areas are DEA, negotiation science, e-Commerce, finance, and engineering. MCDM has several neighboring disciplines, such as decision analysis, mathematical programming, DEA, and negotiation analysis. MCDM concepts and methods are being developed and used in these neighboring disciplines, providing healthy cross-fertilization, but making it difficult to draw sharp disciplinary boundaries. Another interesting trend is that MCDM concepts and techniques are increasingly being applied in diverse engineering fields and other research and development projects.

Research and Developmen (R&D) projects selection is an administrative decision making assignment that is usually found in establishments like universities, government funded and technology-intensive companies, Research houses and organizations[1]. The past five decades have seen a plethora of decision making prototypes and various approaches have been developed for the support of the R&D project selection process [2], [3]. There have been numerous reviews on R&D portfolio selection in literature [4]–[14]. According to Henriksen and Traynor [4], present models and methods of decision making can be categorized as follows:

- Unstructured peer review.
- Scoring.
- Mathematical programming, including integer programming (IP), linear programming (LP), nonlinear programming (NLP), goal programming (GP), and dynamic programming (DP).
- Economic models, such as internal rate of return (IRR), net present value (NPV), return on investment (ROI), cost benefit analysis, and option pricing theory.
- Decision analysis, including multiattribute utility theory (MAUT), decision trees, risk analysis, and the analytic hierarchy process (AHP)
- Interactive methods, such as Delphi, sort, behavioral decision aids (BDA), and decentralized hierarchical modeling (DHM)
- Artificial intelligence (AI), including expert systems and fuzzy sets.
- Portfolio optimization.

According to (Balachandra 1997), factors for the success in research and development projects can be categorized as follows.

- Market
- Technology
- Environment
- Organization

Decision support systems (DSSs) have been proposed and developed to improve the use of decision making models in real life, integrating these models with computer-based simulation tools[15]–[19]. Nonetheless, the task of R&D project prioritization is a chaleging task replete with numerous challenges. Firstly, long-term success of any industry is usually evaluated through the efficiency of its project selection process [20]. Therefore, an organization needs to be extra vigilant in assessing and selecting the R&D projects. Secondly, the resources available to any company are usually in limited supply as compared to the number of prospective projects, and it is obligatory on the organization to actively direct research undertakings in a direction that is consistent with its mission and R&D strategy [4]. So, evaluating the possible worth of a suggested R&D project is a serious challenge faced by the decision makers (Executives, CFOs, CEOs, Program Directors, etc.) who have the responsibility to apportion resources to a surfeit of applicant projects. External reviewers who may also be called as the experts in this case are usually asked to partake in the project selection process. One of their most important assigned task is:

- Evaluation and commenting on the applicant projects as per the decision makers requirements. For example, government funding agencies receive numerous research proposals every year that are handed in by academics from universities or research institutes. These proposals are referred to specialists for peer review. Experts generally assess the proposals as per the directions and criteria defined by the funding agency. The evaluation outcomes are then ranked based on the collection techniques. Cook *et al*. [21] believes that peer review is the fundamental component of the complete decision making process as the final choice of R&Dproject depends on the decisions of assessors.

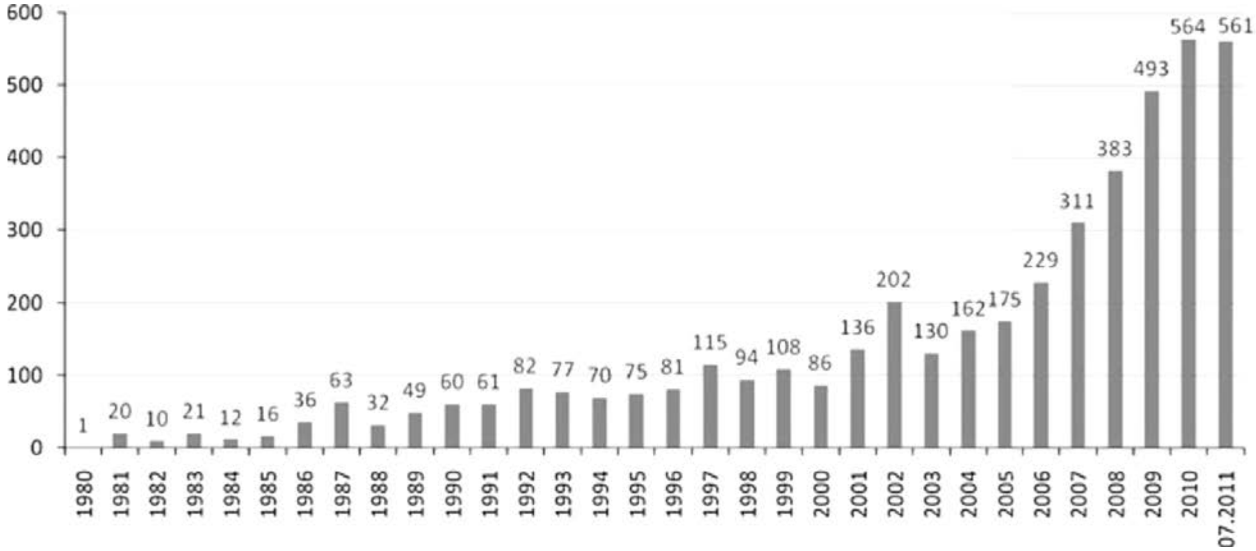
The success of R&D project selection is often determined by the effectiveness of expert selection since experts' opinions have great influence on the outcome of the R&D project selection. Experts with high level of expertise can provide more professional opinions on the R&D projects. Therefore, it is very important to evaluate the experts and assign the right experts to the R&D project selection tasks. Unfortunately, to our knowledge, there is little or no literature on the research of expert evaluation for R&D project selection. Jauch and Glueck (1975) stated that simple count of publications, modified by the quality index of journals, is the best measure of research performance. This study can provide us with some illumination although it is too simple to be used to evaluate experts for R&D project selection. Determination of the expertise level of any reviewer in a specific area is not an easy task. First of all, evaluation of experts deals with different kinds and formats of information. The evaluation information of experts could be either subjective or objective information. For example, the number of publications belongs to objective information while colleagues' opinions on an expert's expertise level are subjective information. At the same time, the evaluation information could be either qualitative or quantitative.

A number of research and developement selection models and methods have been proposed in practitioner and academic literature. Reviews of many of these can be found in Baker and Freeland, Martino, and Henriksen and Traynor. There are numerous studies on research and development (R&D)projects selection. These studies have been developed over the past three decades by leading experts in the field of portfolio management [7–9]. Perrone used an MCDM model based on the fuzzy approach in order to estimate progressive industrial systems. Coffin and Taylor [11] published R&D project selection using fuzzy MCDM. This was followed by a few groundbreaking revisions, e.g., Chan et al. [12] and Hsu et al. [6], articulated their abstract structures based on fuzzy multiple criteria method to analyze technology project selection. Included in the articles reviewed in their papers are those that utilize criteria and methods such as NPV, scoring models, mathematical programming models, and multiattribute approaches. Even with the number of proposed models, the R&D selection problem remains problematic and few models have gained wide acceptance. Liberatore and Titus conducted an empirical study on the use of quantitative techniques for R&D project management. They found that most R&D organizations use one or more traditional financial methods for determining project returns, often in conjunction with other methods. Mathematical programming techniques such as linear and integer programming are not commonly used in industry, primarily because of the diversity of project types, resources, and criteria used. They also found that many managers do not believe that the available methods for project selection improve the quality of their decisions. These findings are supported by other researchers (see, for instance, [1], [5], [7], [9], [16],[19],[21]-[26]). Among the weaknesses identified by Baker and Freeland are:

- Insufficient multiple criteria.

- Insufficient action towards project correlation w.r.t value impact and resource usage.
- Inefficient handling of risk and ambiguity.
- Failure to identify and deal with nonmonetary characteristics;
- Observations that are harbored by the R&D managers are unnecessarily difficult to comprehend and implement.

These along with many other drawbacks call for the need of continuous research into



varying models that address the shortcomings mentioned above. Analytical Hierarchy Process (AHP) and Analytic Network Processes (ANP) are only two of the many methods that target many of the aove cited flaws. Analytic Hierarchy Process (AHP) has attracted growing responsiveness since its institution by Saaty in 1980.

The figure highlights the number of papers per year related to the query "analytic hierarchy process" in the Science Direct Database. AHP has experienced a multitude of applications in numerous different areas such as education, engineering management, manufacturing, and marketing to mention just a few (the overviews by Vaidya and Kumar 2006; Ho 2008; Ho et al 2010). AHP can be combined with (and compared to) other methods where multicriteria decision-making activities are performed and weights or part worth utilities for salient criteria have to be determined. From a marketing point of view, e.g., preference analysis for market share predictions, product development tasks, project portfolio evaluations, quality function deployment, and SWOT (strengths, weaknesses, opportunities, threats) analysis can be mentioned as examples for multiattribute preference measurements in which AHP techniques can be applied (Netzer et al. 2008; Parkvet al. 2008; Meissner et al. 2010; Scholz et al. 2010). One reason for the popularity of AHP is probably the simple description of the approach and the ease of data collection within a judgment process via paired comparisons. However, the limited capabilities of the judging persons lead to inconsistencies with respect to constraints that have to be fulfilled in the AHP approach in order to be able to derive acceptable weights for the criteria used as ingredients for the overall objective function. As a consequence the matrix of paired comparisons reported by a judging person (abbreviated as the reported matrix) is in most cases different from the consistent, "true" matrix which would describe the person's real opinion about the decision situation (assuming that a "true" interior valuation of the judging person with respect to the underlying evaluation task exists) which by the simplified judgment process has been broken down into many paired comparisons. This problem is well known and has led to quite a number of discussions concerning consistency improvement techniques (Harker 1987; Dadkhah and Zahedi 1993; Zeshui and Cuiping 1999; Saaty 2003; Ishizaka and Lusti 2004; Lia and Ma 2007; Cao et al. 2010; Lin et al. 2008; Bozoki et al. 2010) by which the inconsistent reported matrix is adjusted (abbreviated as the adjusted matrix) to an acceptable level of inconsistency.

At the end of the chapter, it is important to see that many countries around the world have a developed ranking system for R&D projects. In EU, a DM ranks any project against the following criteria:

- *S/T QUALITY:* Judge the technical attributes of the project:
  a. Is it of sound Sound concept?What is the quality of the objectives?
  b. Is it progressive as compared to the current technology?
  c. What is the quality of the procedure and the accompanying work plan;
  d. How original and novel is it?
- *IMPLEMENTATION:* Judge the quality and efficacy of the execution and supervision:
  a. Is the management appropriately assigned for the projects execution?
  b. What is the level of expertise of the people participating in the project execution?
  c. what is the quality of the association?
  d. Is the organization adquately equiped with the necessary resources required for the project completion?
  e. What are short-term and long-term risks associated with the project?
- *IMPACT:* Judge the possible impact through the expansion, distribution and utilization of project outcomes:
  a. How will the project impact the community?
  b. How is this project important for the community and the technological advancement in the respective field?
  c. How has the intellectual property been apropriated?

CHAPTER THREE
METHODOLOGY

This chapter develops the progression of the thesis from abstraction to conceptualization. In order to help the reader fully understand the thesis, the methodology has been explained with the help of the following flow diagram that highlights each milestone encountered along the course of the thesis.

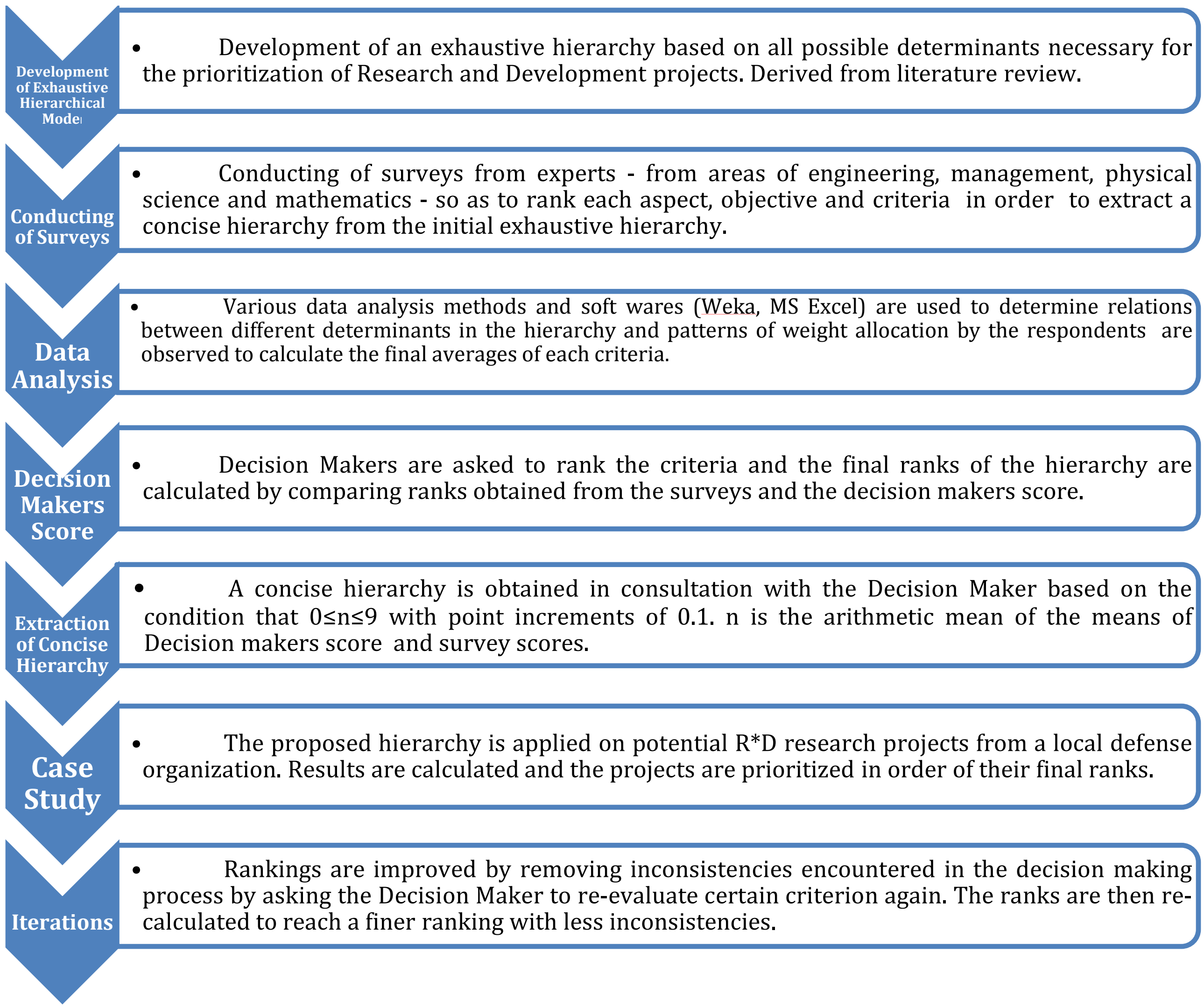


Figure 03- Process Flow Diagram of the Thesis

3.1 DEVELOPMENT OF AN EXHAUSTIVE HIERARCHICAL MODEL

The goal of funding relevant R&D projects from a plethora of available projects is a daunting task for any funding organization. The first step in their selection is the development of a hierarchy where the shortlisted project satisfies certain parameters that fulfill the organizations vision and objectives. A detailed literature survey followed by a firsthand experience in R&D research has led to a thorough set of over forty determinants in order to select the best possible project. These determinants labeled aspects, objectives and criteria have been extracted from various sources: journals [1-10] and interviews with academicians and researchers. Since the decision making process is an extensive practice eliciting both objective and subjective decisions on part of the decision maker, an exhaustive hierarchy has been proposed in the first step of the thesis. The reason for developing an exhaustive hierarchy is twofold:

I. Since each aspect, objective and criteria targets a specific part in the project selection, it makes it easier for the decision maker to weigh candidate projects against a specific attribute hence eliminating ambiguity and decision makers' bias (Status-Quo trap) [13].
II. Since the primary objective of this thesis is to propose a model of R&D project selection for Pakistan, all possible criteria have been added to this hierarchy so that on simplifying it for local setups, a wholesome hierarchy meeting local needs is attained.

All candidate R&D projects must be evaluated against each criterion shown in the decision hierarchy (table 01). The final decision goal is based on the following four aspects, ten objectives and thirty-four criteria.

3.1.1 ASPECTS

The four aspects that have been included in the hierarchy deal with a specific aspect of the project: From theoretical to technical and from implementation to management.

3.1.1.1 **Scientific and Technological Merit:**

The scientific and technological influence of the selected project on existing knowledge base. It focuses on establishing its relevance to present needs, the degree of its competitiveness to prevailing and novel technologies as well as the academic record of the funding seekers.

3.1.1.2 Potential Benefits

Anticipated benefits of the selected project to the country in term of economy boost as well as humanity welfare.

3.1.1.3 Project Execution

The technical aspects involved in the execution and implementation of the selected project revolving majorly around the availability of resources and the technical plan.

3.1.1.4 Project Risk

The probable risks encountered by the selected project. It can be technical, developmental or commercial in nature.

3.1.2 *Objectives*

The ten listed objectives all encompass each of the above mentioned four aspects of the exhaustive hierarchy. These objectives are:

3.1.2.1 Competitiveness of Technology

It deals with the competitiveness of the selected project with the prevailing technologies in the industry. It also focuses on whether the project explores a current technology or implements a novel concept.

3.1.2.2 Relevance of Technology

This objective relates to establishing the currency of the selected project in the industry. It also relates to the potential of extension the proposed technology in other facets of the industry.

3.1.2.3 Academic Record of Funding Seekers

The brain behind an effective research depends chiefly on the researcher working on that project. In order to shortlist an R&D project for funding, it is therefore imperative to evaluate the funding seeker against certain criterion(both subjective and objective) to gauge their research capacity.

3.1.2.4 Economic Benefit

The potential for the economic growth of the nation due to the selected project. It can be in the form of further research, establishment of new enterprises based on the projects technology or in the form of technological spillover.

3.1.2.5 Social Benefit

It deals with the benefits provided to the society due to the shortlisted project in terms of job creation and improvements in the living standards.

3.1.2.6 Quality of Technical Plan

Deals solely with the technical aspects of the proposed project: from its technical plan to its proposed timing of completion, technical capability of the research team and expected cost.

3.1.2.7 Availability of Resources

Covers resources that are either technical or non-technical in nature: From infrastructure support to availability of equipment (compatible hardware and software).

3.1.2.8 Technical Risk

It encompasses risks that are technical in nature. Includes specification of technology, opportunity for market success and evidence of scientific feasibility.

3.1.2.9 Development Risk

It majorly relates to the potential timing delays that can occur in the execution of the selected project as well as the risk incurred in the cost of developing the project.

3.1.2.10 Commercial Risk

Deals with the risk of market success as well as the risk of implementing the results of the selected project in industry.

3.1.3 CRITERION

Thirty-four criterion have been included in the exhaustive hierarchy for R&D project selection that target a specific area of the candidate projects to be prioritized. These are:

3.1.3.1 Propriety of Technology

Is it possible for the selected project to generate a patented technology through the intellectual property rights? According to U.S Patent and Trademark office the total number of patents ever granted globally stands at 4784872 out of which 276796 were granted in 2012. Pakistan has been granted a total of 66 patents with 13 granted in 2012.

3.1.3.2 Key of Technology

Is the technology proposed in the selected project necessary for industry expansion or product development? At present a humble R&D setup limits the technological growth of any nation and as a results impedes in its economic growth.

3.1.3.3 Innovation of Technology

How innovative is the proposed technology. Innovation as a term holds a commercial connotation that is distinct from scientific research. Companies aiming for innovation generate nonexistent capital by commercializing their R&D projects and hence create wealth for themselves and for their country. The relationship between economic growth and innovation lies in technical change [14-16] and can be identified as: a catalyst in leading organizations (such as Microsoft and Apple); a tool promoting leadership (Schlumberger and BP), a mission reinforcing an ambition (think of Adidas or Toyota) and aesthetics attracting the best talent (look at Google and Cisco).

3.1.3.4 Advancement of Technology

Is the proposed technology in the selected project advancement to the existing technology? Advancement of technology comes under the superset of the competitiveness of technology which has a direct effect on the stability of a nation's economy.

3.1.3.5 Technological Connections

Can the results of the project be applied on other products? It is obvious that more technical applications would mean more technical connections.

3.1.3.6 Generics of Technology

Does the candidate project utilize a generic technology that is common to the industry or does it propose an entirely new technology that would completely overhaul the existing infrastructure?

3.1.3.7 Technological Extendibility

To what extent is the proposed technology likely to further technological growth based on the final results?

3.1.3.8 Publications

Perhaps the most common litmus test to measure the research performance of any researcher is their publications (journal and conference), adjusted by the quality index of those journals. An expert is known by the research he publishes in academic journals and hence, publications offer an effective way to assess an expert's research work. Higher Education commission of Pakistan has an approved list of academic journals for different fields which tries to ensure that quality research is being carried out throughout the country.

3.1.3.9 Previous R&D Project History

The second factor to be assessed in a researcher is their previous R&D history: whether the expert is an active researcher and the field in which the expert has previously conducted their research in. Preference should be given to experts who are abreast with the research in their field and are proposing a project that has a logical link to their discipline of study.

3.1.3.10 Number of Previously Supervised PhDs

Another focus of any academician/researcher is the supervision of PhDs'. People generally gauge researchers by the number of PhDs' being supervised by them since that establishes the fact that they are an active researcher.

3.1.3.11 Peer Review

A subjective factor comes to play in order to evaluate an expert for funding a project and that is other experts' opinions about the funding seeker. This qualitative information is coupled with the quantitative information gathered in the previous three criterions.

3.1.3.12 The Potential Size of Market

Can the selected project expand the market by introducing a new product? Examples of the growth of market can be clearly viewed in the case of mobile phones whereby numerous companies (Apple, Samsung, Nokia, Sony Ericsson, etc.) are competing with each other in terms of technical enhancements.

3.1.3.13 Improvement on Research Capability

Can the proposed project generate enough momentum so as to initiate future research prospects for people and will academicians and future researchers be willing to invest in the proposed project?

3.1.3.14 Technology Spillover Effects

Will the proposed technology enhance the market in such a way so to as to influence the production of other firms? A pertinent example would be the invention of the touch screen [17] that has led to a global change in how users interact with their electronic display screens.

3.1.3.15 Improvements on QESIS

Benefits to humanity through improvements in quality, environmental protection, industrial safety, national image and industrial standards.

3.1.3.16 Job Opportunities
The main consideration for any nation is the availability of jobs. Generation of new jobs based on the proposed project is an important consideration for the benefit of the society.

3.1.3.17 Benefits for Human Life
Will the proposed project improve the quality of human life in terms of health? Will it aid in the discovery or alleviation of diseases?

3.1.3.18 The Contributions to the State of Knowledge
To what extent does the suggested technology adds to the current technical knowledge? Will the proposed project result in additional technical publication?

3.1.3.19 Content of Technical Plan
The project must be described by questions including clear and concise planning, clear identification of the core technology, feasible technical approach and the major technical hurdles in substantial details.

3.1.3.20 Capability of Research Team
An important consideration in the selection of an R&D project is the technical expertise of the research team including but not limited to the competence of the project leader and the participating technical staff.

3.1.3.21 Reasonableness for Research Period
The success of any project depends on maximum efficiency with minimum resources. This criterion is important as it deals with the scheduling of the project period, approving fruitful completion of the project goals in a reasonable time frame.

3.1.3.22 Reasonableness for Research Cost
As with the previous criterion, this deals with the scheduling of the project cost, permitting the completion of project goals within reasonable costs.

3.1.3.23 Environmental and Safety Consideration
In present times, it has been a topic of hot debate of how the industries and societies should care for the environment. Hence the proposed project should also cater to the criterion of environment and public safety in its plan.

3.1.3.24 Technical Resource Availability
Are there technical resources available for the proposed project to be initiated? Attention should be given to this criterion while prioritizing projects to be funded.

3.1.3.25 Technical Support
Is the technology used in the proposed project supported by the organization or would it require procurement of outside help? Technical support can be either software or physical in nature, or both.

3.1.3.26 Equipment Support

As explained for technical support in the above criterion, this deals with the equipment maintained at the organization and whether the selected project can be sustained by organizational facilities.

3.1.3.27 Opportunity of Technical Success

Can the proposed project generate considerable technical success in R&D? What is the opportunity for the successful completion of the project and is there any comparable successful project?

3.1.3.28 Evidence of Scientific Feasibility

Are there early research evidences such as a proof of concept, experimentation, or sound theoretical thinking for the proposed project.

3.1.3.29 Specification of Technology

Can the selected project meet the specifications proposed by the funding seeker? Specifications can be the construction of the machine to its output efficiency.

3.1.3.30 Risk for Development Cost

An important risk in the prioritization of R&D projects is the development cost of the prototype that has to be introduced to the industry.

3.1.3.31 Risk for Time Cost

Related to the previous criterion, risk for time cost is the expected tangible time taken to develop the prototype of the proposed project.

3.1.3.32 Timing for Project

Is the present time the right time to fund the project? Is there some other project that is more relevant to present needs? For example projects related to energy efficiency to mitigate prevailing energy crises in the country are more relevant in present times.

3.1.3.33 Opportunity of Market Success

Does the proposed project provide an opportunity for market success? Will it generate a solution, a product, a process or a service that will be readily applied in the market?

3.1.3.34 Opportunity of Project Result Implementation

Will an organization be willing to invest and implement the results of the proposed project?

R&D Project Prioritization- Exhaustive Hierarchy																																	
Scientific and Technological Merit											Potential Benefits							Project Execution								Project Risk							
Competitiveness of Technology				Relevance of Technology			Academic Record of Funding Seekers				Economic Benefit			Social Benefit				Quality of Technical Plan					Availability of Resources			Technical Risk			Development Risk			Commercial Risk	
Propriety of technology	Key of technology	Innovation of technology	Advancement of technology	Technological connections	Generics of technology	Technological extendibility	Publications	Previous R&D project history	Number of previously supervised PhDs	Peer review	The potential size of market	Improvement on research capability	Technology spillover effects	Improvements on QESIS	Job Opportunities	Benefits for human life	The contributions to the state of Knowledge	Content of technical plan	Capability of research team	Reasonableness for research period	Reasonableness for research cost	Environmental and safety consideration	Technical resource availability	Technical support	Equipment support	Opportunity of technical success	Evidence of scientific feasibility	Specification of technology	Risk for development cost	Risk for time cost	Timing for project	Opportunity of market success	Opportunity of project result implementation

Table 01- Exhaustive Decision Hierarchy

3.2 CONDUCTING OF SURVEYS

The reason for the development of an exhaustive hierarchy was to ensure that no determinant discussed about in R&D project prioritization literature was left out. By doing so, a thorough set of criteria could be presented to the decision maker to aid him in his decision making process. However, the following three problems rise as a result of this exhaustive hierarchy:

I. Judging each candidate project against a set of forty eight factors becomes a daunting task which would essentially prove to be a hassle for the decision maker rather than a help.
II. The decision maker might not consider some of the determinants to be of major importance and would hence want to skip judgments on those specific criteria.
III. Some of the criteria might not be ranked high in importance locally even if their comparative importance is of huge proportion globally.

To counter the above mentioned problems, it was decided to conduct surveys and ask experts from varying fields to rank each determinant in the hierarchy in order of their perceived importance. After tabulation and analysis of the surveys, a final concise hierarchy would then be extracted that could be applied on any funding organization as part of its decision making process.

So, after proposing over thirty criterions for prioritizing Research and Development projects, the hierarchy was put up for discussion with four senior experts-from the areas of Engineering, Science and Management-who were asked to review the initial hierarchy model for the sake of practical application in R&D project prioritization. These experts were interviewed to review the initial Exhaustive hierarchy. This was done so as to directly revise the hierarchy model in direct consultation with these experts if need be.

Then, surveys were conducted for this exhaustive hierarchy from academicians and researchers belonging to various universities and R&D organizations in Pakistan. Consideration was made to conduct surveys from experts from different disciplines (Engineering, Mathematics, Science and Management) having a PhD and experience of six or more years.

Respondents were asked to rank each aspect, objective and criteria of the hierarchy on a modified likert scale (0-9) with zero being the least important and nine being the most important. A detailed brochure explaining each of the criterion was also given to the experts to help them understand the specific nature of each criterion. A total of hundred surveys were gathered from varying fields of Engineering, Sciences and Management. A sample survey has been appended in Appendix A. The tables (02-07) give the total tally of the surveys broken down by area of research and experience of each survey taker.

Surveys by Area of Research	
Area of Research	**Number of Surveys**
Engineering & Computer Science	36
Management and Social Science	30
Physical Science	26
Mathematics	8
Total Number of Surveys	100

Table 02-Surveys by Area of Research

Surveys by Experience	
Experience	**Number of Surveys**
Less than ten years	28
Ten to twenty years	46
More than twenty years	26
Total Number of Surveys	100

Table 03- Surveys by Experience

Surveys by Engineering & Computer Science	
Experience	**Number of Surveys**
Less than ten years	14
Ten to twenty years	16
More than twenty years	06
Total Number of Surveys	36

Table 04-Surveys by Engineering & Computer Science

Surveys by Management & Social Science	
Experience	**Number of Surveys**
Less than ten years	04
Ten to twenty years	22
More than twenty years	04
Total Number of Surveys	30

Table 05-Surveys by Management & Social Science

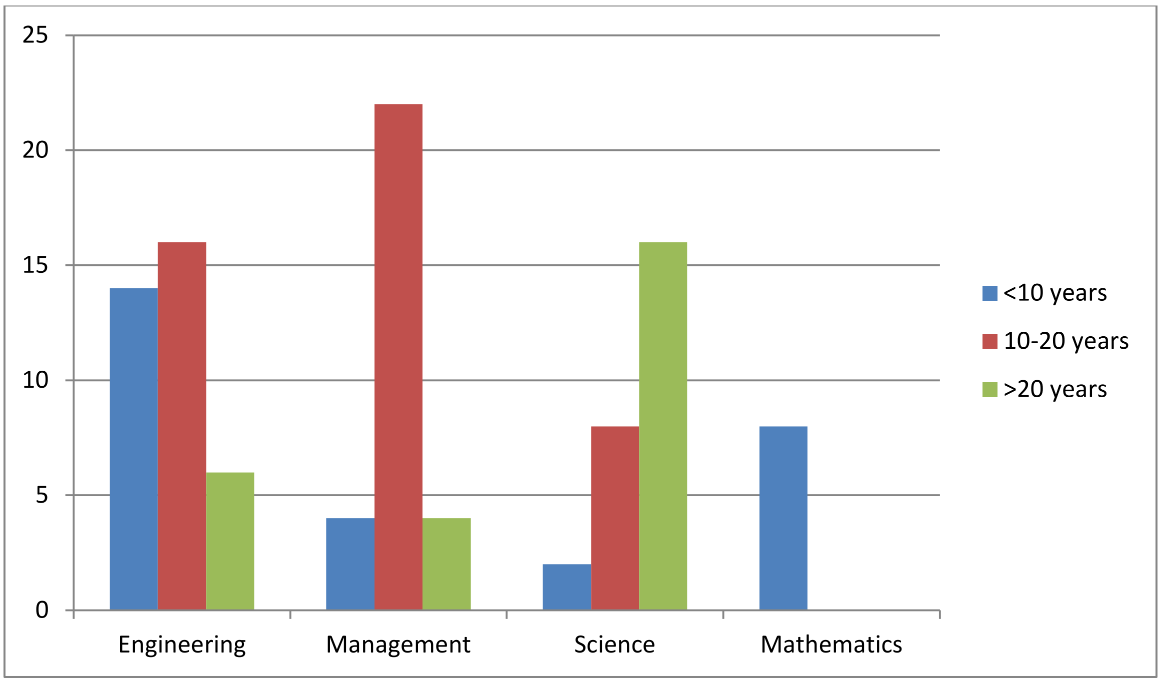
Surveys by Physical Science	
Experience	**Number of Surveys**
Less than ten years	02
Ten to twenty years	08
More than twenty years	16
Total Number of Surveys	28

Table 06-Surveys by Physical Science

Surveys by Mathematics	
Experience	**Number of Surveys**
Less than ten years	08
Ten to twenty years	00
More than twenty years	00
Total Number of Surveys	08

Table 07-Surveys by Mathematics

The graph bellows visually explains the number of respondents with reference to their experience coupled with respect to their area of research.

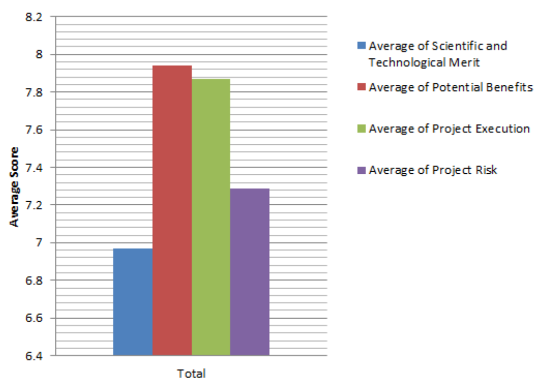


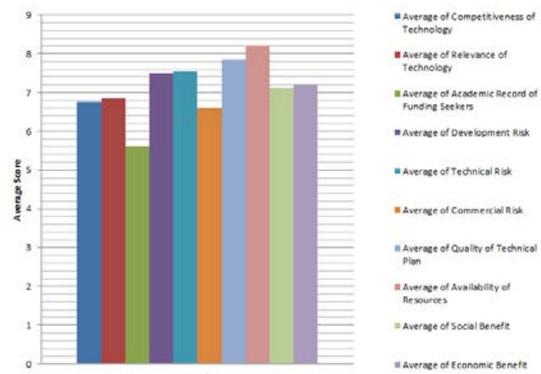
Graph 01-Area of Research versus of Experience of Respondents

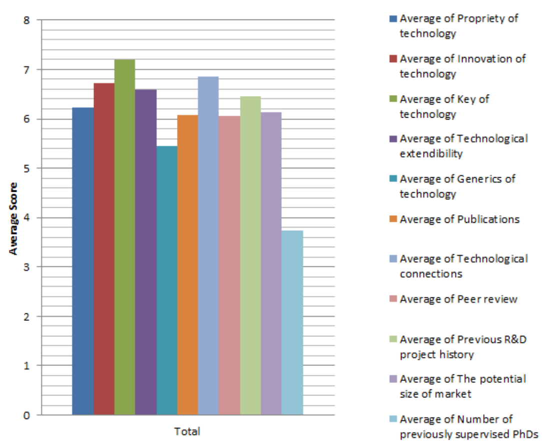
3.3 Data Analysis

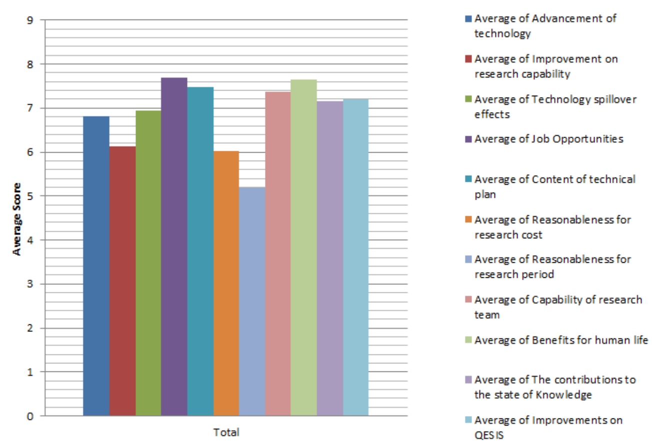
After the surveys were handed in, Computational tools were used to extract information from the surveys which was then mathematically analyzed using MS Excel and Wekka. The purpose of this step was:

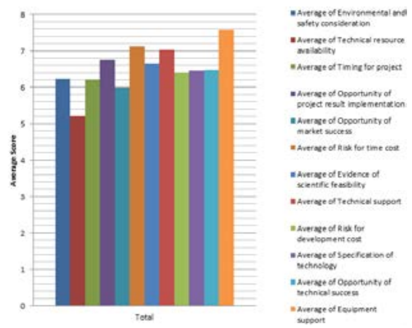
I. Observe the pattern of how the survey takers responded to each criterion.
II. Extract useful numerical data against each criterion from the surveys.
III. Evaluate and plot each criterion for its relevance using arithmetic means and histograms.
IV. Perform a clustering analysis to see the pattern of voting for each criterion.
V. Eliminate redundant and/or unimportant criterion.

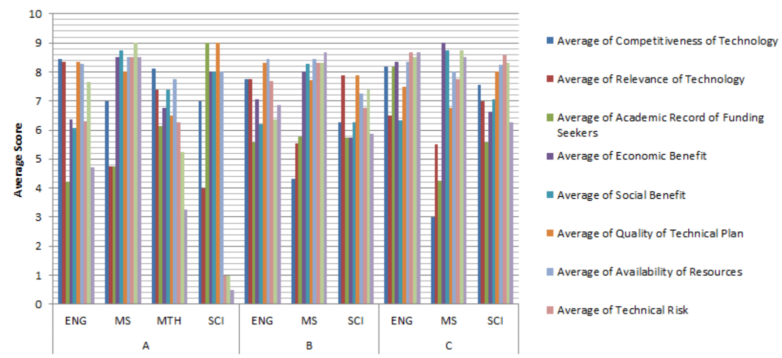


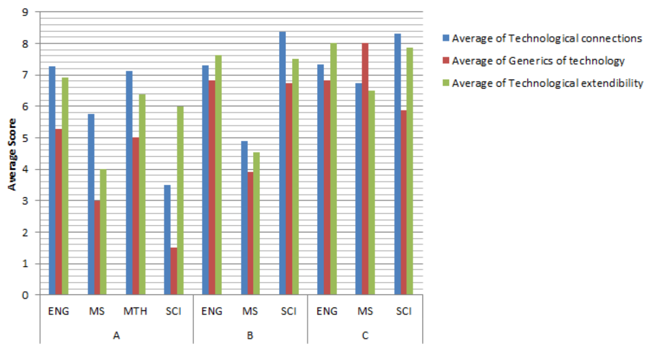


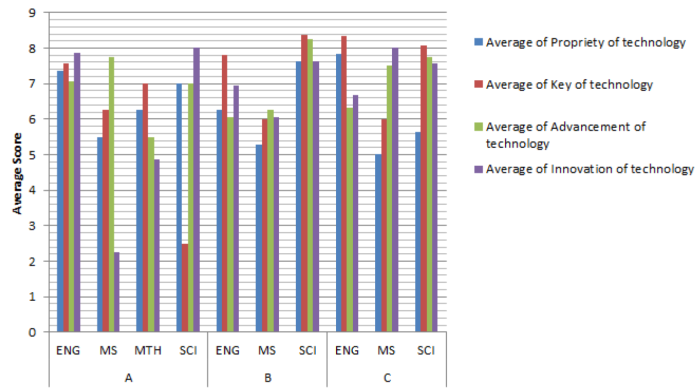


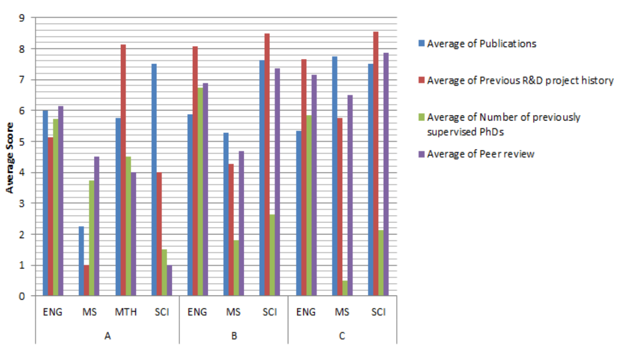


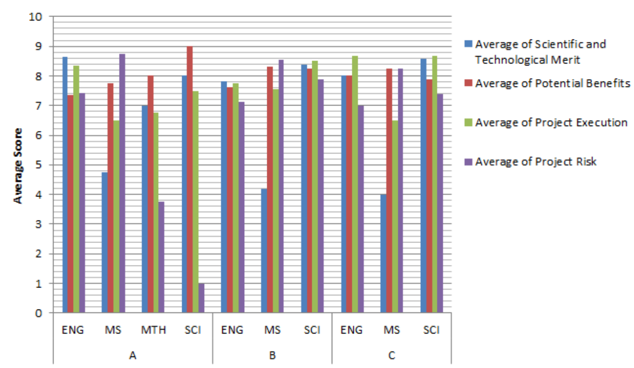

Average of Environmental and safety consideration
Average of Technical resource availability
Average of Timing for project
Average of Opportunity of project result implementation
Average of Opportunity of market success
Average of Risk for time cost
Average of Evidence of scientific feasibility
Average of Technical support
Average of Risk for development cost
Average of Specification of technology
Average of Opportunity of technical success
Average of Equipment support
Average Score
Total

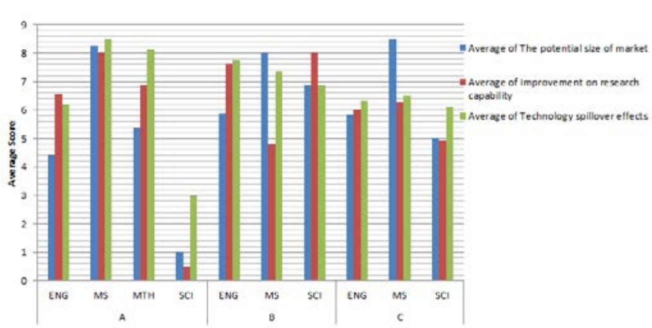

Average of Competitiveness of Technology
Average of Relevance of Technology
Average of Academic Record of Funding Seekers
Average of Economic Benefit
Average of Social Benefit
Average of Quality of Technical Plan
Average of Availability of Resources
Average of Technical Risk
Average Score
ENG MS MTH SCI ENG MS SCI ENG MS SCI
A B C

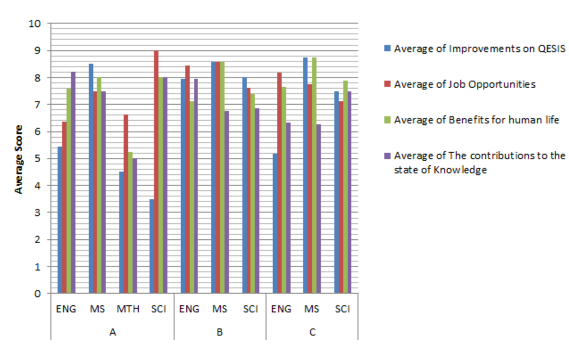

Average of Technological connections
Average of Generics of technology
Average of Technological extendibility
Average Score
ENG MS MTH SCI ENG MS SCI ENG MS SCI
A B C

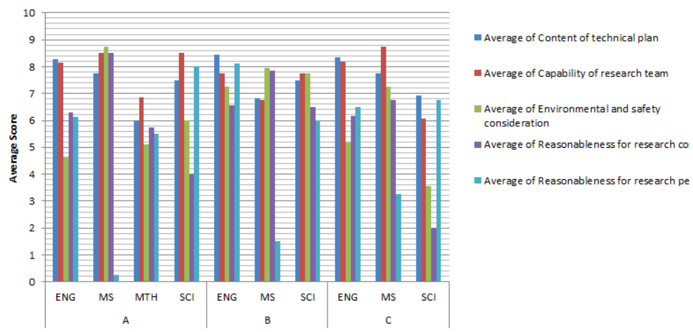

Average of Propriety of technology
Average of Key of technology
Average of Advancement of technology
Average of Innovation of technology
Average Score
ENG MS MTH SCI ENG MS SCI ENG MS SCI
A B C

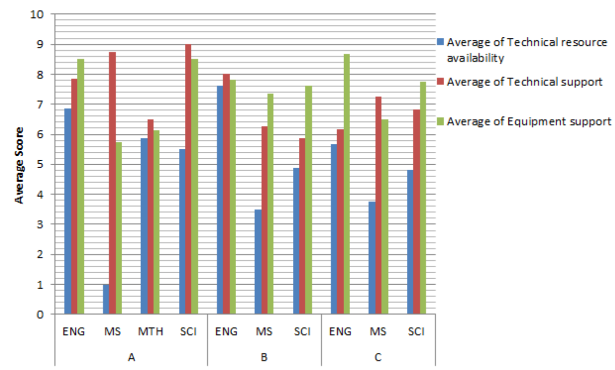

Average of Publications
Average of Previous R&D project history
Average of Number of previously supervised PhDs
Average of Peer review
Average Score
ENG MS MTH SCI ENG MS SCI ENG MS SCI
A B C

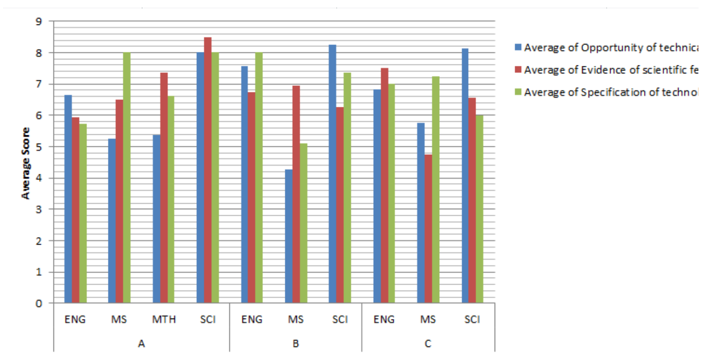

Average of Scientific and Technological Merit
Average of Potential Benefits
Average of Project Execution
Average of Project Risk
Average Score
ENG MS MTH SCI ENG MS SCI ENG MS SCI
A B C

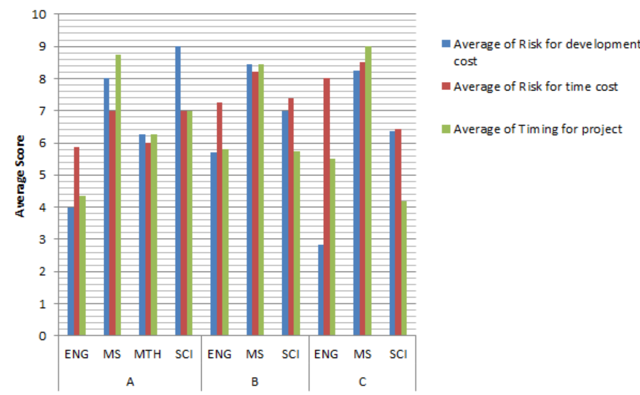

Average of The potential size of market
Average of Improvement on research capability
Average of Technology spillover effects
Average Score
ENG MS MTH SCI ENG MS SCI ENG MS SCI
A B C


Average of Improvements on QESIS
Average of Job Opportunities
Average of Benefits for human life
Average of The contributions to the state of Knowledge
Average Score
ENG MS MTH SCI ENG MS SCI ENG MS SCI
A B C


Average Score
Average of Content of technical plan
Average of Capability of research team
Average of Environmental and safety consideration
Average of Reasonableness for research co
Average of Reasonableness for research pe


Average Score
Average of Technical resource availability
Average of Technical support
Average of Equipment support


Average Score
Average of Opportunity of technic
Average of Evidence of scientific fe
Average of Specification of techno


Average Score
Average of Risk for development cost
Average of Risk for time cost
Average of Timing for project

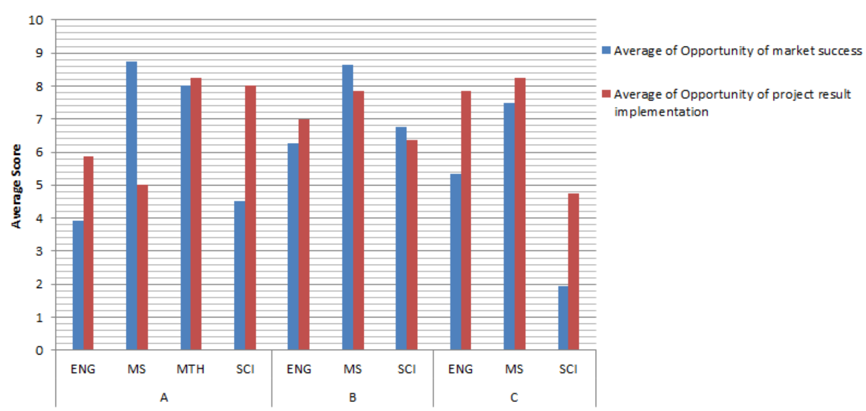

Average Score
Average of Opportunity of market success
Average of Opportunity of project result implementation

Table 08-Histogram for Aspects				
Bin	**A-1**	**A-2**	**A-3**	**A-4**
0	0	0	0	2
1	6	1	0	4
2	2	0	1	0
3	7	0	3	2
4	4	0	0	1
5	7	8	5	9
6	3	3	6	4
7	12	18	12	17
8	18	21	26	22
9	41	49	47	39

Table 09-Histogram for Objectives										
Bin	**O-1**	**O-2**	**O-3**	**O-4**	**O-5**	**O-6**	**O-7**	**O-8**	**O-9**	**O-10**
0	0	0	2	2	1	0	0	2	0	3
1	5	0	5	2	2	1	0	1	4	4
2	5	1	4	1	1	0	1	3	1	5
3	3	8	8	2	5	1	0	3	3	7
4	3	8	13	3	4	1	0	1	0	2
5	11	9	18	10	8	7	2	4	8	12
6	8	10	7	6	9	6	2	4	2	3
7	14	20	18	17	11	13	14	11	16	9
8	20	14	10	20	25	24	30	26	23	18
9	31	30	15	37	34	47	51	45	43	37

Table 10-Histogram for Criterion																	
Bin	**C-1**	**C-2**	**C-3**	**C-4**	**C-5**	**C-6**	**C-7**	**C-8**	**C-9**	**C-10**	**C-11**	**C-12**	**C-13**	**C-14**	**C-15**	**C-16**	**C-17**
0	2	0	1	0	0	3	1	3	3	24	3	1	1	0	3	0	0
1	2	1	3	3	1	7	3	5	6	12	8	6	5	1	2	0	1
2	2	1	3	1	3	7	3	1	1	12	3	2	0	1	4	0	2
3	9	2	4	8	6	10	3	9	8	9	7	8	7	11	2	4	1
4	4	6	6	1	4	6	10	9	6	2	3	5	11	3	1	1	2
5	21	9	6	17	14	14	10	11	8	5	13	18	20	10	9	8	7
6	6	12	10	4	9	10	6	8	5	6	7	5	5	8	2	3	3
7	20	15	21	15	14	17	21	21	16	9	19	18	20	14	13	15	15
8	13	22	24	25	19	13	20	9	15	10	15	19	7	17	25	31	30
9	21	32	22	26	30	13	23	24	32	11	22	18	24	35	39	38	39

Histogram for Criterion-Cont'd																	
Bin	**C-18**	**C-19**	**C-20**	**C-21**	**C-22**	**C-23**	**C-24**	**C-25**	**C-26**	**C-27**	**C-28**	**C-29**	**C-30**	**C-31**	**C-32**	**C-33**	**C-34**
0	0	0	0	12	1	2	7	0	0	2	2	2	4	3	2	6	3
1	1	0	1	8	11	8	5	2	2	2	0	3	3	2	8	8	2
2	0	1	1	3	3	4	8	1	0	3	3	2	4	1	2	6	2
3	3	2	4	12	5	4	11	4	1	8	7	7	8	1	7	6	2
4	5	2	6	2	5	5	7	1	1	4	4	5	5	2	8	4	8
5	13	11	7	10	16	13	12	16	9	11	13	11	7	12	12	7	12
6	8	7	8	10	5	5	11	9	5	9	11	7	11	5	9	3	9
7	20	18	13	14	16	18	13	15	18	20	16	22	10	18	6	17	13
8	18	23	17	9	14	15	11	24	28	18	17	21	17	22	14	13	14
9	32	36	43	20	24	26	15	28	36	23	27	20	31	34	32	30	35

Table 11- Subject Wise Averages for Aspects				
Bin	**A-1**	**A-2**	**A-3**	**A-4**
All	7.0	7.9	7.9	7.3
Engineering	8.2	7.6	8.1	7.2
Management	4.2	8.2	7.3	8.5
Science	8.1	8.1	8.1	6.3

Table 12-Subject Wise Averages for Objectives										
Bin	**O-1**	**O-2**	**O-3**	**O-4**	**O-5**	**O-6**	**O-7**	**O-8**	**O-9**	**O-10**
All	6.8	6.9	5.6	7.2	7.1	7.9	8.2	7.5	7.5	6.6
Engineering	8.1	7.8	5.5	7.0	6.2	8.2	8.4	7.3	7.2	6.3
Management	4.5	5.4	5.4	8.2	8.4	7.6	8.4	8.3	8.5	8.6
Science	7.4	7.1	5.9	6.5	7.0	7.7	7.9	7.1	6.9	5.1

Table 13-Subject Wise Averages for Criterion (Condition: mean≥6.9)																	
Bin	**C-1**	**C-2**	**C-3**	**C-4**	**C-5**	**C-6**	**C-7**	**C-8**	**C-9**	**C-10**	**C-11**	**C-12**	**C-13**	**C-14**	**C-15**	**C-16**	**C-17**
All	6.2	**7.2**	6.7	6.8	**6.9**	5.5	6.6	6.1	6.5	3.7	6.1	6.1	6.1	**7.0**	**7.2**	**7.7**	**7.7**
ENGG	**6.9**	**7.8**	**7.3**	6.5	**7.3**	6.2	**7.4**	5.8	**6.9**	6.2	6.6	5.3	**6.9**	**6.9**	6.5	**7.6**	**7.4**
MNGT	5.3	6.0	5.8	6.6	5.3	4.3	4.7	5.2	4.0	1.9	4.9	**8.1**	5.4	**7.4**	**8.6**	**8.3**	**8.5**
SCI	6.3	**7.6**	**7.0**	**7.3**	**7.8**	5.6	**7.3**	**7.1**	**8.2**	2.8	6.4	5.3	5.9	6.6	6.7	**7.2**	**7.1**
Subject Wise Averages for Criterion-Cont'd																	
Bin	**C-18**	**C-19**	**C-20**	**C-21**	**C-22**	**C-23**	**C-24**	**C-25**	**C-26**	**C-27**	**C-28**	**C-29**	**C-30**	**C-31**	**C-32**	**C-33**	**C-34**
All	**7.2**	**7.5**	**7.4**	5.2	6.0	6.2	5.2	**7.0**	**7.6**	6.5	6.7	6.5	6.4	**7.1**	6.2	6.0	6.8
ENGG	**7.8**	**8.4**	**8.0**	**7.1**	6.4	5.9	**7.0**	**7.6**	**8.2**	**7.1**	6.6	**6.9**	4.6	6.8	5.2	5.2	6.7
MNGT	6.8	**7.1**	**7.3**	1.6	**7.8**	**8.0**	3.2	6.7	**7.0**	4.6	6.6	5.8	**8.4**	**8.1**	**8.6**	**8.5**	**7.5**
SCI	6.8	**6.9**	6.8	6.4	4.1	5.1	5.1	6.6	**7.4**	**7.5**	6.8	6.6	6.6	6.6	5.2	4.6	6.1

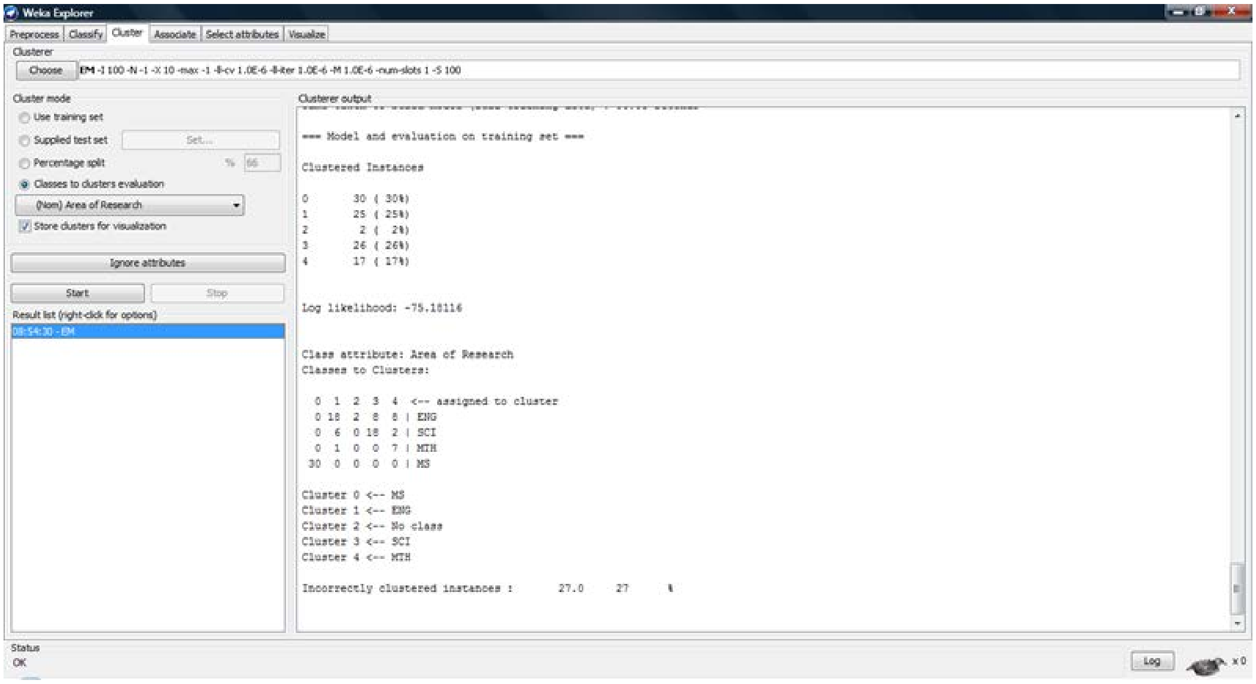
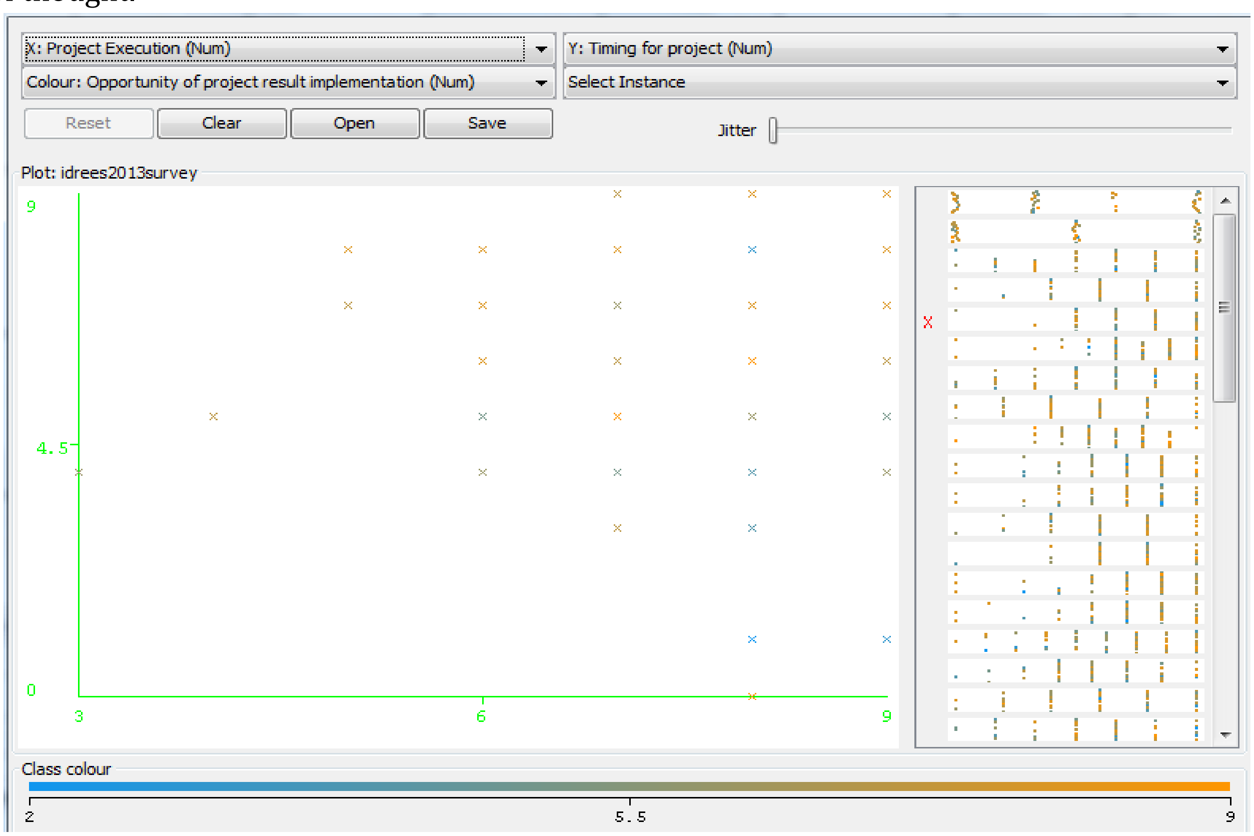


Figure 04- Clustering Analysis from Wekka

An interesting observation that was found out from the clustering analysis in Wekka (figure above) was that where engineering and natural sciences had a varying opinion about the four aspects, people from management sciences all belonged to the same school of thought.



The possible reason for this can be associated to the fact that people belonging to management sciences tend to focus more on the monetary aspect of things as opposed to research whereas people from engineering and natural sciences have a varying degree of bias towards technical and monetary aspects.

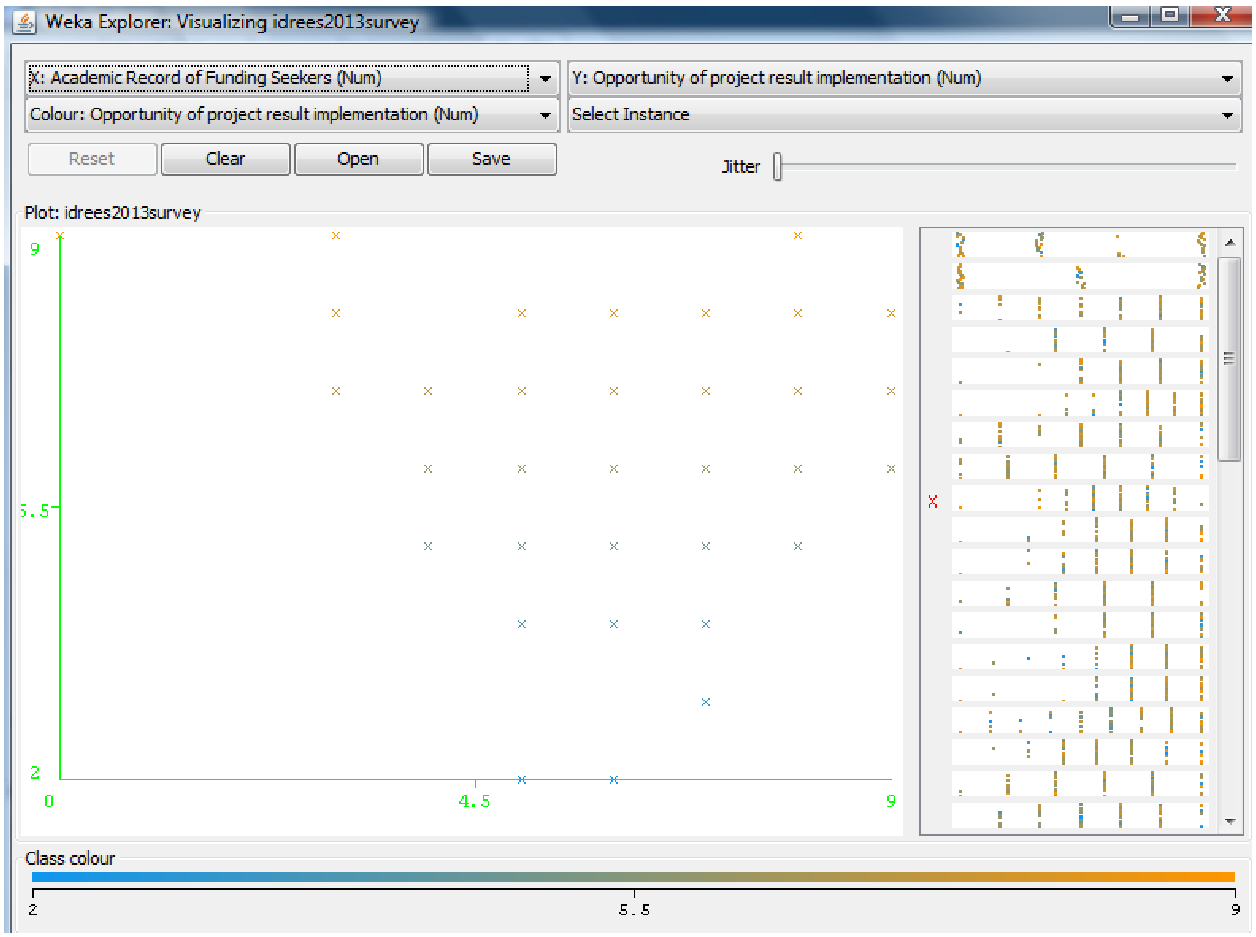


Figure 06- Clustering Analysis from Wekka

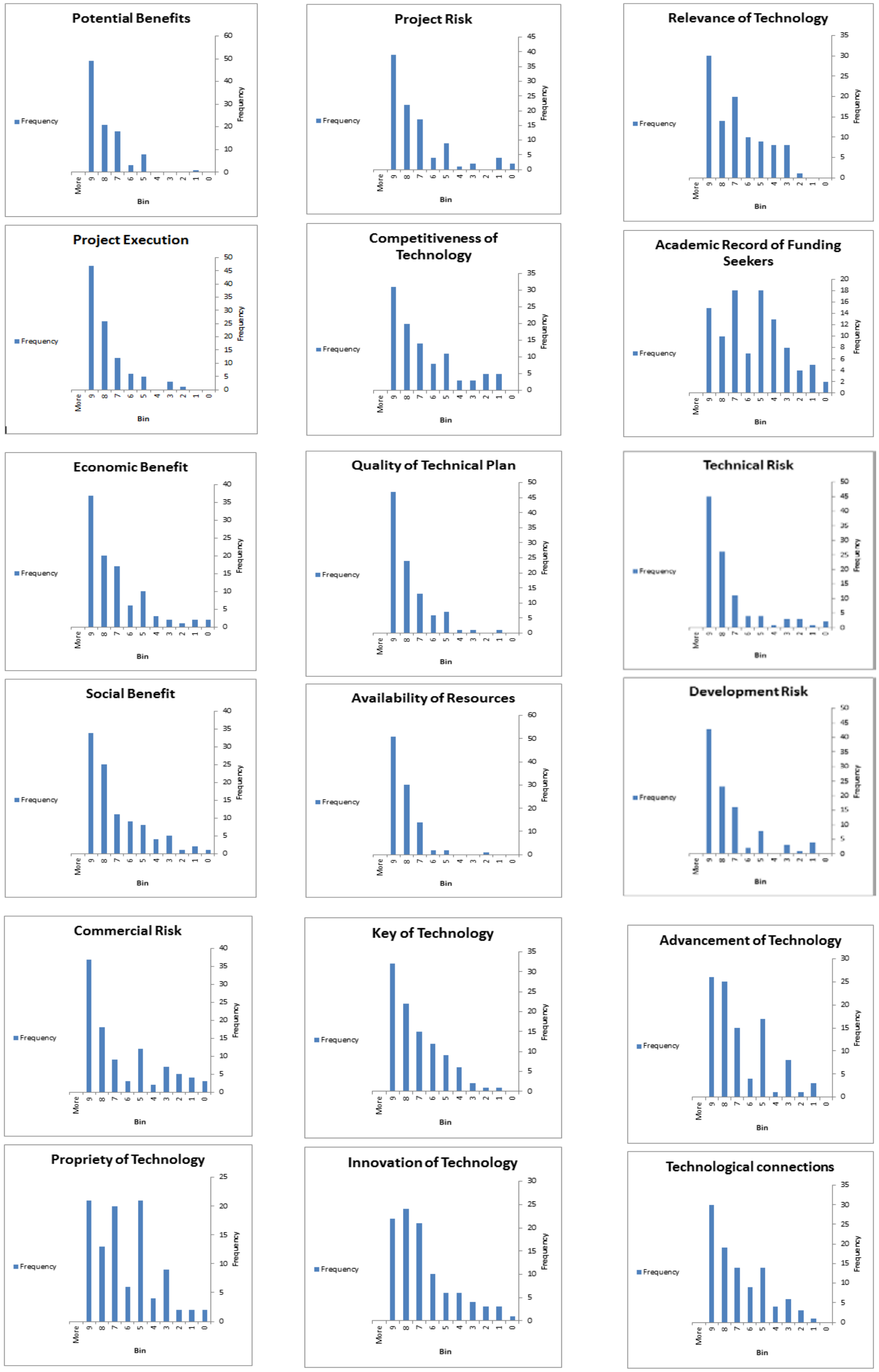


Figure 07- Histogram Analysis of Criteria

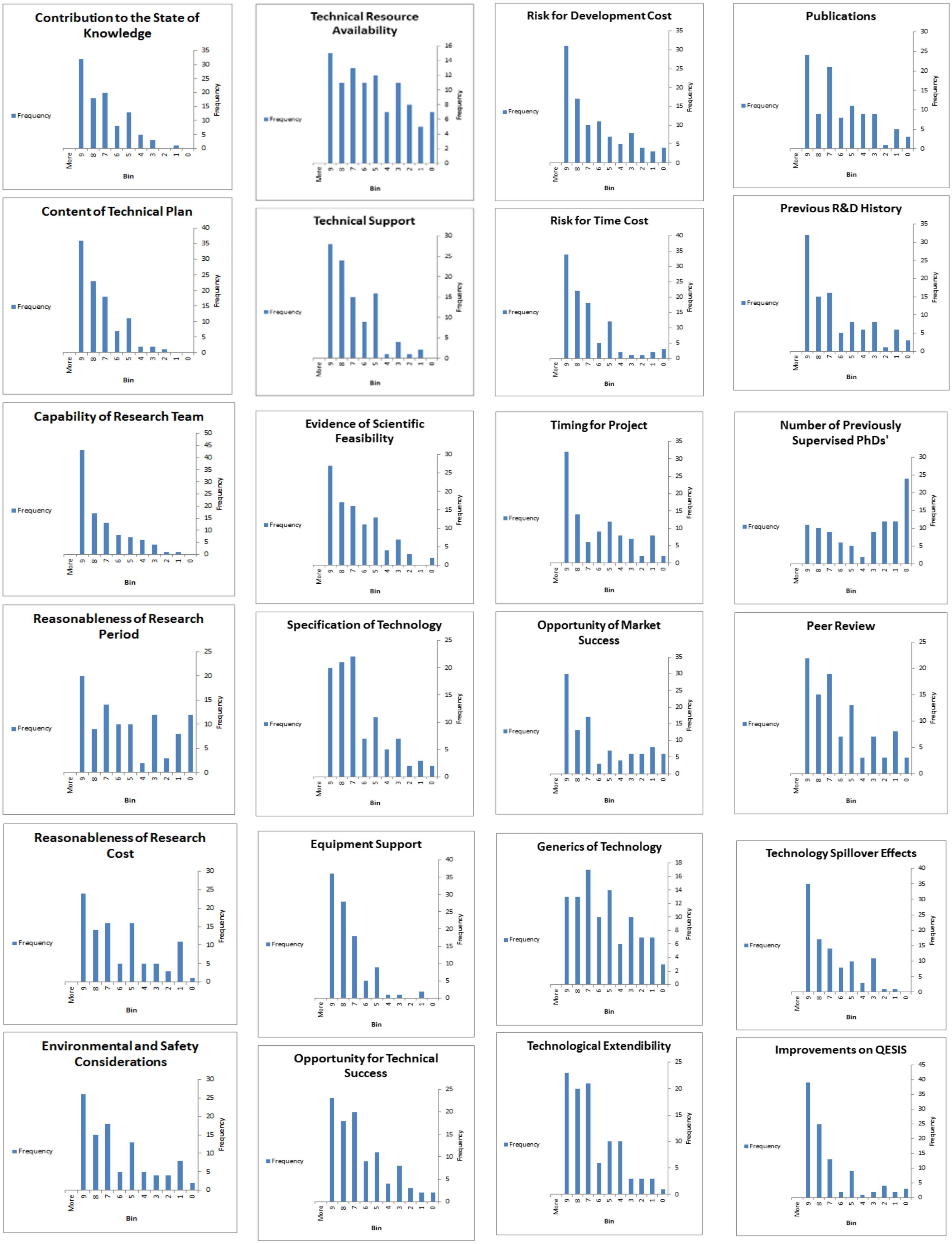


Figure 08- Histogram Analysis of Criteria

3.4 DECISION MAKERS RANKING OF THE EXHAUSTIVE HIERARCHY

After the analysis of the data acquired from the surveys, decision makers were interviewed to evaluate the exhaustive hierarchy. The aim of this interview was to understand the decision makers' opinions on the following aspects:

01. Their decisions regarding the various decision criteria.
02. Their approach towards Analytical hierarchy Process used in this thesis.
03. Their attitude towards adopting an R&D project prioritizing policing in general.
04. To correlate Decision makers' ranking with the funding seekers ranking so as to extract a concise hierarchy.

A mean of atleast 6.9 was chosen and criterion who fell below this mean were excluded from the final concise hierarchy. The choice of mean is completely up to the discretion of the decision maker. The variation in mean can be considered as a sensitivity tool that allows the decision maker to introduce more criteria to make the decision more objective and free from biases.

Table 14-Decision Makers' Ranking for Aspects

	A-1	A-2	A-3	A-4
DM01	8	7	9	7
DM02	7	7	8	7

Table 15-Decision Makers' Ranking for Objectives

	O-1	O-2	O-3	O-4	O-5	O-6	O-7	O-8	O-9	O-10
DM01	5	7	5	7	7	8	9	8	7	5
DM02	4	8	6	5	9	8	9	6	7	5

Table 16-Decision Makers Ranking for Criterion

	C-1	C-2	C-3	C-4	C-5	C-6	C-7	C-8	C-9	C-10	C-11	C-12	C-13	C-14	C-15	C-16	C-17
DM01	5	7	6	7	8	6	7	8	8	3	8	6	5	7	6	6	7
DM02	3	6	5	4	7	4	9	7	7	5	8	8	6	5	9	8	9

Decision Makers Ranking for Criterion-Cont'd

	C-18	C-19	C-20	C-21	C-22	C-23	C-24	C-25	C-26	C-27	C-28	C-29	C-30	C-31	C-32	C-33	C-34
DM01	7	8	7	5	4	7	5	7	7	8	6	5	5	9	4	5	5
DM02	7	7	6	7	7	8	9	8	9	6	5	5	6	6	4	6	5

Table 17-Final Ranking for Aspects (Condition: Mean ≥ 6.9)				
	A-1	**A-2**	**A-3**	**A-4**
Mean of Surveys	7	7.9	7.9	7.3
DM01	8	7	9	7
DM02	7	7	8	7
New Mean	7.33	7.30	8.30	7.10

Table 18-Final Ranking for Objectives (Condition: Mean ≥ 6.9)										
	O-1	**O-2**	**O-3**	**O-4**	**O-5**	**O-6**	**O-7**	**O-8**	**O-9**	**O-10**
Mean of Surveys	6.8	6.9	5.6	7.2	7.1	7.9	8.2	7.5	7.5	6.6
DM01	5	7	5	7	7	8	9	8	7	5
DM02	4	8	6	5	9	8	9	6	7	5
New Mean	5.27	7.30	5.53	6.40	7.70	7.97	8.73	6.00	7.17	5.53

Table 19-Final Ranking for Criterion (Condition: Mean ≥ 6.9)																	
	C-1	**C-2**	**C-3**	**C-4**	**C-5**	**C-6**	**C-7**	**C-8**	**C-9**	**C-10**	**C-11**	**C-12**	**C-13**	**C-14**	**C-15**	**C-16**	**C-17**
Mean of Surveys	6.2	**7.2**	6.7	6.8	**6.9**	5.5	6.6	6.1	6.5	3.7	6.1	6.1	6.1	**7.0**	**7.2**	**7.7**	**7.7**
DM01	5	7	6	7	8	6	7	8	8	3	8	6	5	7	6	6	7
DM02	3	6	5	4	7	4	9	7	7	5	8	8	6	5	9	8	9
New Mean	4.73	6.73	5.90	5.93	**7.30**	5.17	**7.53**	**7.03**	**7.17**	3.90	**7.37**	6.70	5.70	6.33	**7.40**	**7.23**	**7.90**
Decision Makers Ranking for Criterion-Cont'd																	
	C-18	**C-19**	**C-20**	**C-21**	**C-22**	**C-23**	**C-24**	**C-25**	**C-26**	**C-27**	**C-28**	**C-29**	**C-30**	**C-31**	**C-32**	**C-33**	**C-34**
Mean of Surveys	**7.2**	**7.5**	**7.4**	5.2	6.0	6.2	5.2	**7.0**	**7.6**	6.5	6.7	6.5	6.4	**7.1**	6.2	6.0	6.8
DM01	7	8	7	5	4	7	5	7	7	8	6	5	5	9	4	5	5
DM02	7	7	6	7	7	8	9	8	9	6	5	5	6	6	4	6	5
New Mean	**7.07**	**7.50**	6.80	5.73	5.67	**7.07**	6.40	**7.33**	**7.87**	6.83	5.90	5.50	5.80	**7.37**	4.73	5.67	5.60

3.5 Extraction of concise hierarchy

Based on the surveys and its analysis, a concise hierarchy is extracted in this step. This hierarchy has been based on the decision makers(the R&D defense industry) chosen mean of at least 6.9. Increasing the mean will increase the number of criterion that have to be analyzed by the DM and will result in more time on part of the DM. If the nature of the problem is sensitive the mean can be adjusted to include more criteria. In the present case therefore, as a result of the chosen mean, an interesting observation can be made:

- As a result of the cumulative surveys and the chosen mean, many important objectives have been left out. Each of these objectives can be vitally important if the problem under consideration gets more sensitive.

Table 20: Concise Hierarchy

Scientific and Technological Merit						Potential Benefits					Project Execution				Project Risk		
Competitiveness of Technology	Relevance of Technology		Academic Record of Funding Seekers			Economic Benefit	Social Benefit				Quality of Technical Plan		Availability of Resources		Technical Risk	Development Risk	Commercial Risk
	Technological connections	Technological extendibility	Publications	Previous R&D project history	Peer review		Improvements on QESIS	Job Opportunities	Benefits for human life	The contributions to the state of Knowledge	Content of technical plan	Environmental and safety consideration	Technical support	Equipment support		Risk for time cost	

CHAPTER FOUR
CASE STUDY

From the decision makers of the R&D defense industry that we are considering, we were given the following four projects which we are supposed to evaluate against the derived concise hierarchy.

Projects for Case Study	
P01	Digital Neutron radiography and tomography facility for non-destructive testing
P02	Development of higher-efficiency thermoelectric materials that recover waste heat
P03	Development of position sensitive neutron detectors
P04	Cheap re-useable blood glucose sensors based on nano-materials

Each of these four projects are to be individually assessed by the DM against all the criteria in the hierarchy as shown in the accompanying figure using AHP. Based on mathematical calculations of the AHP and using estimation software (developed by my co-supervisor) PriEST "Precise Estimation Tool" we are able to extract decision matrices. Pairwise comparisons are carried out between all the aspects, objectives and criteria and these are then evaluated against each project to each the decision matrix. These decision matrices are then mathematically analyzed using geometric mean to calculate weights. The matrices are then normalized. AS an example of how the matrices are solved, consider an arbitary matrix:

	A01	A02	A03
A01	1	1/2	3
A02	2	1	4
A03	1/3	1/4	1

The Geometric Mean is calculated as follows:

Geometric Mean:

Row 01: (1*0.5*3)^(1/3) = 1.61
Row 02: (2*1*4)^(1/3) = 1.91
Row 03: (0.33*0.25*1) ^(1/3)= 1.16

Summation:

Row 01 + Row 02 + Row 03: (1.61+1.91+1.16)= 4.68

Normalization:

Row 01: (1.61/4.68) = 0.34
Row 02: (1.91/4.68) = 0.40
Row 03: (1.16/4.68) = 0.2

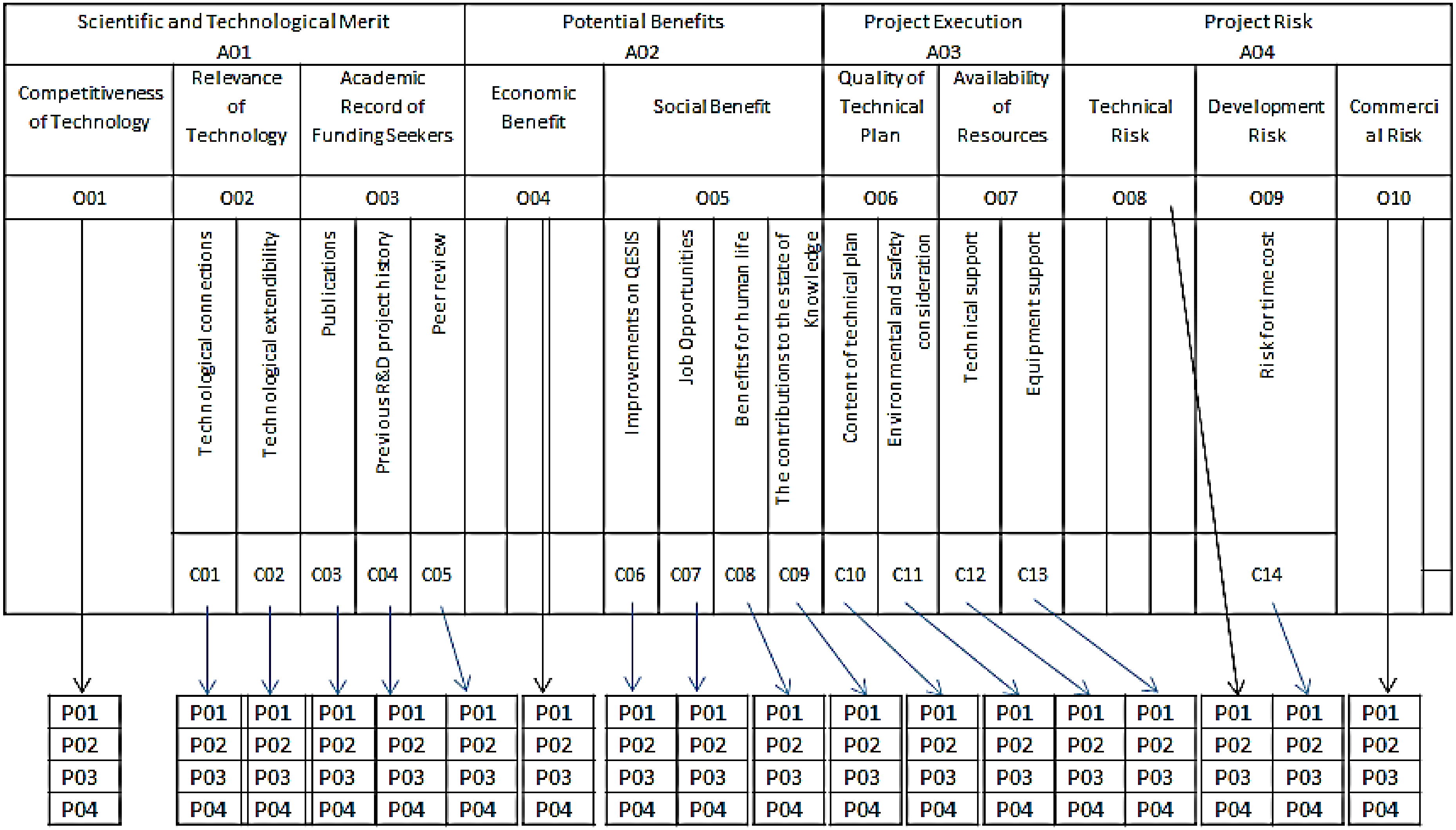


Table 21-Project Rankings against Criteria

4.1 Pairwise comparison between Aspects

	A01	A02	A03	A04
A01	1	1/7	1/8	1/8
A02	7	1	1/9	1/9
A03	8	9	1	9
A04	8	9	1/9	1

4.2 Pairwise comparison between objectives

A01	O01	O02	O03
O01	1	1	1/9
O02	1	1	1/3
O03	9	3	1

A02	O04	O05
O04	1	7
O05	1/7	1

A03	O06	O07
O06	1	5
O07	1/5	1

A04	O08	O09	O10
O08	1	1	7
O09	1	1	1
O10	1/7	1	1

4.3 Pairwise comparison between criteria

O01	C01	C02
C01	1	3
C02	1/3	1

O02	C03	C04	C05
C03	1	1	1/3
C04	1	1	8
C05	3	1/8	1

O03	C06	C07	C08	C09
C06	1	3	1	5
C07	1/3	1	2	3
C08	1	½	1	5
C09	1/5	1	1/3	1

O04	C10	C11
C10	1	3
C11	1/3	1

O05	C12	C13
C12	1	1
C13	1	1

O06	C14
C14	1

4.4 PAIRWISE COMPARISON BETWEEN PROJECTS AND CRITERIA

O04	P01	P02	P03	P04
P01	1	5	7	4
P02	1/5	1	1/3	4
P03	1/7	3	1	4
P04	1/4	1/4	1/4	1

O01	P01	P02	P03	P04
P01	1	1/4	1	1/5
P02	4	1	4	1/7
P03	1	1/4	1	1/5
P04	5	5	7	1

O02	P01	P02	P03	P04
P01	1	1/6	1/6	1/8
P02	6	1	3	1
P03	6	1/3	1	1/4
P04	8	1	4	1

O07	P01	P02	P03	P04
P01	1	1/3	1	1/7
P02	3	1	3	1/6
P03	1	1/3	1	1/9
P04	7	6	9	1

O03	P01	P02	P03	P04
P01	1	1/5	1/7	1/2
P02	5	1	1	1
P03	7	1	1	3
P04	2	1	1/3	1

O05	P01	P02	P03	P04
P01	1	6	7	7
P02	1/6	1	6	5
P03	1/7	1/6	1	4
P04	1/7	1/5	1/4	1

O10	P01	P02	P03	P04
P01	1	3	1	3
P02	1/3	1	1/4	1
P03	1	4	1	4
P04	1/3	1	1/4	1

O06	P01	P02	P03	P04
P01	1	1	6	1/8
P02	1	1	6	1/7
P03	1/6	1/6	1	1/9
P04	8	7	9	1

O08	P01	P02	P03	P04
P01	1	1/8	4	1/8
P02	8	1	7	1/6
P03	1/4	1/7	1	1/9
P04	8	6	9	1

O09	P01	P02	P03	P04
P01	1	1/8	1	1/8
P02	8	1	8	1
P03	1	1/8	1	1/8
P04	8	1	8	1

O11	P01	P02	P03	P04
P01	1	1	1	1
P02	1	1	1	1
P03	1	1	1	1
P04	1	1	1	1

O12	P01	P02	P03	P04
P01	1	3	2	6
P02	1/3	1	1/2	1
P03	1/2	2	1	2
P04	1/6	1	1/2	1

O14	P01	P02	P03	P04
P01	1	1/7	2	1/6
P02	7	1	6	1
P03	1/2	1/6	1	1/5
P04	6	1	5	1

O13	P01	P02	P03	P04
P01	1	1	1	1
P02	1	1	1	1
P03	1	1	1	1
P04	1	1	1	1

PriEST tool can be employed to easily compute the MCDM problem and get a ranking of the projects. The figure below shows a matrix as made through the PriEST tool.

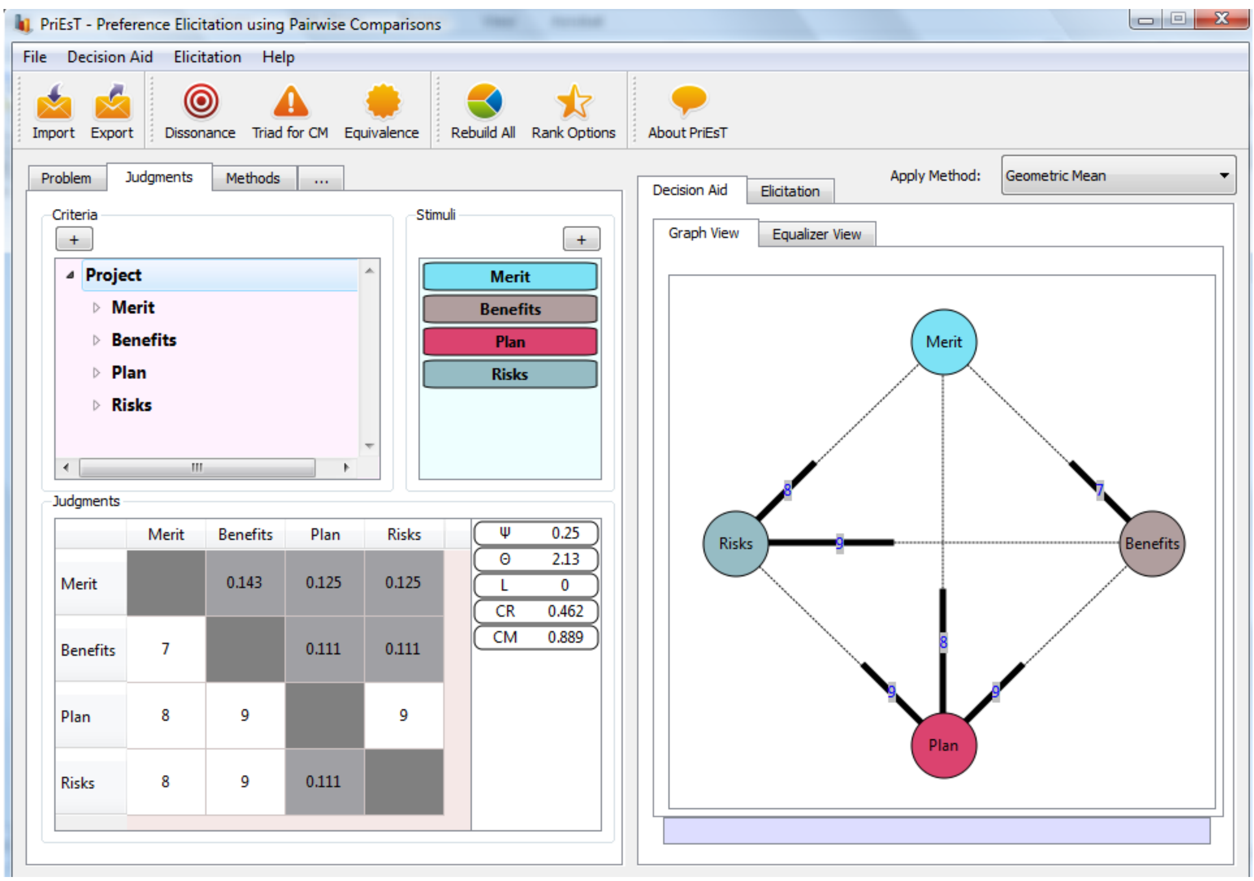


Figure 09- Decision Matrix (PriEST)

CHAPTER FIVE
RESULTS AND ITERATIONS

5.1 RESULTS

Based on the pairwise comparison matrices and applying the AHP on those matrices we reach a decision on the prioritization of the projects. The ranking obtained is as follows:

Projects for Case Study		
Initial Rank	Final Rank	
P01	P02	Digital Neutron radiography and tomography facility for non-destructive testing
P02	P03	Development of higher-efficiency thermoelectric materials that recover waste heat
P03	P01	Development of position sensitive neutron detectors
P04	P04	Cheap re-useable blood glucose sensors based on nano-materials

A final ranking is obtained using the PriEST tool as shown below:

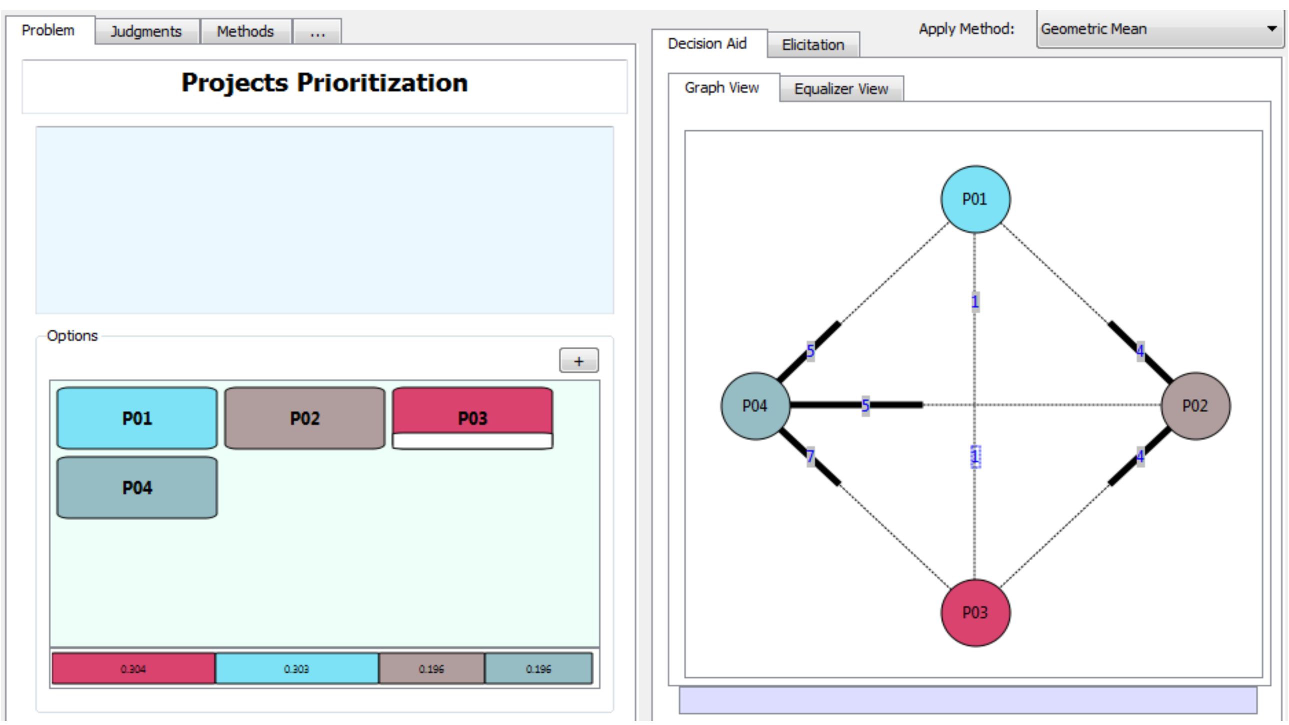


Figure 10- Final Ranks of Projects (PriEST)

Based on this result, it can be inferred that given the resources at the hand of the R&D industry and given the weights given by each DM to the corresponding criteria P03 is the most feasible project to be carried out by the industry.

5.2 INCONSISTENCIES

A feature of PriEST tool is that it can show if a decision taken by a DM is inconsistent or not. Based on the nature of the decisions, the inconsistency can be either

- Ordinal
- Cardinal

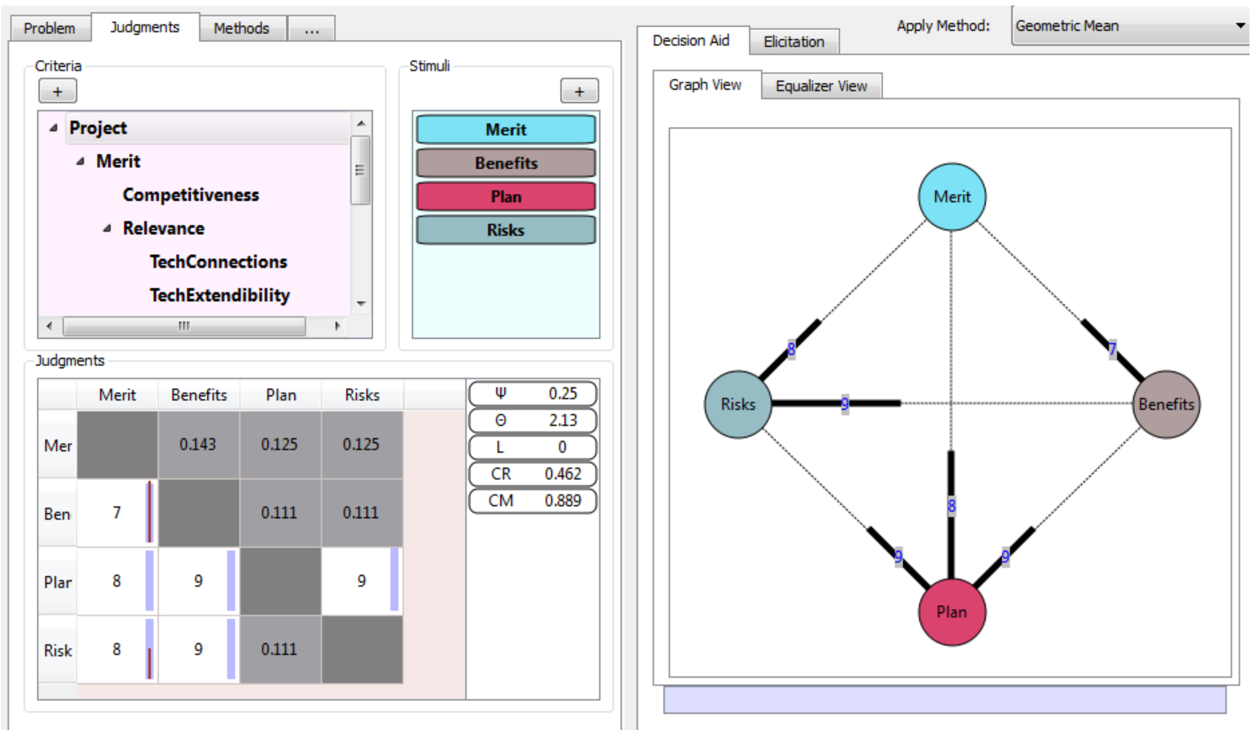


Figure 11- Inconsistencies in Decision Making

It is a fundamental rule of nature that if a>b and b>c than by logic a>c. PriEST tells the DM if any such inconsistency arises in the decision made. In the figure above, we can see that the red line in the matrices correspond to order inconsistency and the purple line corresponds to cardinal inconsistency which have to be removed in order to improve the rankings. As a result, the tool advises the DM to redo the pairwise comparisons for those particular criteria. The figure below shows the re-ranked matrix.

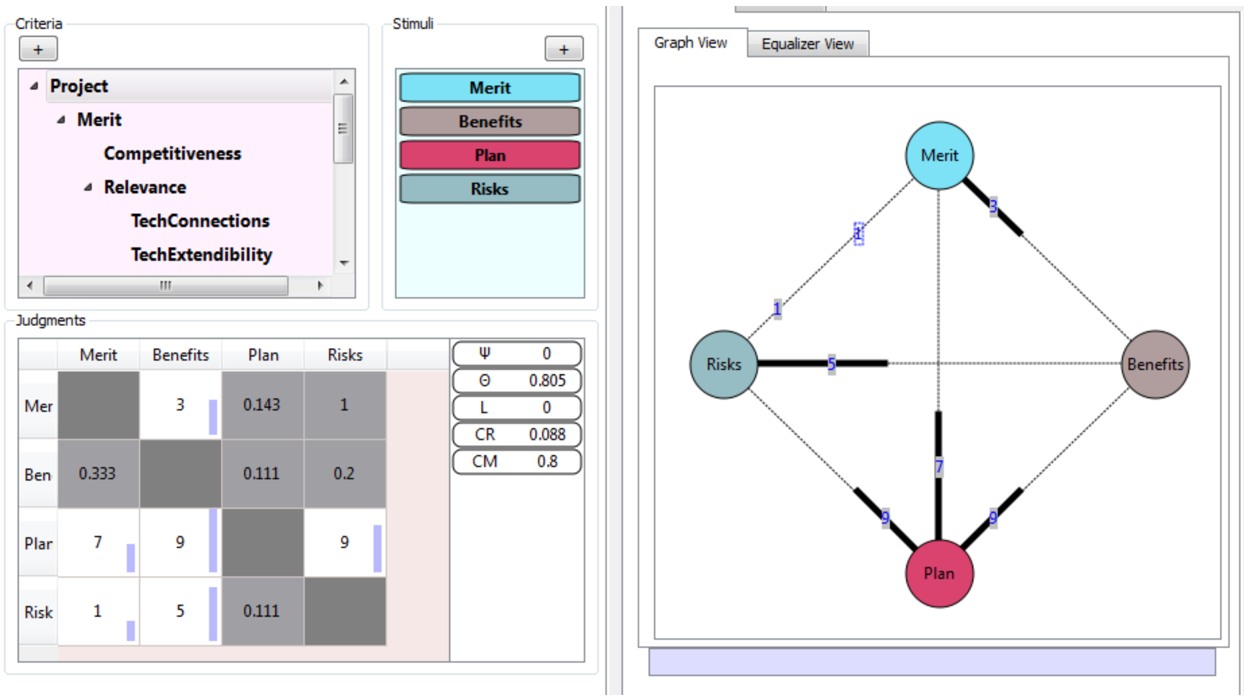


Figure 12: Re-ranked Matrix

Here we can see that he ordinal inconsistency has been greatly reduced. The cardinal inconsistency can be reduced by asking the DM to do the pairwise comparisons again but as was mentioned in the beginning that the purpose of AHP is not to provide the "correct" answer but rather generate the best possible one based on the decisions and al decisions cannot be completely efficient since trying to reduce the inconsistency to zero would result in more time lapses and other delays. The following figures provide other inconsistent matrices and their re-ranked versions.

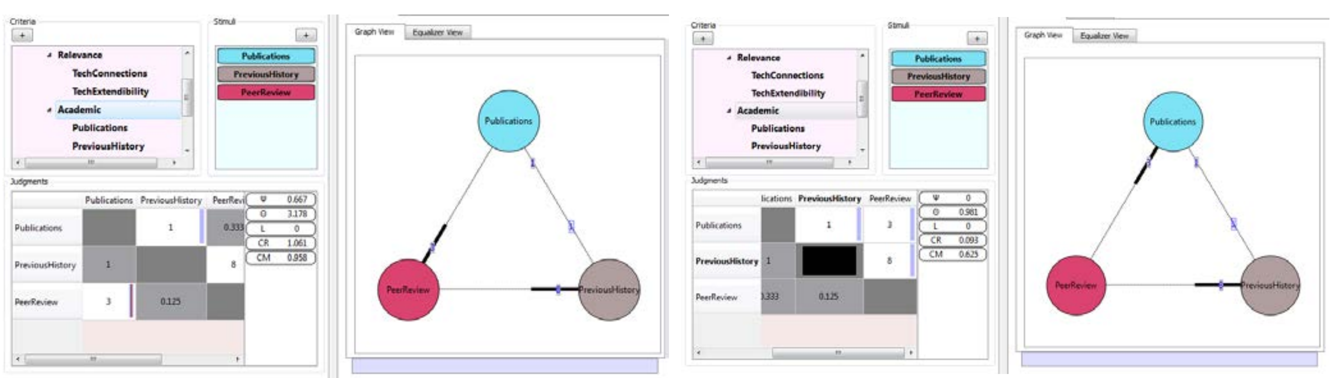


Figure 13- Inconsistency in Academic History and re-ranked Matrix

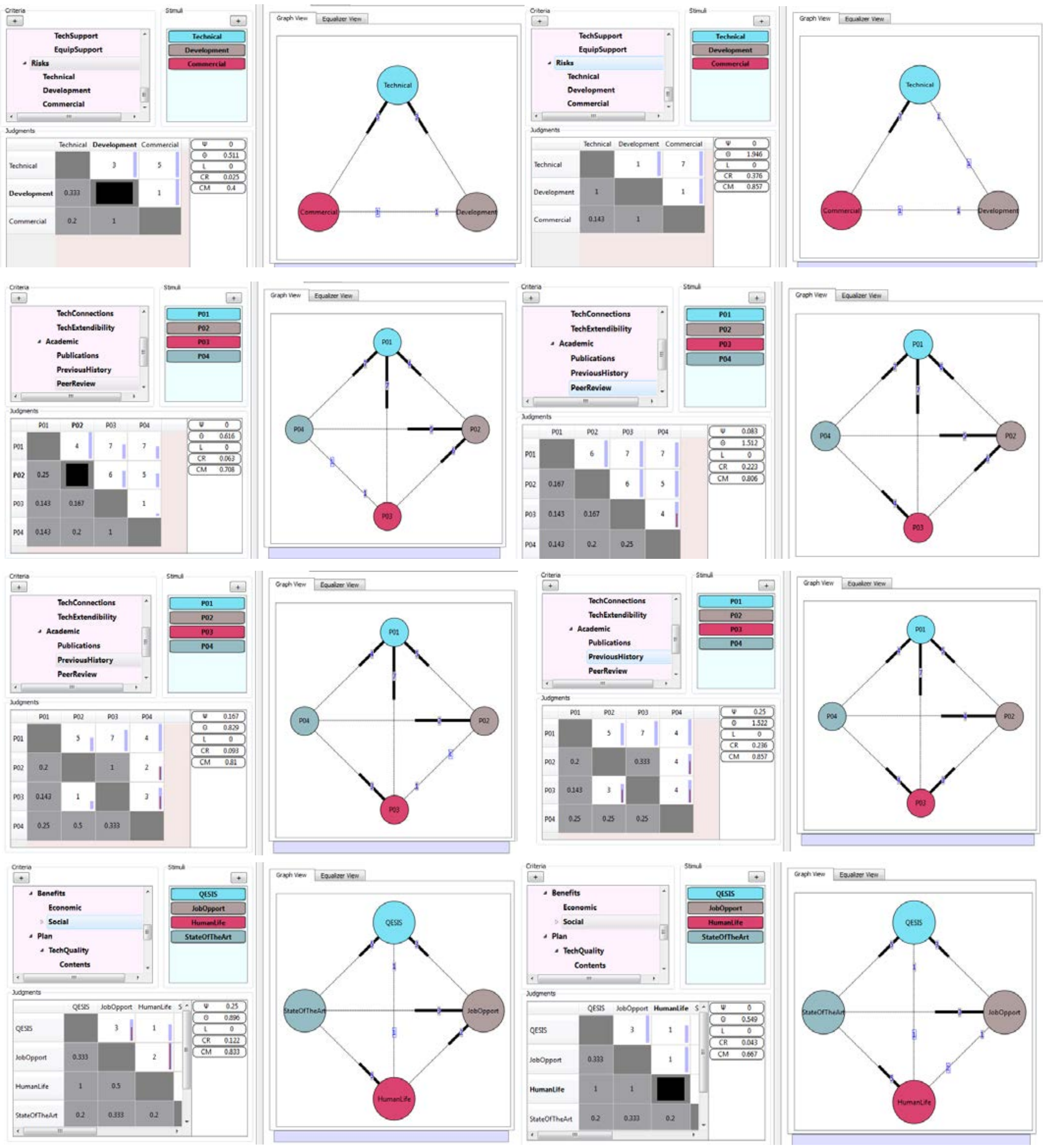


Figure 14- Inconsistencies and re-ranked matrices for Previous History, Peer Review, Risk and Social Benefits

After the majority of the inconsistencies have been removed from the decisions, a final ranking is re-calculated in order to check if the rankings have changed or not.

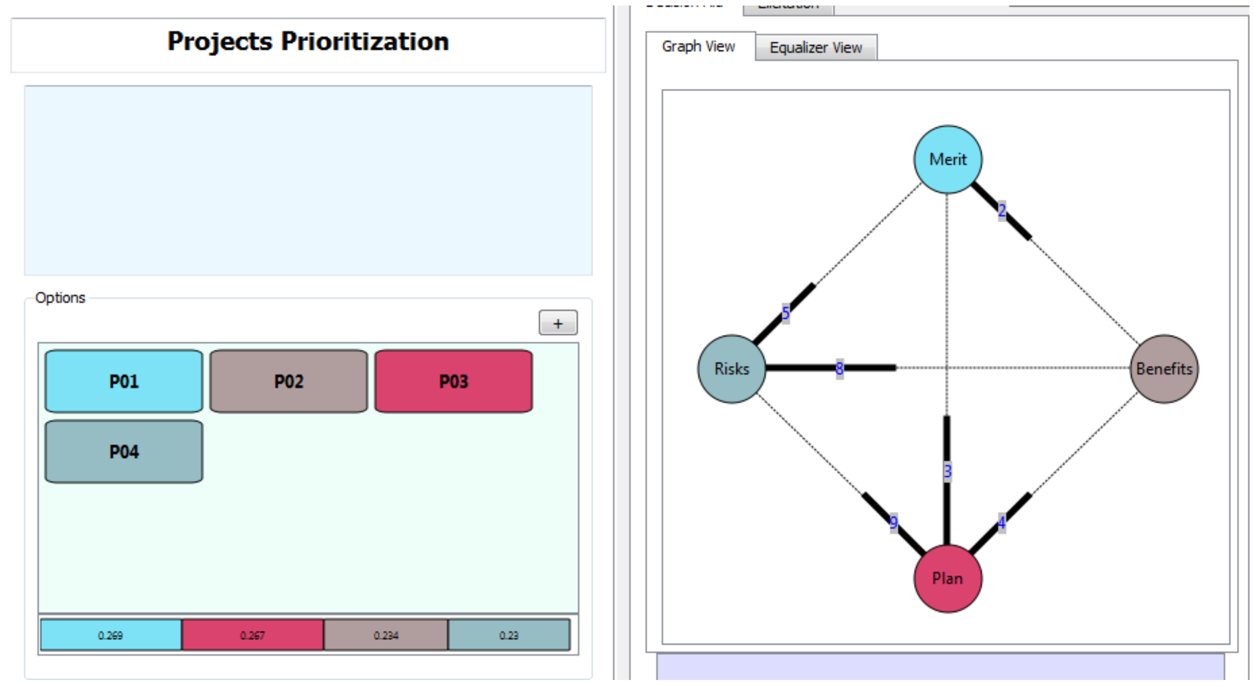


Figure 15- Final Ranks of Project after removal of inconsistencies (PriEST)

Projects for Case Study			
Initial Rank	Final Rank	Re-Ranked Projects	
P01	P02	P01	Digital Neutron radiography and tomography facility for non-destructive testing
P02	P03	P03	Development of higher-efficiency thermoelectric materials that recover waste heat
P03	P01	P02	Development of position sensitive neutron detectors
P04	P04	P04	Cheap re-useable blood glucose sensors based on nano-materials

We can see that after the iterations, P01 becomes higher in rank than P03. In this way, the number of biases that any DM might have are removed from the decision making process as a result of a through literary process. Based on a satisfaction survey conducted from the R&D industry, the decision makers were satisfied with the ranking based on their available resources and infrastructure.

CHATER SIX
CONCLUSION

Innovative products and services are developed to permit people to efficiently do the tasks better than they previously could not. However, inventions also have a certain risk associated to them. The level of this risk depends on the choices that people make in consuming it. Based on the thesis and the extensive research into the topic of decision making and operations research, I have come to the conclusion that MCDM is a necessary part for an effective decision making process and even more when t comes to R&D project prioritization. For a fledgling economy such as Pakistan, each Rupee spent should have a logical value and where and how it is spent depends on the decision made by the decision maker.

Many studies have been carried out the use AHP, however using AHP to prioritize research projects in private and/or public sector using a uniform hierarchy is discussed less. This thesis used Analytic Hierarchy Process in order to prioritize R&D projects. A simulation tool, PriEST was used to realize deviations in the decisions of the decision committee when they measured diverse decision risks. Any inconsistencies arising from personal biases were removed and the process of decision making was made efficient. Surveys were conducted from experts in various fields (engineering, natural sciences, management and the Industry) to understand how people from different fields react to various criteria. Therefore, the influence of this thesis was to range AHP for research and development project selection in the public and/or private sector. Moreover, existing studies on AHP in R&D projects like Hsu et al. [36] and Wang et al. [29] do not take into consideration the decision risk and inconsistencies associated with the decision making process. I tried to unify a certain degree of assurance to simulate professional decisions in various risks and inconsistencies.

Assessing R&D projects typically necessitates an expert understanding of the process as well as relevant experience and specialists may show prejudiced decisions. The method of Analytical Hierarchy process proposed in this thesis has the following advantages to overcome this problem:

- AHP assists decision-makers in segregating the main decision problem into a tiered decision structure.
- This hierarchial approach helps in the formulation of judgment ambiguity for project selection.
- The PriEST simulation tool assists the DM in understanding how judgments change in diverse decision risks by integrating a certain degree of optimism.
- Finally Analytical Hierarchy Process assists in resolving difference of opinion among the experts.

While this approach of Analytical Hierarchy Process presented in this thesis is appropriate for R&D Project Prioritization, as with all things there are a few restrictions to this appraoch:

- The criteria used in to conduct this research are considered independent. Additional refinement in the hierarchy is essential in order to better comprehend the connections amongst criteria.
- It can debated upon as to whether this shortlisting process can actually be a two phase process subdivided into:
    a. Prescreening Phase: whereby every project is to be gauged against a set of pre-requisite criteria and whether some of the criteria included in the hierarchy should in actuality be a part of the screening process for example resource availability.
    b. Weight Allocation Phase: Each candidate project is evaluated against each criterion as shown above (Section 3&4).
- The threshold of the mean that is identified by the decision maker may pose a possible hurdle as the DM may decide to overly complicate the decision making process and as a result may actually adversely affect the overall efficiency of the proces

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APPENDIX A
ANALYTICAL HIERARCHY PROCESS-AN EXAMPLE

This Appendix tries to explain the mathematics behind the Analytical Hierarchy Process by solving an example. Suppose we have to solve an MCDM problem of prioritizing three projects using AHP.

- Project 01: Production of Unmanned Aerial Vehicles (UAVs')
- Project 02: Efficient Energy Transfer Utilizing Smart Grids
- Project 03: Design and Implementation of a Centralized Patient Management System

Based on the flow diagram of AHP (figure 02 above) we will decompose the problem in the following phases:

- CONCEPTUALIZE: Define the problem: To prioritize R&D Projects
- FORMULATE: Determine the Criteria for comparison
    1. Social Benefits
    2. Availability of Resources
    3. Developmental Risks
- DISCOVER: Candidate Projects are provided to be prioritized
    1. Project 01
    2. Project 02
    3. Project 03
- EVALUATE: Candidate Projects are prioritized based on comparison with each criteria

The following hierarchy is developed based on the above discussion

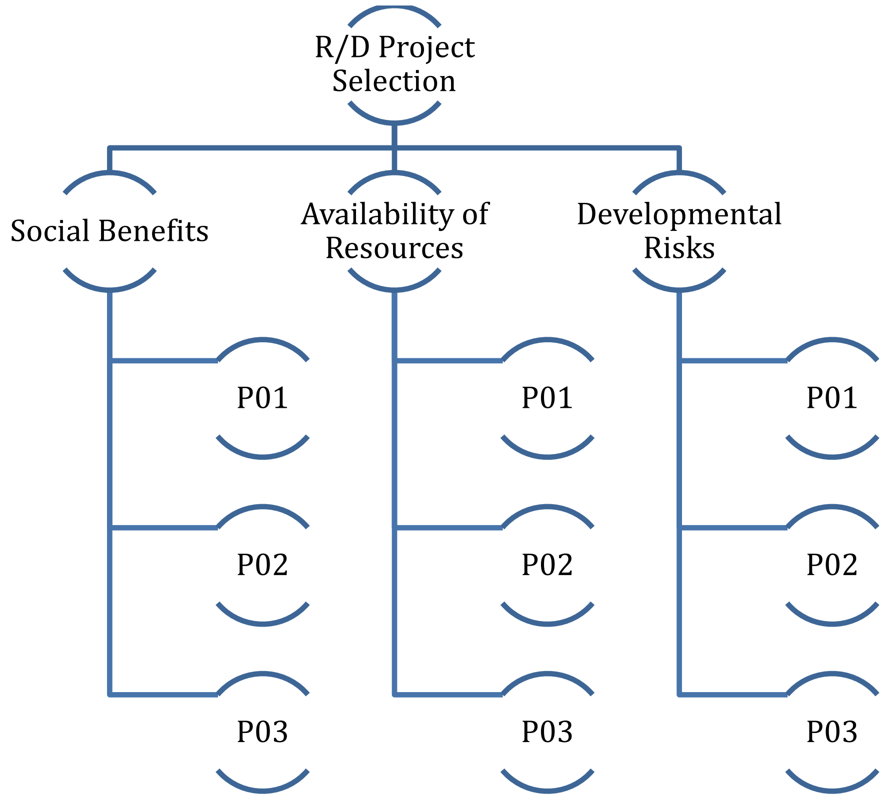

Figure A1- Hierarchy for AHP Example

The next step is the pairwise comparisons. The pairwise comparisons are done initially between each criterion:

Criteria	Social Benefits	Availability of Resources	Developmental Risks
Social Benefits	1	1/2	3
Availability of Resources	2	1	4
Developmental Risks	1/3	1/4	1

Figure A2- Pairwise Comparison between Criterion

The next step is to calculate the weights. This is done through Geometric Mean:

Geometric Mean:

- Row 01: (1*0.5*3)^(1/3) = 1.61
- Row 02: (2*1*4)^(1/3) = 1.91
- Row 03: (0.33*0.25*1) ^(1/3)= 1.16

Summation:

- Row 01 + Row 02 + Row 03: (1.61+1.91+1.16)= 4.68

Normalization:

- Row 01: (1.61/4.68) = 0.34
- Row 02: (1.91/4.68) = 0.40
- Row 03: (1.16/4.68) = 0.24

The next step is to evaluate each project against each criterion individually:

Social Benefits	Project 01	Project 02	Project 03
Project 01	1	1/3	5
Project 02	3	1	5
Project 03	5	1/5	1

Figure A3- Pairwise Comparison between Projects for Social Benefits

The respective weights are:

Geometric Mean:

- Row 01: 1.15
- Row 02: 2.08
- Row 03: 1.83

Summation:

- Row 01 + Row 02 + Row 03: 5.06

Normalization:

- Row 01: 0.22
- Row 02: 0.41
- Row 03: 0.36

Availability of Resources	Project 01	Project 02	Project 03
Project 01	1	3	5
Project 02	1/3	1	3
Project 03	1/5	1/3	1

Figure A4- Pairwise Comparison between Projects for Availability of Resources

Geometric Mean:

- Row 01: 2.08
- Row 02: 1.62
- Row 03: 1.15

Summation:

- Row 01 + Row 02 + Row 03: 4.85

Normalization:

- Row 01: 0.42
- Row 02: 0.33
- Row 03: 0.23

Developmental Risks	Project 01	Project 02	Project 03
Project 01	1	3	3
Project 02	1/3	1	4
Project 03	1/3	1/4	1

Figure A5-Pairwise Comparison between Projects and Developmental Risks

Geometric Mean:

- Row 01: 1.91
- Row 02: 1.74
- Row 03: 1.16

Summation:

- Row 01 + Row 02 + Row 03: 4.81

Normalization:

- Row 01: 0.39
- Row 02: 0.36
- Row 03: 0.24

The resulting hierarchy as a result of these pairwise comparisons is as follows:

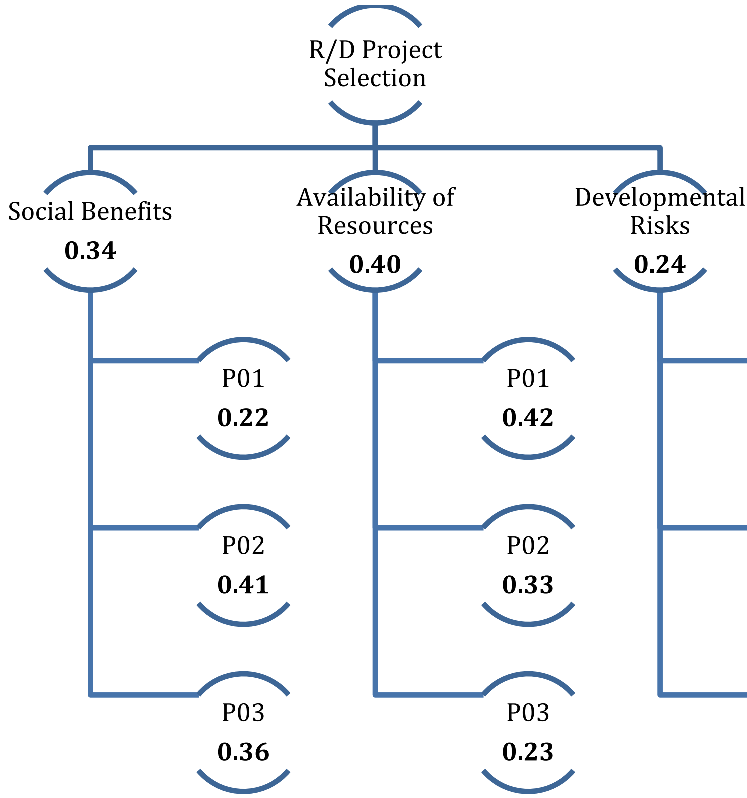

Figure A6- Hierarchy with Weights

The final step is to draw the decision matrix. This is made from all the calculated weights from the pairwise comparisons.

Decision Matrix

$$\begin{bmatrix} 0.22 & 0.42 & 0.39 \\ 0.41 & 0.33 & 0.36 \\ 0.36 & 0.23 & 0.24 \end{bmatrix} \begin{bmatrix} 0.34 \\ 0.40 \\ 0.24 \end{bmatrix}$$

Matrix Multiplication:

- Row 01 * Column 01: (0.22*0.34)+(0.42*0.40)+(0.39*0.24)= 0.33
- Row 02 * Column 01: (0.41*0.34)+(0.33*0.40)+(0.36*0.24)= 0.35
- Row 03 * Column 01: (0.36*0.34)+(0.23*0.40)+(0.24*0.24)= 0.27

Resultant Matrix:

$$\begin{bmatrix} \mathbf{0.33} \\ \mathbf{0.35} \\ \mathbf{0.27} \end{bmatrix} \Rightarrow \begin{bmatrix} \boldsymbol{Project\ 01} \\ \boldsymbol{Project\ 02} \\ \boldsymbol{Project\ 03} \end{bmatrix}$$

Therefore the final rankings of the projects are as follows

Rank	Final Weights	Project Number	Project Title
01	0.35	02	Production of Unmanned Aerial Vehicles (UAVs’)
02	0.33	01	Efficient Energy Transfer Utilizing Smart Grids
03	0.27	03	Design and Implementation of a Centralized Patient Management System